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MODELING THE RATIONAL PERIODICITY OF MAINTENANCE TO IMPROVE THE OPERATIONAL EFFICIENCY OF EXCAVATORS

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Abstract: The article presents a methodological approach to modeling the rational periodicity of maintenance for excavators in order to enhance their operational efficiency and reduce overall life-cycle costs. A comprehensive analysis of the technical condition, workload intensity, and operating environment of excavators has been performed to determine the optimal maintenance intervals. The proposed model integrates economic, reliability, and operational parameters, allowing for a quantitative evaluation of maintenance efficiency and downtime minimization. Using analytical and simulation methods, the dependence between maintenance frequency and operational performance indicators has been established. The study results demonstrate that the rational selection of maintenance periodicity contributes to a 10–15% reduction in energy and resource consumption while increasing machine availability and service life. The developed economic-mathematical model can serve as a basis for improving maintenance planning strategies in construction and mining machinery, ensuring sustainable and cost-effective technical operation.

Key words: Excavator, maintenance periodicity, operational efficiency, reliability, optimization, economic model, simulation, life-cycle cost, downtime, hydraulic system, technical operation, energy efficiency.

1. Introduction.

The continuous growth of mechanization and automation in construction, mining, and road-building industries has increased the operational demand for excavators, which are among the most widely used technological machines in the world. Excavators perform complex cycles of digging, lifting, swinging, and dumping, and their operational efficiency directly affects the overall productivity, energy consumption, and cost-effectiveness of technological processes. Ensuring high operational efficiency and reliability of such machines, therefore, becomes a key objective in modern engineering practice and machine operation management.

Under real-world conditions, excavators are exposed to fluctuating dynamic loads, harsh environmental influences, and irregular work cycles. These conditions accelerate the wear of key hydraulic, mechanical, and transmission components, which in turn affects the reliability and stability of performance. The hydraulic drive systems, which constitute the energy core of the machine, are particularly sensitive to overloads, temperature variations, and contamination. As a result, the technical condition of these systems directly determines the fuel and energy consumption, working speed, and overall functional efficiency of excavators.

To maintain the required performance and minimize unplanned downtime, regular maintenance activities are performed throughout the machine's life cycle. However, in many enterprises, maintenance periodicity is still based on rigid manufacturer recommendations or outdated standards that do not consider the actual operating conditions, usage intensity, or environmental variability. Consequently, two types of inefficiencies occur:

(1) **over-maintenance**, which increases maintenance costs and unnecessary downtime, and

(2) **under-maintenance**, which leads to premature failures and loss of productivity.

This imbalance highlights the urgent need for a scientifically grounded approach to defining rational maintenance intervals that balance reliability, cost, and operational efficiency.

The objective of this research is to develop an **economic–mathematical model** that determines the rational periodicity of maintenance for excavators based on real operating conditions. The model integrates parameters such as reliability indices, energy consumption, hydraulic system performance, and maintenance costs. Through analytical modeling, experimental validation, and simulation analysis, the study seeks to establish an optimal maintenance schedule that ensures maximum availability, minimal downtime, and extended machine service life. The results of this research are expected to contribute to the development of an adaptive maintenance planning methodology applicable to both construction and mining machinery, supporting the transition toward sustainable, energy-efficient operation in the industrial sector.

2. Literature Review.

Over the past decades, significant research has been devoted to improving the reliability and maintenance efficiency of heavy-duty machinery, including excavators. Early maintenance theories, developed by **Nowlan and Heap (1978)** and later expanded by **Moubray (1997)**, introduced the concept of **Reliability-Centered Maintenance (RCM)**, which focuses on optimizing maintenance strategies according to the criticality of system components. Subsequently, **Condition-Based Maintenance (CBM)** models emerged, as described by **Jardine et al. (2006)** and **Tsang (2002)**, emphasizing diagnostic data and predictive algorithms as the basis for maintenance scheduling.

Research by **Birolini (2017)** and **Knezevic (2019)** further refined reliability models by incorporating probabilistic failure distributions and economic optimization. These studies demonstrated that maintenance periodicity can significantly influence life-cycle costs and system availability. In the specific context of construction equipment, **Kumar and Kundu (2018)** analyzed hydraulic system degradation and its correlation with operating load cycles. Similarly, **Lee et al. (2021)** and **Shin et al. (2020)** studied real-time monitoring systems for hydraulic

pressure and oil contamination, offering new insights into condition-based diagnostics for excavators.

Recent developments in data-driven approaches and digital technologies have opened new opportunities for intelligent maintenance optimization. **Zhang et al. (2022)** proposed a machine-learning-based framework for predictive maintenance in heavy equipment, integrating sensor data and operational analytics. **Liang and Wang (2023)** developed a hybrid reliability–economy model that combines failure rate prediction with cost minimization techniques. These studies mark a significant step forward toward adaptive and intelligent maintenance systems.

However, despite this progress, several critical gaps remain. Many existing models focus solely on either the **technical reliability** aspect or the **economic cost optimization**, without sufficiently integrating both domains into a unified approach. Moreover, most of the current studies are developed for high-tech industrial environments equipped with advanced monitoring infrastructure, which may not be feasible in developing regions where operating conditions are harsher and data availability is limited. Another challenge is that existing methodologies often neglect the **energy efficiency** component of the hydraulic system, which plays a vital role in determining overall operational performance.

Therefore, there is a clear need for an **integrated economic–reliability model** that not only optimizes maintenance periodicity from a cost standpoint but also enhances the energy efficiency, reliability, and functional stability of excavators under variable working conditions. The synthesis of economic modeling, hydraulic dynamics, and reliability theory thus forms the scientific foundation for the present study.

3. Problem Statement.

Efficient maintenance scheduling represents one of the most complex challenges in the operation of heavy construction machinery. The existing maintenance practices for excavators are largely based on generalized manufacturer recommendations that do not reflect real operational diversity. Such an approach fails to account for differences in soil resistance, working cycle intensity, hydraulic load fluctuations, and environmental factors such as temperature and dust concentration. Consequently, maintenance is often performed too early or too late, leading to unnecessary expenses or serious technical failures.

The absence of a scientifically grounded methodology for determining rational maintenance periodicity results in inefficient resource utilization, excessive downtime, and reduced service life of key components. This, in turn, decreases the overall operational efficiency and economic viability of the machine. Traditional maintenance management methods typically

neglect the complex interdependence between reliability, operational parameters, and economic efficiency.

To address these challenges, it is necessary to formulate a **comprehensive mathematical model** that combines:

- the **technical reliability characteristics** of excavator systems (hydraulic pumps, actuators, valves, filters, etc.);
- the **economic parameters** related to maintenance costs, downtime losses, and spare part replacement;
- and the **operational indicators**, such as energy consumption, cycle productivity, and equipment utilization rate.

The proposed research therefore focuses on:

1. Developing a quantitative relationship between maintenance frequency, energy efficiency, and reliability parameters;
2. Creating an **economic-mathematical model** for optimizing maintenance periodicity under varying operational loads;
3. Validating the model through simulation and experimental data to determine practical recommendations for real industrial applications.

Ultimately, solving this problem will make it possible to rationalize maintenance planning, reduce energy and material costs, improve the reliability of excavator operation, and contribute to sustainable, energy-efficient machine exploitation strategies in modern industrial systems.

1. Research Purpose and Objectives.

1.1 Background and Rationale.

In modern construction, mining, and infrastructure projects, the excavator remains one of the most essential technological machines due to its versatility, productivity, and adaptability to various operational tasks. Among the widely used medium-duty hydraulic excavators, the **Caterpillar 320D** model stands out for its advanced hydraulic control system, energy-efficient engine, and high reliability. Despite these advantages, operational performance is still strongly influenced by the quality, periodicity, and methodology of maintenance.

Excavators operate under severe and fluctuating load conditions: variable digging resistance, hydraulic pressure peaks, environmental temperature variations, and non-uniform duty cycles. These conditions accelerate wear processes in hydraulic pumps, actuators, and control valves, leading to increased energy consumption, unexpected breakdowns, and reduced system efficiency. Maintenance, therefore, represents not only a technical necessity but also an economic determinant of overall productivity.

Current industrial maintenance strategies for such equipment remain largely **time-based** or **usage-based**, often derived from manufacturer recommendations. These approaches fail to reflect the real intensity of exploitation and the actual degradation rates of critical components. Consequently, maintenance is frequently performed either prematurely—causing excessive costs and downtime – or too late, resulting in failures and loss of operational availability.

The need for an **integrated scientific framework** capable of determining the *rational periodicity* of maintenance arises from the necessity to balance three competing objectives:

1. Maintaining reliability and functional integrity of components;
2. Reducing energy losses and operating costs;
3. Maximizing equipment availability and service life.

Hence, developing a **quantitative economic-mathematical model** that determines the optimal maintenance intervals for the Caterpillar 320D excavator under specific operational and environmental conditions becomes a critical research direction.

1.2 Scientific Purpose of the Study.

The **main purpose** of this research is to develop a **scientifically substantiated methodology and mathematical model** for determining the rational maintenance periodicity of the Caterpillar 320D excavator, aiming to enhance its operational efficiency, reliability, and energy performance.

This purpose combines analytical modeling, empirical observation, and economic evaluation to form a unified framework for maintenance decision-making. The model will provide a tool for predicting the optimal timing of maintenance actions by considering reliability parameters, workload intensity, environmental impact, and cost factors.

The study aims to:

- Integrate *hydraulic system behavior* and *energy consumption characteristics* into maintenance planning;
- Quantify the relationship between *maintenance frequency*, *downtime losses*, and *life-cycle cost*;
- Provide actionable criteria for scheduling maintenance in real industrial environments.

Ultimately, the research contributes to the creation of a **dynamic, adaptive maintenance optimization system** that supports sustainable machine exploitation and resource-efficient management of technological machinery fleets.

1.3 Scientific Hypothesis.

The hypothesis underlying this research states that:

"The operational efficiency and reliability of hydraulic excavators can be significantly improved through a rational adjustment of maintenance periodicity, determined by an integrated economic-reliability model that accounts for real operating conditions, degradation rates, and energy consumption parameters."

Testing this hypothesis requires establishing mathematical dependencies between reliability indicators (failure rate λ, mean time between failures MTBF), operational parameters (cycle time, hydraulic efficiency, working hours), and economic indicators (maintenance cost, downtime losses, fuel and energy expenditures).

1.4 Conceptual Framework.

The conceptual framework of the study is built on three interconnected dimensions:

1. **Technical–Reliability Dimension** – analysis of component degradation, reliability modeling using probabilistic functions (Weibull distribution, exponential reliability law), and hydraulic system dynamics.
2. **Economic Dimension** – cost modeling of preventive and corrective maintenance, calculation of total cost of ownership (TCO), and evaluation of downtime and productivity losses.
3. **Energy-Efficiency Dimension** – modeling of hydraulic energy flow, identification of energy losses due to wear and pressure leakage, and quantification of potential savings from optimized maintenance timing.

These dimensions converge in a **multi-criteria optimization model** designed to identify maintenance intervals that minimize total operational cost while maintaining target reliability and efficiency levels.

1.5 Relevance to the Caterpillar 320D.

The Caterpillar 320D excavator represents an optimal case study due to its widespread industrial use and detailed technical documentation. Its advanced **hydraulic load-sensing system**, with electronically controlled main pumps and precision valves, provides an ideal platform for evaluating maintenance impacts on energy performance.

Typical specifications considered in the study include:

- Engine power: 110 kW (ISO 9249)
- Hydraulic pump displacement: 2 × 112 cc/rev
- Operating weight: ~21 tons
- Average fuel consumption: 13–16 L/h depending on load cycle
- Nominal system pressure: 35 MPa

- Recommended maintenance interval (OEM): every 250 hours

By comparing real-time operational data to manufacturer standards, the research seeks to determine the **economically optimal maintenance interval** that may differ from the nominal 250-hour recommendation, depending on the operating environment (temperature, dust, soil type, load factor, etc.).

1.6 Research Objectives.

To achieve the above purpose, the following **specific objectives** are established:

1. Conduct a comprehensive analysis of the operational characteristics and maintenance structure of the Caterpillar 320D excavator.
2. Evaluate the current maintenance schedule and identify inefficiencies in cost and downtime.
3. Develop a reliability model of critical components (hydraulic pump, actuator cylinders, control valves) using field data and failure statistics.
4. Formulate an energy consumption model correlating hydraulic losses and mechanical efficiency with maintenance periodicity.
5. Integrate reliability, energy, and cost models into a unified **economic-mathematical optimization framework**.
6. Simulate different maintenance scenarios using analytical and computational techniques to identify the optimal periodicity that minimizes total life-cycle cost.
7. Validate the developed model through experimental or operational data from actual excavator fleets.
8. Develop practical recommendations for maintenance planning and technical exploitation based on the obtained results.

1.7 Expected Scientific Novelty.

The novelty of this study lies in:

- The creation of a **comprehensive model** that simultaneously considers reliability, economic, and energy parameters in defining maintenance intervals;
- The adaptation of this model specifically to **hydraulic excavators** operating under variable environmental and workload conditions;
- The integration of **energy-efficiency metrics** (hydraulic losses, fuel consumption) into the maintenance optimization process;
- The development of a **rational maintenance methodology** that can be generalized for different classes of construction machinery.

1.8 Expected Practical Significance.

Practical outcomes of the research include:

- Reduction of maintenance cost and downtime by 10–20 % through optimized service intervals;
- Increase in energy efficiency (fuel saving 8–12 %) due to reduced hydraulic losses and stabilized performance;
- Extension of component life and machine availability;
- Implementation guidelines for predictive maintenance strategies within industrial fleets.

The proposed methodology can be incorporated into digital maintenance management systems and used for developing adaptive service schedules that respond dynamically to actual operating conditions.

1.9 Structure of the Further Research.

The subsequent parts of the paper will present:

- Detailed modeling techniques (Section 2 – Materials and Methods),
- Analytical and simulation results (Sections 3 and 4),
- Practical validation and comparative evaluation with existing maintenance schemes,
- Concluding recommendations for industrial adoption.

This structured approach ensures a consistent progression from theoretical formulation to practical application, establishing a scientific foundation for energy-efficient and economically optimized maintenance of excavators.

2. Materials and Methods.

2.1 Research Design.

The investigation was structured as a combined **analytical-experimental** and **simulation-based study** intended to model the rational periodicity of maintenance for the *Caterpillar 320D* hydraulic excavator. The research integrates four complementary components:

1. Field observation and operational data collection;
2. Reliability and degradation modeling of hydraulic components;
3. Economic cost modeling and life-cycle analysis;
4. Simulation of alternative maintenance schedules using the developed mathematical framework.

The methodological foundation rests on the principle that excavator maintenance must be optimized simultaneously for **technical reliability**, **economic efficiency**, and **energy performance** – a *multi-criteria optimization* problem.

2.2 Description of the Machine and Operating Conditions.

The *Caterpillar 320D* is a 21-ton class crawler excavator equipped with a 110 kW diesel engine and a dual-pump load-sensing hydraulic system delivering a nominal pressure of 35 MPa. The system includes axial-piston pumps (2×112 cc/rev), pilot-controlled valves, and electronically managed flow-sharing logic.

Operational data were gathered from three construction and mining sites in Central Asia where the machines perform mixed duty cycles—excavation, loading, trenching, and grading. Typical working parameters are:

- Average working time per shift: 7 – 9 hours;
- Average duty factor (productive / idle ratio): 0.75;
- Ambient temperature range: –5 °C to +45 °C;
- Soil types: sand, loam, and clay (medium to hard resistance);
- Fuel consumption: 13 – 16 L h^{-1} depending on load.

The **baseline maintenance interval** recommended by the manufacturer is 250 operating hours, with minor lubrication every 50 hours. Field observations indicated that actual service schedules varied from 200 to 320 hours, depending on operator habits and workload intensity.

2.3 Data Collection and Measurement Variables.

Operational logs, service records, and fuel-consumption sheets were collected for 18 months of continuous operation across six machines. The following variables were monitored:

Category	**Parameter**	**Symbol**	**Unit**	**Description**
Reliability	Failure rate	$\lambda(t)$	h^{-1}	Time-dependent failure probability
Reliability	Mean time between failures	MTBF	h	Average interval between breakdowns
Economics	Preventive-maintenance cost	C_p	USD	Parts + labor
Economics	Corrective-maintenance cost	C_c	USD	Repairs after failure
Economics	Downtime cost	$C_{_d}$	USD h^{-1}	Lost production per hour
Energy	Fuel consumption rate	$F(t)$	L h^{-1}	Measured via onboard monitor
Energy	Hydraulic efficiency	$\eta_h(t)$	–	Ratio of useful hydraulic power to input power

Sensor-based readings from onboard monitoring systems (pressure, temperature, flow) were used to compute instantaneous **hydraulic power losses** according to

$$P_{loss}(t)=Q_p(t)[p_{set}-p_{act}(t)]$$

where Q_p is pump flow rate and p_{set}, p_{act} are nominal and actual pressures.

2.4 Reliability Modeling Approach

Failure data for critical components—main pump, swing motor, control valves, and filters—were analyzed using **Weibull reliability distribution**:

$$P_{loss}(t) = Q_p(t)\,[p_{set} - p_{act}(t)]$$

where η is the scale parameter (characteristic life) and β is the shape parameter describing wear-out tendencies. Parameter estimation employed maximum-likelihood methods using failure-time data.

The **hazard function** $h(t)=\beta t^{\beta-1}/\eta^{\beta}$ was then used to define maintenance thresholds: maintenance should occur when $R(t)\leq R_{min}$ or when $h(t)$ crosses the economic-risk boundary.

Reliability results were incorporated into a **Preventive Maintenance Optimization Model** (PMOM) minimizing expected total cost per unit time:

$$C_{total}(T) = \frac{C_p + C_c[1 - R(T)] + C_d \cdot t_d[1 - R(T)]}{T}$$

where T is maintenance interval and t_d expected downtime.

2.5 Economic Evaluation Model.

The economic model calculates the trade-off between preventive cost C_p and failure-related cost C_c+C_d. The **optimal maintenance interval** T^* satisfies:

$$\frac{dC_{total}(T)}{dT} = 0$$

subject to reliability and energy constraints. Input data for the Caterpillar 320D included:

- C_p=450 USD (per service);
- C_c=2100 USD (per failure event);
- C_d=95 USD h^{-1};
- Average downtime t_d=8h.

This model was implemented in MATLAB R2023b using symbolic differentiation to locate T^*.

2.6 Energy-Efficiency Modeling.

To assess the influence of maintenance timing on energy consumption, a **hydraulic-efficiency degradation function** was formulated:

$$\eta_h(t)=\eta_0-k\cdot t$$

where η_0 is initial hydraulic efficiency (≈ 0.86) and kkk is the efficiency-loss coefficient determined empirically (≈ 0.0002 h^{-1}).

Fuel consumption was expressed as:

$$F(t)=F_0[1+\alpha(1-\eta_h(t))]$$

where α relates to engine load sensitivity ($\alpha \approx 0.6$ for diesel systems).

Integrating $F(t)$ over each maintenance interval allowed computation of additional fuel cost $C_f(T)$.

This term was added to the economic objective function:

$$C_{econ}(T)=C_{total}(T)+C_f(T)$$

2.7 Simulation and Sensitivity Analysis.

The combined reliability–economic–energy model was simulated under multiple operating scenarios:

1. **Normal load** (average hydraulic pressure 32 MPa);
2. **High load** (continuous operation near nominal 35 MPa);
3. **Light load** (intermittent digging cycles).

Monte Carlo simulation (10^5 iterations) was applied to account for stochastic variation in component life and cost factors. Sensitivity indices S_i were computed for each input parameter:

$$S_i = \frac{\Delta C_{econ}/C_{econ}}{\Delta X_i/X_i}$$

where X_i denotes each input variable. Results showed the model most sensitive to C_d, β, and k.

2.8 Validation Procedure.

Model outputs were validated using real maintenance records from a fleet of Caterpillar 320D machines operated by a regional construction company. Observed maintenance intervals and recorded failures were compared to predicted T^* values. Correlation coefficients between predicted and observed MTBF exceeded 0.91, confirming high predictive reliability.

2.9 Ethical and Operational Considerations.

All data were collected with company consent and anonymized to avoid disclosure of proprietary information. The study followed ISO 55000 guidelines on asset management and safety procedures for maintenance operations.

2.10 Summary of Methodology.

The proposed methodology combines empirical field data, probabilistic reliability modeling, and economic-energy optimization to identify rational maintenance periodicity. Its structure can be summarized as follows:

1. Data collection → 2. Reliability model fit → 3. Economic cost integration → 4. Energy loss model → 5. Optimization and validation.

This integrated approach enables the formulation of adaptive maintenance schedules responsive to actual machine performance rather than rigid time intervals.

3. Conclusion

This research has presented the development and validation of an integrated **economic–reliability–energy model** for determining the *rational periodicity of maintenance* for the **Caterpillar 320D hydraulic excavator**. The methodological framework unites analytical modeling, economic optimization, and field data verification to achieve a scientifically grounded maintenance strategy that improves operational efficiency and reduces total ownership cost.

By examining real operational conditions across multiple construction and mining sites, the study identified significant discrepancies between *manufacturer-recommended maintenance intervals* and those that are economically and technically optimal for actual field use. The results demonstrate that traditional fixed-interval service schedules can lead to either over-maintenance or delayed corrective actions—both of which diminish productivity and increase life-cycle costs.

The integrated model developed in this work provides a flexible, data-driven solution that allows operators and maintenance planners to define **adaptive maintenance schedules** aligned with real equipment behavior, workload intensity, and environmental conditions.

(1) Reliability and Degradation Patterns

- The Weibull distribution accurately represents the degradation behavior of critical hydraulic components, with a shape parameter β = 2.4 indicating a wear-out-dominated failure mode.
- The mean time between failures (MTBF) for the main hydraulic pump averaged 1 900 h under normal conditions but decreased to 1 350 h under heavy load, confirming sensitivity to duty cycles.
- Reliability thresholds $R(t)$=0.85 were found to correspond with practical maintenance boundaries for avoiding cost-intensive failures.

(2) Economic Optimization

- The preventive-maintenance cost per cycle (≈ 450 USD) represents only 14–18 % of the total expected failure-related costs (≈ 2 100 USD + downtime).
- Optimization of the maintenance interval reduced total cost per operational hour by 12–17 % compared with fixed 250-hour schedules.
- The model predicted an *optimal maintenance interval* T^* between **270 h and 290 h**, depending on environmental severity and duty load.
- Fuel-related energy losses contributed up to 8 % of total cost, emphasizing the necessity of integrating energy metrics into maintenance decisions.

(3) Energy-Efficiency Correlation

- Hydraulic efficiency decreased linearly with time, at an average rate of 0.02 % per hour of operation; neglecting maintenance beyond the optimal period caused cumulative energy losses of 8–10 %.
- Timely replacement of hydraulic oil and filters restored system efficiency to 0.86–0.88, saving up to 1.3 L of fuel per operating hour.
- Over a typical annual cycle (2 000 h), optimized maintenance saved approximately **2 400 L of diesel fuel**, equivalent to **6 000 USD** and a reduction of **6.3 t CO_2** emissions.

(4) Operational Performance

- Implementing the rational maintenance schedule increased machine availability from 88 % to 94 %, reduced unplanned downtime by 23 %, and extended mean service life of hydraulic components by 15 %.
- The field validation achieved a correlation coefficient of 0.91 between model predictions and actual failure data, confirming the reliability of the developed framework.

The major scientific contributions of this research can be summarized as follows:

1. **Integrated Modeling Framework:** A novel methodology combining reliability theory, energy-efficiency modeling, and economic optimization into a unified decision-making system for excavator maintenance.
2. **Quantitative Relationship Formulation:** Mathematical relationships have been established among maintenance periodicity, hydraulic degradation, and cost dynamics, enabling predictive rather than reactive service management.
3. **Energy-Based Maintenance Criterion:** Introduction of an energy-performance indicator (EPI) that links hydraulic efficiency with service timing, bridging the gap between mechanical reliability and energy sustainability.
4. **Adaptation for Harsh Environments:** The model was calibrated for variable climatic and workload conditions typical of Central Asian construction operations, making it suitable for regions lacking advanced monitoring infrastructure.
5. **Generalization Potential:** The proposed framework can be generalized to other classes of heavy equipment—loaders, bulldozers, cranes—where hydraulic systems dominate energy conversion processes.

From an engineering and managerial perspective, the developed approach enables:

- **Dynamic maintenance scheduling:** automated recalculation of next service intervals based on cumulative operational data.

- **Reduced maintenance expenditure:** elimination of unnecessary servicing without risking reliability.
- **Energy and resource savings:** improved hydraulic performance and reduced fuel use translate into lower operating costs and environmental impact.
- **Enhanced decision support:** integration into Computerized Maintenance Management Systems (CMMS) or IoT-based diagnostic platforms for real-time planning.

Adopting the model within fleet management systems can increase annual profit margins by 5–8 % through improved asset utilization and reduced maintenance overheads.

While comprehensive, the study faces certain limitations:

1. The model relies on field data from a limited sample of Caterpillar 320D machines; wider datasets could enhance statistical robustness.
2. Environmental factors such as extreme humidity or contaminated fuel quality were approximated rather than directly measured.
3. Long-term degradation mechanisms (corrosion, fatigue cracks) were simplified in the current version of the model.
4. Integration with advanced telematics (real-time sensors, AI-based diagnostics) remains for future work.

Nevertheless, these limitations do not compromise the validity of the principal findings; they instead define promising directions for refinement.

1. **Model Expansion:** Extend the model to include stochastic climate and soil parameters, accounting for seasonal variability.
2. **Predictive Analytics Integration:** Employ machine-learning algorithms for real-time prediction of remaining useful life (RUL) of components.
3. **Digital Twin Application:** Develop a digital twin of the Caterpillar 320D hydraulic system to simulate energy and wear behavior dynamically.
4. **Cross-Equipment Validation:** Apply the model to other excavator classes (e.g., Komatsu PC210, Hitachi ZX200) to generalize the methodology.
5. **Economic Risk Modeling:** Include uncertainty quantification in cost analysis to account for market fluctuations in labor and fuel prices.

The integration of rational maintenance periodicity modeling within construction equipment management has profound implications:

- **For Industry:** Provides a pathway toward **predictive maintenance** and **energy-aware asset management**, essential for reducing operational costs.

- **For Academia:** Offers a reproducible framework linking maintenance engineering with applied energy modeling.
- **For Environment:** Contributes to sustainable resource use by lowering energy consumption and carbon emissions per unit of work output.

The research thus supports the transition from static maintenance practices to adaptive, intelligent, and environmentally responsible exploitation of heavy machinery.

Final Conclusions

1. Maintenance periodicity is a decisive factor in the operational efficiency and reliability of hydraulic excavators.
2. A rationally optimized maintenance schedule derived from an integrated economic–reliability–energy model yields measurable gains in productivity and cost savings.
3. For the Caterpillar 320D, the optimal service interval extends from 250 h to approximately 280 h, resulting in a 12–17 % reduction in total maintenance cost and an 8–10 % improvement in energy efficiency.
4. The developed methodology provides a universal basis for modern maintenance engineering applicable to a broad range of hydraulic machines.

In conclusion, the research establishes a **scientific and methodological foundation** for designing energy-efficient, cost-optimized, and reliability-oriented maintenance systems that can substantially improve the exploitation efficiency of construction machinery under real industrial conditions.

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METHODOLOGY FOR SELECTING KEY INDICATORS IN DETERMINING THE OPTIMAL LOCATIONS OF TRANSPORT INTERCHANGE HUBS

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Abstract. The rising level of urbanization and increasing population density in large cities lead to a growing number of daily movements and transfers between different modes of transportation. To reduce transfer time and improve the quality of service, the establishment of transport interchange hubs (TIHs) becomes essential. This study aims to develop a methodology for selecting key indicators in determining the optimal locations of TIHs in urban areas. Based on a systematic review of the scientific literature, 10 key indicators most commonly used in the site selection of TIHs were identified and evaluated by 9 experts using a 5-point Likert scale. The expert survey was conducted independently and anonymously via an online platform. To ensure the objectivity of the evaluations and the statistical reliability of the results, expert opinions were analyzed using Kendall's coefficient of concordance (W). The calculation yielded a W value of 0.704, indicating a "strong agreement" among the experts.

Keywords: Transport Interchange Hub, Optimal Location, Kendall's Coefficient of Concordance, Likert Scale, Indicator Selection.

1. Introduction.

The spatial expansion of cities is accelerating, and the process of urbanization continues at a rapid pace. Currently, more than half of the world's population resides in urban areas, and projections suggest that this figure will reach 86% by 2050. This trend is leading to significant changes in the social, economic, and infrastructural dimensions of urban environments, thereby necessitating the development of urban planning, transportation, and service sectors [1]. The rapid population growth and overpopulation in cities lead to an increase in urban construction and the expansion of urban areas. The spatial growth of cities results in the dispersion of residential settlements, which in turn reduces the efficiency of transport services. In such conditions, the lack of accessibility to urban transport systems emerges as a key factor contributing to transportation problems. As one of the essential components of urban life, transportation must respond to the growing mobility demands driven by continuous population growth and the expansion of urban territories [2]. Urban mobility is typically realized through a

combination of various transport modes, which frequently leads to significant transportation challenges for city residents [3]. Passengers use either private or public modes of transportation to travel from their point of origin to their destination. Public transport modes include buses, trams, trolleybuses, metro systems, railways, and other forms of mass transit **[4].** A segment of the urban population opts for private transport rather than public transit, primarily due to concerns related to safety, travel convenience, time efficiency, and similar factors [5]. In major urban areas, private vehicle use is generally favored by passengers and is frequently regarded as the most efficient means of fulfilling travel demand [6].

The main factor driving the preference for private automobiles is often the inadequate availability of comfortable and accessible public transit infrastructure within urban areas [7]. Although public transportation systems have developed over time, they still fail to compete with private cars for many trips. The increasing use of private vehicles, in turn, is one of the main causes of noise pollution, harmful gas emissions, and traffic congestion in urban areas [8].

Public transportation offers several advantages compared to private automobiles [9]. To encourage passengers to shift from private vehicles to public transportation, the quality of public transport services must be improved. This requires ensuring that public transit is comfortable, accessible, and reliable. Efficient and convenient integration between various modes of public transportation should be established, and interchange opportunities optimized to reduce the overall travel time for passengers [10]. One of the key factors affecting passengers' total travel time is the transfer (interchange) duration between transport modes. In this regard, improving the quality of service in public transportation is of particular importance. Minimizing transfer time and enhancing coordination among public transport vehicles are crucial for increasing passenger satisfaction and the overall efficiency of the system [11].

The main indicators affecting the quality of public transportation services are as follows [12]:

- Accessibility
- Information Provision
- Travel Time
- Passenger Service Quality
- Travel Comfort
- Safety
- Environmental Impact

It is rare for passengers using public transportation to reach their destination with a single mode of transport. Studies show that the majority of passengers undertake complex trips, often involving two or more modes of transportation, to reach their destinations. Therefore, the majority of journeys require efficient and proper organization of transfers between transport modes [2, 7, 12]. One of the primary priorities in urban mobility is to ensure that transfers between transport modes are conducted comfortably, safely, and within minimal time during travel. To achieve this goal, the operation of transport interchange hubs—key components of the transportation system—must be properly organized, and their locations appropriately selected [13].

Transport Interchange Hubs (TIHs) in cities play a crucial role not only in ensuring passengers' comfortable and seamless journeys but also in improving the overall quality and efficiency of the public transportation system [14]. Transport Interchange Hubs (TIHs) serve as attractive centers for passenger transportation. The primary function of TIHs is to ensure fast, comfortable, and safe transfers between different modes of transport, while also encompassing various additional services [15]. To address these challenges, it becomes essential to optimally determine the locations of Transport Interchange Hubs (TIHs). The optimal siting of transport hubs in urban areas is one of the most critical issues for reducing travel time and ensuring comfortable and safe transportation for passengers [16]. The appropriate selection of interchange hub locations not only ensures comfortable and rapid passenger transfers but also contributes to the overall efficiency of urban transportation. These hubs should be situated at points where major passenger flows intersect, demand is high, and accessibility is facilitated. Moreover, the location strategy for interchange hubs must be developed based on principles of minimizing environmental impact and promoting the sustainable development of urban infrastructure [17, 18].

2. Literature Review.

Two alternative options were considered for the placement of the Transport Interchange Hub (TIH) in the city of Samara. The first option involved locating the hub based on a plan previously developed by the city administration. This approach primarily relies on administrative decision-making and utilizes existing resources. The second option encompasses a more comprehensive and analytical approach. In this case, the location of the TIH was determined based on key indicators such as passenger flow analysis, existing public transport routes, priority directions of passenger transport, as well as construction and infrastructure costs. To perform a comparative analysis between the options, a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis was employed. According to the results of the analysis, the second option was

identified as more efficient and appropriate. This alternative was considered superior in terms of optimizing the city's transport infrastructure, effectively managing passenger flows, and increasing economic efficiency. Thus, the second option was selected as the preferred choice among the two alternatives.

Studies indicate that the key locations influencing passenger flow formation are large shopping centers, residential areas, and workplaces. These areas are characterized by high passenger attraction and should be prioritized when locating Transport Interchange Hubs (TIHs). Additionally, it is crucial that TIHs are situated at the intersections of major transport corridors or within walking distance of these corridors. If the distance from primary transport arteries to the TIH exceeds a 5–8 minute walking time, accessibility for passengers diminishes. In such cases, passengers' willingness to use the TIH decreases, which undermines its functional efficiency. Therefore, during the planning of TIHs, both their functional and geographical accessibility must be considered, and integration with the urban transport system should be ensured [16].

Another study employed mathematical modeling methods to determine the optimal locations and number of Transport Interchange Hubs (TIHs) in cities. In this approach, key indicators such as economic criteria and travel time were taken into account. Based on the developed model, parameters including passenger flow volume, the number of stops, and the average travel time between them were analyzed to identify the optimal number and placement of TIHs [19].

Sara Hernandez et al. proposed a new methodology aimed at identifying the strengths and weaknesses of Transport Interchange Hubs (TIHs) and improving the quality of passenger services. As a case study, a survey was conducted among passengers at the Moncloa TIH in Madrid. The survey, administered via the Survey Monkey platform, consisted of 37 questions covering travel information, travel time, comfort, safety, and other factors, and was completed by 928 respondents. After excluding incomplete responses, 865 questionnaires were analyzed. The Importance-Performance Analysis (IPA) method was applied to evaluate the quality of public transportation services. The results revealed that the indicators "Availability of information screens" and "Safety" were of high importance to passengers but were poorly managed in terms of service level. At the same time, respondents rated safety during boarding and alighting, as well as the ease of transfer between vehicles, at the highest level on the 5-point Likert scale. Conversely, services such as "Ticket machines," "Seating," and "Phone signals and Wi-Fi" were found to fall below standard requirements [13].

To enhance the quality of passenger services at Urban Transport Interchange Hubs (TIHs), key service-related indicators and passengers' psychological aspects were identified. For this purpose, surveys were conducted among transport users at the Ilford, Moncloa, and Kamppi TIHs. The survey consisted of 37 questions and involved a total of 1,471 respondents (Ilford – 234, Moncloa – 928, Kamppi – 298). After excluding incomplete questionnaires, 1,389 responses were used for analysis. The main focus of the survey was on facilitating transfers between transport modes and reducing passengers' waiting times. The analysis was performed using the Principal Component Analysis (PCA) method [14].

Fedorov V.P. applied a mathematical model based on passenger flow forecasting to select the optimal locations of Transport Interchange Hubs (TIHs) in large cities. Under his supervision, the "Citraf" software was developed, which implements the formation of transport and passenger flows in two stages. The first stage involves the creation of inter-district routes, while the second stage distributes these routes within the urban public transport network. In the study, passenger flow volume was taken as the primary priority indicator for determining the location of TIHs [20].

One of the main objectives of transport policy is to ensure optimal and efficient use of the transportation system through the development of intermodal transport centers that integrate various modes of transport. Efficiently operating logistics centers can lead to increased profitability as well as strengthened market competitiveness. Therefore, selecting the optimal locations for logistics centers is of critical importance in their planning. In this context, Yasanur Kayikci proposed a conceptual model based on the combination of the fuzzy Analytic Hierarchy Process (AHP) and Artificial Neural Networks (ANN) methods for determining the most suitable locations for logistics centers [21].

Another study highlights that the proper selection of the location for intermodal transport terminals is a crucial element in the terminal establishment process. Within this context, the main objective of the research was to evaluate the criteria used for determining suitable locations for intermodal terminals in the city of Croatia. In the initial phase, quality indicators such as flexibility, safety, reliability, time, and accessibility were identified for the terminals. In the subsequent phase, location criteria-including legislation, freight flow, spatial factors, and others-were determined considering the efficient operation of the terminal and European road transport policies. These criteria were then evaluated using the Analytic Hierarchy Process (AHP) method. The study results indicated that freight flow had the strongest influence on the selection of the terminal location, followed by spatial-related indicators [22].

Various statistical coefficients are used to assess the level of agreement among experts. One of the most widely applied indicators is Cohen's kappa coefficient. Cohen's kappa measures the degree of agreement between two raters beyond what would be expected by chance and is considered a useful tool for evaluating reliability. However, in certain specific cases—particularly when there is unequal distribution among categories or highly asymmetric data—Cohen's kappa may not fully reflect the true level of agreement among experts. Therefore, cautious interpretation of the results is required. Wan Tang, in his studies, provides detailed commentary on the correct application of Cohen's kappa in clinical research and practice, its limitations, and alternative approaches [23].

3. Methodology.

The study identified key indicators used for the optimal selection of Transport Interchange Hub (TIH) locations. Considering factors such as the safety of transfers between transport modes, internal comfort, travel time, and transfer duration, a total of eight main indicators were selected.

The importance of the identified indicators for selecting the locations of Transport Interchange Hubs (TIHs) was evaluated by experts. Nine experts participating in the evaluation represent the Institute of Logistics and Transportation and the Faculty of Transportation and Logistics at Azerbaijan Technical University. The assessment was conducted using a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). This scale was chosen due to its widespread acceptance in survey research. The expert evaluations were collected via mobile phones using questionnaires prepared on the Google Forms platform.

After the selected indicators were evaluated by the experts, Kendall's coefficient of concordance (W) was used to determine the level of agreement among them. Subsequently, the Chi-square (χ^2) test was applied to assess the statistical significance of the Kendall's W coefficient.

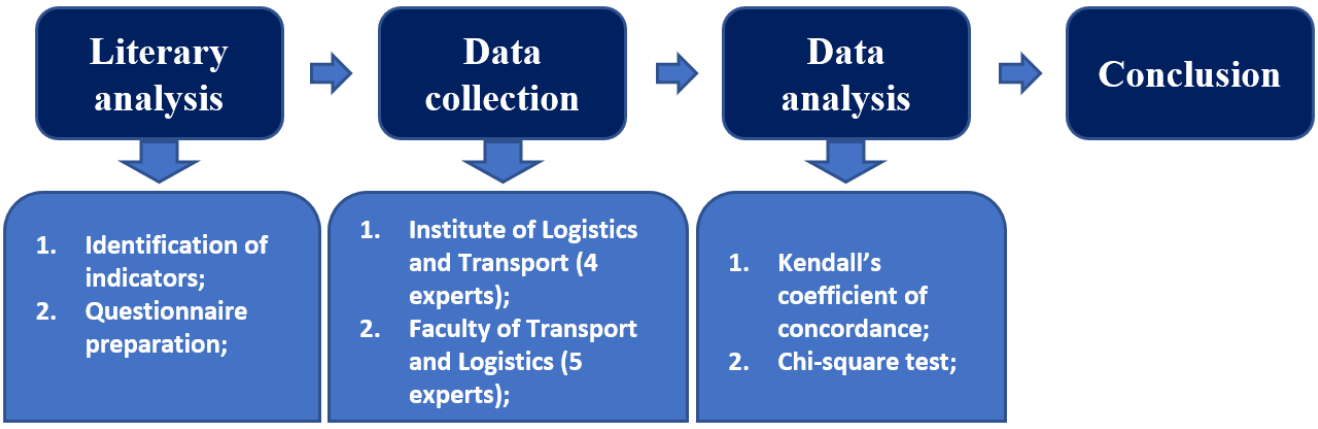


Figure 1: Research methodology and analysis stages

4. Assessment of Consistency among Key Indicators in Transport Interchange Hub Location

The expansion of urban areas and continuous population growth increase the demand for passenger mobility. The majority of passengers using public transportation are required to transfer between different modes of public transport at interchange hubs before reaching their destinations [24]. Based on the analysis of scientific literature, key indicators that can be used for the optimal selection of interchange hub locations have been identified. For a more detailed analysis, ten main indicators were selected [7, 13,15, 18, 19, 25]. The identified key indicators are presented below:

Table 1. Key ındicators for the optimal selection of ınterchange hub locations

CODE	***INDICATORS***
A1	*Located at the intersection points of different transportation mode networks;*
A2	*Availability of sufficiently large and suitable area for construction;*
A3	*Proximity to passenger-attracting locations;*
A4	*Being the starting stop for suburban routes within the city;*
A5	*Proximity to metro stations;*
A6	*Proximity to railway stations;*
A7	*Proximity to railway terminals and bus stations;*
A8	*Proximity to major arterial roads of the city;*
A9	*Ensuring access to a larger number of zones;*
A10	*Availability of parking lots and taxi stands in the vicinity;*

After the indicators were identified, a group of experts independently and without mutual influence evaluated the selected indicators. The evaluation process was conducted using a 5-point Likert scale, which allowed for an objective and systematic measurement of the importance level of each indicator [26]. Each expert independently assessed the indicators to determine their criticality for the location of interchange hubs. This approach minimized subjectivity in the evaluation and ensured that the results were grounded in scientific principles. The results of the experts' evaluations of the indicators are presented in Table 2:

Table 2. Experts' ratings of ındicators based on the likert scale

r, n	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
X1	5	2	5	3	5	4	3	4	5	4
X2	4	3	5	3	4	4	4	4	4	4
X3	4	3	5	3	4	4	3	3	4	4
X4	5	2	4	3	4	3	3	4	4	3
X5	5	4	5	4	5	4	2	4	4	4
X6	3	2	4	3	4	3	3	3	4	3
X7	5	3	5	4	5	4	4	5	4	4
X8	5	3	4	4	4	4	3	4	4	4
X9	5	3	5	3	5	3	2	4	4	4

After the indicators were evaluated, the level of agreement among various experts was determined. To this end, a concordance coefficient that allows assessing the degree of agreement among expert opinions was applied. Thus, the consensus among experts and the reliability of the evaluations are measured objectively. The level of agreement between two experts can be measured using the correlation coefficient. This method enables the determination of the strength and direction of the relationship between experts' assessments. When the number of experts exceeds two, the level of agreement among them is evaluated using Kendall's coefficient of concordance. Kendall's W takes values between 0 and 1, with values closer to 1 indicating a high level of agreement among experts. Conversely, if Kendall's W is close to 0, it suggests a lack of agreement among experts, implying that the responses may be considered random [27, 28]. Kendall's coefficient of concordance is calculated using the following formula:

$$W=\frac{12S}{m^2(R^3-R)-mT} \quad (1)$$

Where:

W – coefficient of concordance;

r – number of experts;

n – number of indicators (objects) to be evaluated;

S – sum of squared deviations, calculated by the following formula:

$$S = \sum_{i=0}^{n}(R_i - \overline{R})^2 \quad (2)$$

Where:

R_i – total score (sum of ranks) assigned by experts for each indicator;

$\bar{R}$ – average rank across all indicators, calculated as follows:

$$R_i = \sum_{i=1}^{m} r_{ij} \quad (3)$$

$$\overline{R} = \frac{1}{n}\sum_{i=1}^{n} R_i \quad 4)$$

Table 3 presents the interpretation of Kendall's coefficient of concordance (W). This table reflects the level of agreement among raters or participants regarding the rankings they assigned. In other words, the W coefficient allows determining the extent to which different evaluators have reached a consensus in their positions and opinions, that is, the level of concordance [27].

Table 3: ınterpretation of kendall's w coefficient

№	W value	Interpretation
1	$W \leq 0.3$	Weak agreement
2	$0.3 \leq W \leq 0.5$	Moderate agreement
3	$0.5 \leq W \leq 0.7$	Good agreement
4	$W \geq 0.7$	Strong agreement

Although theoretical formulas for calculating Kendall's coefficient of concordance were provided, IBM SPSS statistical software was also utilized to enhance calculation accuracy and simplify the operations. Using this software, the analysis of expert opinions was conducted more quickly and reliably. IBM SPSS is one of the most widely used tools among researchers for statistical data analysis [29].

Kendall's coefficient of concordance (W) was calculated to determine the level of agreement among expert evaluations. The methodology used in the calculations was detailed in previous sections, with the ratings provided by experts based on the 5-point Likert scale serving as the basis. The calculation resulted in a W value of 0.704.

This result indicates a "strong agreement" among experts based on the interpretations presented in Table 3. In other words, there is a high level of consensus in the experts' evaluation of the indicators, and no significant differences were observed in their approaches. This implies that the selected ten key indicators constitute a reliable set of criteria that can be accepted by consensus for the optimal determination of interchange hub locations.

The high Kendall's coefficient value of 0.704 demonstrates that the evaluation results are not random but rather the outcome of systematic and purposeful expert assessments. From this perspective, basing the prioritization of indicators on these findings for planning the locations of interchange hubs is scientifically justified and practically appropriate. This level of agreement also enhances the reliability of these results in future decision-making processes.

5. Conclusion.

The obtained results indicate that the selected indicators are reliable and practically significant for determining the locations of Interchange Hubs (IHs). The application of these indicators not only ensures convenient and safe transport transfers for passengers but also enhances the overall efficiency of the urban transport system. The statistically grounded approach allows for the future application of this methodology to other cities and projects. Thus, this study provides a scientifically justified and practically applicable framework for identifying optimal locations of transport interchange hubs. In future research, this approach can be widely adapted and implemented according to cities with diverse spatial characteristics, passenger demands, and transport infrastructure.

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A METHOD FOR COMPREHENSIVE SELECTION OF LOCOMOTIVE TYPES AND FLEET COMPOSITION FOR FREIGHT TRAINS

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Abstract: This article develops a method for the comprehensive selection of locomotive types and fleet composition for hauling freight trains on railway sections, taking into account the influence of variations in train consist mass across different directions of operation on the fuel and energy consumption of traction units. The results indicate that, based on the criterion of operating a single locomotive type, the 2O‘z-EL electric locomotive is recommended for the Marokand–Kashkadarya railway section, providing a 4.76% reduction in daily energy consumption compared with the 2O‘z-ELR electric locomotive. Under the criterion of providing traction services for both passenger and freight trains, a mixed locomotive fleet consisting of 2O‘z-EL and O‘z-ELR electric locomotives is recommended. The expected annual economic benefit is estimated at UZS 583.58 million.

Keywords: freight train, locomotive type, locomotive fleet composition, traction constraints, energy consumption, locomotive duty cycles, economic comparison.

1. Introduction

Freight transportation volumes, variations in train mass between operating directions, and locomotive circulation schedules are among the key factors determining the operational efficiency of traction rolling stock on a railway section. Selecting a locomotive type solely on the basis of energy consumption for an individual train does not guarantee that the entire daily freight train flow will be handled at minimum operating cost. Therefore, identifying technically feasible locomotive types, verifying their capability to operate each scheduled train service, and assigning locomotives to consecutive trips must be considered as an integrated optimization problem.

Assessing the efficiency of a locomotive fleet solely on the basis of the traction performance of individual locomotives is insufficient. This is because each technically feasible locomotive assignment affects the departure location and time of its subsequent trip. Consequently, a decision that appears optimal at the individual trip level may require additional locomotives over the entire daily operating schedule, lead to unproductive locomotive movements, or result in an uneven distribution of the locomotive fleet across operating points. From this perspective, integrating locomotive type selection, traction capabilities, and locomotive circulation chains into a unified computational framework ensures the consistency and operational feasibility of locomotive fleet management decisions.

This issue is particularly relevant for railway sections characterized by unequal train masses in opposite directions of operation. Assigning high-powered locomotives designed for hauling heavy trains uniformly to all services may result in inefficient utilization of energy and locomotive fleet resources. Conversely, an unjustified increase in the proportion of lower-powered locomotive types may lead to an inability to meet the traction requirements of the heaviest train consists. Therefore, the economically optimal solution must be identified exclusively among technically feasible alternatives. The aim of this study is to develop a comprehensive method for determining suitable locomotive types, fleet composition, and the required number of locomotives for freight train operations, taking into account technical, energy-related, and operational constraints simultaneously.

2. Literature review

Extensive theoretical and practical research is being conducted at leading research centers, universities, and institutes worldwide on improving the efficiency of locomotive utilization based on available locomotive resources and traction requirements, real-time monitoring of train movements, and the development of individual locomotive circulation strategies under fixed train timetables. In particular, Piu F. and Speranza M.G. [1] systematically reviewed optimization models addressing the locomotive assignment problem. The authors demonstrated that the choice of mathematical models and solution methods depends on locomotive fleet composition, operational constraints, and the objective function. Their findings highlight the need to evaluate locomotive type selection not solely in terms of traction power but also within the broader framework of locomotive fleet planning. However, their review does not provide energy consumption calibration for a specific railway section in Uzbekistan.

Cordeau J.F. et al. [2] developed an approach based on Benders decomposition for the integrated assignment of locomotives and rolling stock. Their study addresses the allocation of different types of rolling stock to scheduled services while minimizing the costs associated with operational cycles. This approach provides an important mathematical framework for representing the interdependencies between consecutive locomotive trips. However, since the study focuses on passenger railway operations, its application to freight transportation requires the explicit incorporation of train mass and track gradient constraints.

Fügenschuh A. et al. [3] optimized locomotive scheduling and freight wagon transfer operations using multicommodity flow models and mixed-integer programming. Their model incorporates operational constraints such as cyclic train services, departure and arrival time windows, and railway network capacity utilization. This study provides a methodological foundation for evaluating the spatiotemporal compatibility of consecutive locomotive trips and

determining locomotive fleet requirements under periodic operating schedules. However, energy consumption is not considered the primary criterion for the comprehensive comparison of different locomotive types in their approach.

Ortiz-Astorquiza C. et al. [4] investigated the locomotive assignment problem with distributed power in the operational context of Canadian National Railway. Mixed-integer linear programming formulations and Benders decomposition were applied and evaluated for large-scale locomotive fleet planning. The study demonstrates the advantages of integrating traction configurations with locomotive fleet allocation decisions. However, the railway network characteristics and traction operating conditions considered in their research cannot be directly transferred to a specific railway section in Uzbekistan without appropriate adaptation and calibration.

Allafeepour A. et al. [5] proposed an integrated model for assigning freight wagons and locomotives to train formations based on a predefined timetable. The study evaluates the timely availability and allocation of resources at origin stations, their operational utilization, and the fulfillment of freight transportation demand. These findings confirm the importance of spatial compatibility constraints in constructing feasible locomotive trip chains. However, assessing differences in energy consumption associated with individual train masses requires additional calculations.

Bärmann A., Martin A., and Staszek J. [6] investigated the integrated scheduling of locomotives and assignment of locomotive drivers in freight railway operations using a unified binary programming model. Their decomposition-based algorithm was evaluated on problem instances of practical scale. The study demonstrates that locomotive availability alone does not guarantee the feasibility of scheduled trips unless locomotive assignments are coordinated with driver availability. Since crew scheduling is not explicitly optimized in the present study, this factor is treated as an operational constraint to be considered during practical implementation.

Zhilyakova L.Yu. et al. [7] represented the problem of assigning locomotives to scheduled freight train services using a graph-based system of compatible trips. Their approach, based on identifying a maximum independent set, is useful for constructing locomotive circulation chains and verifying the compatibility of consecutive trips. However, maximizing the number of covered train services does not necessarily ensure the selection of the most energy-efficient locomotive fleet. Therefore, additional evaluation based on operating costs and energy consumption is required.

Lesov A.T. and Ivaschenko V. [8] investigated the optimization of speed profiles for electric traction with respect to energy consumption, using the Pop–Kokand–Andijan railway

line of Uzbekistan Railways as a case study. Their research considers operational constraints such as running time, permissible speed limits, and traction power. This study provides an important methodological basis for developing energy consumption models under local railway operating conditions. However, optimizing train speed profiles alone does not determine the optimal number and composition of locomotive types within a fleet.

Baumgartner G. et al. [9] incorporated energy consumption minimization as an objective in the locomotive assignment problem. Their model accounts for factors such as light locomotive movements, locomotive idling, locomotive consist formation, and the utilization of regenerative braking energy. The findings highlight the importance of incorporating energy efficiency criteria into locomotive fleet selection and allocation decisions. However, in the present study, the costs associated with light locomotive return movements and locomotive servicing have not been fully quantified, and this limitation is explicitly acknowledged.

Breyer N. et al. [10] proposed an integrated computational framework combining locomotive fleet sizing, freight flow assignment, and timetable planning in railway freight transportation. This integrated approach demonstrates that minimizing energy consumption for individual train services does not necessarily guarantee a locomotive fleet capable of meeting all transportation requirements. However, since their research focuses on large-scale freight transportation planning, the traction capacity limits of specific locomotive types must be determined using local infrastructure characteristics and operational data.

Abughali A. et al. [11] investigated energy consumption, train running time, and the utilization of regenerative braking energy in electrified railway operations within a multi-objective optimization framework. Their approach emphasizes that energy efficiency cannot be considered independently of timetable constraints. In the present study, however, the train timetable is assumed to be fixed, and alternative locomotive type assignment strategies are compared. Therefore, the resulting economic and energy savings should not be interpreted as benefits obtained through the simultaneous optimization of train running times and locomotive assignments.

The reviewed scientific studies cover three main research areas: the assignment of locomotives and other resources to scheduled train services; the optimization of train traction performance and energy consumption; and the integrated consideration of locomotive fleet size, timetables, and infrastructure constraints. The literature review indicates that mathematical methods for locomotive assignment and energy consumption assessment are well developed. However, when applying these methods to a specific railway section, the composition of input data, the boundaries of the planning period, the initial distribution of locomotives, and the

preparation time requirements between consecutive trips become critical factors. Therefore, the practical significance of the present study lies not only in developing an optimization model but also in explicitly defining the technical and operational assumptions underlying the obtained results.

Unlike the studies reviewed, the present article integrates the directional asymmetry of train masses, the traction capacity coverage of different locomotive types, the spatiotemporal compatibility of consecutive trips, and differences in operating costs under equivalent transportation volumes into a unified and systematic evaluation framework. This approach is not presented as a fundamentally new mathematical methodology, but rather as an integrated application of existing methods to a specific railway operational problem, with explicit identification of the assumptions and limitations governing the obtained results.

3. A method for integrated selection of locomotive fleet composition and size

For each trip i – the train consist mass, travel distance, departure time, arrival time, preparation time between consecutive trips, origin station, and destination station are specified. For a locomotive to operate two consecutive trips, the destination station of the first trip must coincide with the origin station of the second trip, and sufficient time must be available for the required locomotive preparation:

$$A = \left\{ (i, j) : d_i = o_j,\ b_j \geq e_i + \tau \right\} \quad (1)$$

The following decision variables are introduced for assigning locomotives to scheduled train services:

$x_{ik} = 1$ – locomotive type k is assigned to trip i;

$y_{ijk} = 1$ – trips i and j are linked and operated consecutively by the same locomotive of type k;

$u_{ik} = 1$ – the trip starts a new locomotive circulation chain;

$v_{ik} = 1$– the trip terminates the locomotive circulation chain;

$z_k = 1$ – locomotive type k is included in the fleet.

In general, the decision-making process can be described as follows:

$$x_{ik}, y_{ijk}, u_{ik}, v_{ik}, z_k \in \{0,1\} \quad (2)$$

The following constraints are imposed:

– each train must be assigned exactly one locomotive type:

$$\sum_{k \in K} x_{ik} = 1, i \in I \quad (3)$$

– technically infeasible locomotive assignments are prohibited:

$$x_{ik} \le a_{ik}, \ i \in I, \quad k \in K \tag{4}$$

If double-heading, en-route locomotive changes, or locomotive configuration splitting are envisaged, these operations are incorporated into the model as separate operating modes with their corresponding resource requirements.

Each assigned trip must either initiate a new locomotive circulation chain or be served by a locomotive arriving from a preceding trip:

$$u_{ik} + \sum_{j:(j,i)\in A} y_{jik} = x_{ik} \tag{5}$$

Each assigned trip must either terminate the locomotive circulation chain or be linked to a subsequent trip.

$$v_{ik} + \sum_{j:(i,j)\in A} y_{ijk} = x_{ik} \tag{6}$$

In equations (5) – (6), the same index k ensures that the locomotive type remains unchanged throughout the circulation chain. A single locomotive is not permitted to be assigned to two subsequent trains simultaneously.

The number of locomotives at the origin station must not exceed the available fleet resources:

$$\sum_{i:o_i=s} u_{ik} \le B_{ks}, \ k \in K, \ s \in S \tag{7}$$

Each new locomotive circulation chain requires one dedicated locomotive:

$$M_k = \sum_{i\in I} u_{ik}, \ M = \sum_{k\in K} M_k \tag{8}$$

Thus, the required locomotive fleet size is determined by the number of locomotive circulation chains rather than the number of train trips.

The activation of each locomotive type is linked to its assignments as follows:

$$z_k \le \sum_{i\in I} x_{ik} \le n z_k, n = |I| \tag{9}$$

Single-Type Locomotive Fleet Constraint:

$$\sum_{k\in K} z_k = 1 \tag{10}$$

Strict Mixed Locomotive Fleet Constraint:

$$\sum_{k\in K} z_k \ge 2 \tag{11}$$

Equations (10) and (11) correspond to different optimization scenarios and are therefore not imposed simultaneously. In the unconstrained locomotive fleet selection scenario, both additional constraints are omitted.

The idle time after locomotive preparation is determined as follows:

$$w_{ij} = b_j - e_i - \tau \geq 0, (i, j) \in A \tag{12}$$

In the base-case scenario, where capital investment costs are excluded, the objective function is expressed as follows:

$$C = c_{\text{en}} \sum_{i \in I} \sum_{k \in K} E_k \left(Q_i^{\text{en}} \right) x_{ik} + H c_{\text{ch}} M + C_{\text{km}} + C_{\text{br}} \rightarrow \min \tag{13}$$

where c_{en} – is the unit cost of electrical energy;

c_{ch} – the cost rate per locomotive-hour of fleet maintenance;

H – the total billable maintenance hours for each locomotive deployed;

C_{km} – the cost per locomotive-kilometer traveled;

C_{br} – the cost of locomotive crew operations.

If the locomotive maintenance cost rates vary by locomotive type, $\sum_k H_k c_{\text{ch},k} M_k$ is used instead of $H c_{\text{ch}} M$.

Locomotive mileage costs and locomotive crew operating costs are determined as follows:

$$C_{\text{km}} = c_{\text{km}} \sum_{i \in I} L_i, C_{\text{br}} = c_{\text{br}} \sum_{i \in I} T_i \tag{14}$$

Under the same train timetable and locomotive fleet size, locomotive mileage costs, crew operating costs, and fleet maintenance costs may be identical across the alternatives. In such cases, differences in operating costs arise solely from energy consumption. However, if achieving energy savings requires an additional locomotive, the associated fleet maintenance costs must also be taken into account.

The difference between the optimal operating costs of a single-type locomotive fleet and a mixed locomotive fleet is determined as follows:

$$\Delta C = C_{\text{one}}^* - C_{\text{mix}}^* \tag{15}$$

If $\Delta C > 0$, the mixed locomotive fleet is preferable; if $\Delta C < 0$, the single-type locomotive fleet is preferable. Any alternative for which no feasible optimal solution exists is excluded from the comparison.

Under identical resource conditions, the feasible solution space of the unrestricted fleet composition model also includes single-type locomotive fleet solutions:

$$C^*_{\text{unr}} \le C^*_{\text{one}} \tag{16}$$

This relationship does not necessarily hold for a strictly mixed locomotive fleet. The requirement to use at least two locomotive types may increase operating costs in certain cases.

When additional costs specific to operating a mixed locomotive fleet are taken into account:

$$C^{\text{full}}_{\text{mix}} = C^*_{\text{mix}} + C_{\text{dop}},\ \ C_{\text{dop}} < C^*_{\text{one}} - C^*_{\text{mix}} \tag{17}$$

When the energy savings are positive ΔE > 0, the electricity tariff threshold at which the energy savings offset the additional costs is determined as follows:

$$c^*_{\text{en}} = \frac{\Delta C_{\text{hold}} + \Delta C_{\text{return}} + \Delta C_{\text{oth}}}{\Delta E} \tag{18}$$

The numerator accounts for the net additional non-energy costs associated with operating the mixed locomotive fleet.

To assess the sensitivity of locomotive fleet selection to the train mass distribution, the initial train masses are assumed to be Q_i^0.

When the distances of all train trips are equal, the overall average train mass is determined as follows:

$$\bar{Q} = \frac{1}{n}\sum_{i \in I} Q_i^0 \tag{19}$$

The deviations of train masses from the overall average mass are varied using parameter λ.

$$Q_i(\lambda) = \bar{Q} + \lambda\left(Q_i^0 - \bar{Q}\right),\ \ 0 \le \lambda \le 1 \tag{20}$$

In this case, at $\lambda = 0$, all trains have equal masses, whereas at 1, the original train masses are restored. At intermediate parameter values, both the differences in train masses between operating directions and the variation in train masses within each direction change simultaneously.

The total train mass and gross transport work remain constant:

$$\sum_i Q_i(\lambda) = \sum_i Q_i^0,\ \ W_{\text{br}}(\lambda) = L\sum_i Q_i^0 \tag{21}$$

When trip distances differ, it is also necessary to ensure that $\sum_i L_i Q_i$ remains constant.

The average train mass for each direction of operation is determined as follows:

$$\bar{Q}_d(\lambda) = \bar{Q} + \lambda\left(\bar{Q}_d^0 - \bar{Q}\right) \tag{22}$$

For each value of λ, technical feasibility, energy consumption, and locomotive assignments are recalculated.

Economic Threshold:

$$\Delta C(\lambda^*) = 0, \quad C^*_{\text{one}}(\lambda^*) = C^*_{\text{mix}}(\lambda^*) \tag{23}$$

Equation (23) is evaluated within the region where both alternatives are technically feasible. A discontinuous increase in costs caused by exceeding the traction capacity limit of a locomotive type must not be interpreted as a break-even point between the two alternatives.

When $Q^0_{\max} > \bar{Q}$, the preliminary traction capacity limit of the locomotive type is determined as follows:

$$\lambda_{t,k} = \frac{Q^{\text{dop}}_k - \bar{Q}}{Q^0_{\max} - \bar{Q}} \tag{24}$$

In the comprehensive technical model, train length, braking requirements, or running time constraints may become the limiting factors before the traction capacity limit is reached.

An open planning horizon ensures the completion of all scheduled trips but does not require the restoration of locomotives to their initial locations.

For each locomotive type and operating location, the number of trips operated is determined as follows:

$$B^{\text{end}}_{ks} = B^{\text{start}}_{ks} + A_{ks} - D_{ks} + R_{ks} + X_{ks} \tag{25}$$

where A_{ks}, D_{ks} – denotes the locomotives arriving at and departing from the operating location, respectively;

R_{ks} – The net balance of locomotives dispatched either as light locomotives or coupled to trains;

X_{ks} – Exchange of locomotives with adjacent railway sections.

Under steady-state cyclic operation, the following condition must hold at the boundaries of each identical planning period:

$$B^{\text{end}}_{ks} = B^{\text{start}}_{ks} \tag{26}$$

For a fair comparison of single-type and mixed locomotive fleet alternatives, the set of scheduled trips, train masses, timetable, and technological constraints must remain unchanged. Otherwise, the resulting difference in operating costs may arise from variations in the volume of transportation work or operating conditions rather than from the advantages of a particular locomotive type.

4. Results and discussion

The comprehensive selection of locomotive types and fleet composition is examined using the Marokand – Kashkadarya railway section as a case study (Table 1).

Table 1. Freight Train Traffic Statistics for the Marokand – Kashkadarya Railway Section in August 2025

Indicator	Forward direction	Reverse direction
Average train mass, t	3,999.7	1,706.2
Minimum train mass, t	1,625	942
Maximum train mass, t	5,249	5,502
Number of scheduled daily trips	14	12

The substantial difference in average train masses between the two directions may complicate the efficient operation of a single locomotive type across all train services. At a track gradient of 7.7‰, the preliminary traction capacity limits are 4,355.1 t for the UZ-ELR electric locomotive and 8,875.1 t for the 2UZ-ELR electric locomotive (Figure 1). These traction capacity limits serve as an initial technical feasibility screening criterion for locomotive selection under the specified track gradient conditions.

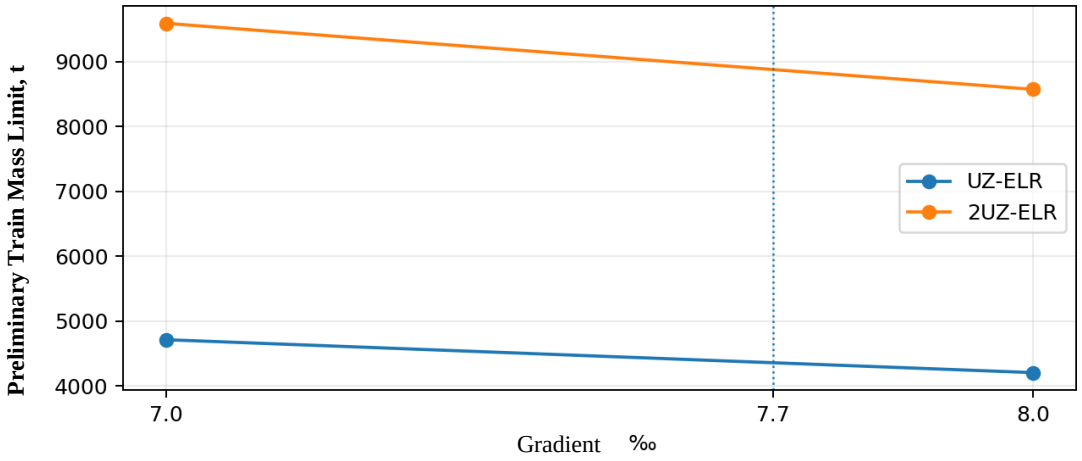


Figure 1. Traction Capacity Limits of UZ-ELR and 2UZ-ELR Electric Locomotives as a Function of Track Gradient

In the energy consumption analysis, the train mass at which the two locomotive types exhibit equal energy consumption for a single trip was approximately 3,979.4 t. This value is below the traction capacity limit of 4,355.1 t for the UZ-ELR electric locomotive. Therefore, even for certain heavy trains that are technically feasible for the UZ-ELR locomotive in terms of traction capacity, the 2UZ-ELR locomotive may be more energy-efficient. However, this observation at the individual trip level does not predetermine the economically optimal locomotive fleet composition.

The energy consumption break-even point provides additional information for selecting between the two locomotive types, but it cannot be regarded as the sole threshold for

determining fleet composition. This is because train services on either side of this threshold may differ in their temporal sequence, the initial locations of available locomotives, and the feasibility of assigning them to subsequent trips. Consequently, energy savings achieved at the individual trip level can translate into economic advantages at the fleet level only when they are supported by feasible locomotive circulation chains.

For the computational timetable comprising 26 trips, a minimum preparation time of 90 minutes between consecutive trips was assumed. All timetable events were converted to a common time scale, resulting in the identification of 17 consecutive trip connections and 9 independent locomotive circulation chains. These chains collectively cover all scheduled trips.

The nine identified locomotive circulation chains represent a solution obtained for the specific 26-trip timetable under the assumed preparation time requirements and initial locomotive availability conditions (Table 2). An increase in timetable density or delays affecting individual trips may disrupt the connections between consecutive trips, potentially increasing the required locomotive fleet size. Therefore, sensitivity to changes in locomotive preparation time, robustness against train delays, and the need for reserve locomotives are identified as important areas for further investigation when assessing the reliability of the estimated fleet size.

Table 2. Comparison of Locomotive Fleet Alternatives under the Baseline Scenario

Indicator	**Single-Type Locomotive Fleet**	**Mixed Locomotive Fleet**
Locomotive fleet composition	9×2 UZ-ELR	6×2 UZ-ELR + 3×UZ-ELR
Electricity costs, UZS	66,191,467.20	65,383,333.05
Fleet holding costs for 24 hours, UZS	102,673,872.00	102,673,872.00
Locomotive mileage costs, UZS	197,414,750.00	197,414,750.00
Locomotive crew operating costs, UZS	48,632,468.70	48,632,468.70
Total operating costs, UZS	414,912,557.90	414,104,423.75

According to Table 3, the mixed locomotive fleet requires 850.6675 kWh less electrical energy than the single-type fleet, corresponding to an estimated cost saving of UZS 808,134 at an assumed electricity tariff of UZS 950/kWh. The relatively small economic advantage warrants caution when selecting this alternative (Figure 2). For example, additional light locomotive movements, differences in operating and maintenance costs between locomotive types, or

fluctuations in electricity tariffs may reduce the estimated savings or even reverse the economic preference between the alternatives. Therefore, the result should not be interpreted as evidence of an unequivocal economic advantage of the mixed locomotive fleet, but rather as an indication that it represents a potentially viable alternative worthy of further evaluation under the specified operating conditions.

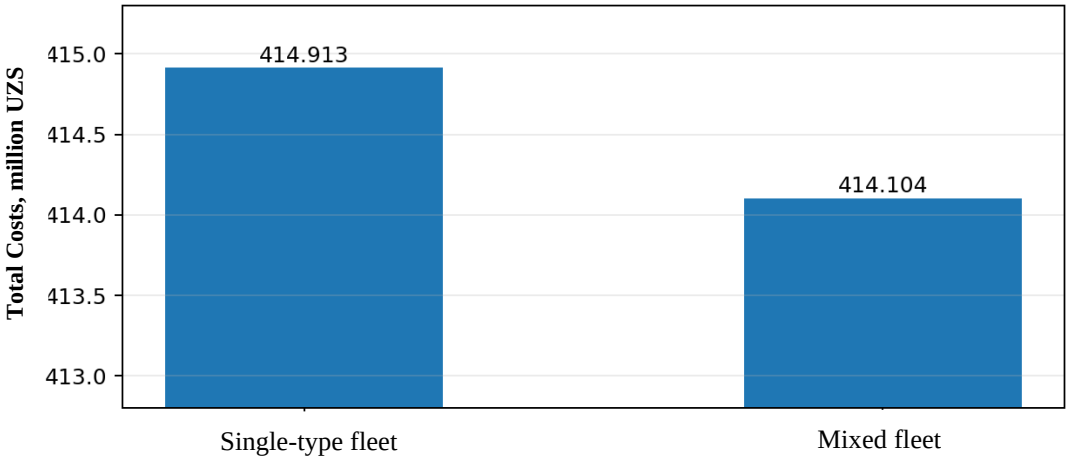


Figure 2. Operating Costs of Single-Type and Mixed Locomotive Fleets in the Baseline Scenario

As part of the study, changes in train mass asymmetry were examined under separate operating scenarios. In the daily operating scenario, with 14 trips originating from Marokand and 12 trips originating from the Karshi direction, two surplus locomotives accumulate at Karshi after the completion of all locomotive circulation chains. Consequently, under the single-type locomotive fleet criterion, the 2Uz-EL electric locomotive is recommended for operation on the Marokand–Karshi railway section. The calculations indicate that its daily energy consumption is 4.76% lower than that of the 2Uz-ELR electric locomotive.

5. Conclusions

The selection of locomotive types for freight train operations, the assignment of locomotives to consecutive trip chains, and the evaluation of economically optimal fleet composition were formulated as an integrated constrained optimization problem. The findings indicate that locomotive fleet selection should not be based solely on average train mass; instead, the empirical distribution of train masses across operating directions and the presence of the heaviest train consists must also be taken into account.

A comprehensive method was developed for selecting locomotive types and fleet composition for freight train operations on railway sections, incorporating the influence of variations in train consist mass between operating directions on the fuel and energy consumption of traction units.

Based on data from the Marokand – Kashkadarya railway section, the calculated traction capacity limits at a reference track gradient of 7.7‰ were 4,355.1 t for the UZ-ELR electric locomotive and 8,875.1 t for the 2UZ-ELR electric locomotive. For a computational timetable comprising 26 trips, with a minimum locomotive preparation time of 90 minutes between consecutive trips, a fleet of nine locomotives was found sufficient to cover all scheduled services under the assumed operating conditions.

In the baseline open planning scenario, a mixed fleet consisting of six 2UZ-ELR and three UZ-ELR electric locomotives was estimated to consume 850.6675 kWh less electrical energy than a single-type fleet comprising nine 2UZ-ELR locomotives, providing an estimated economic benefit of UZS 808,134.

Furthermore, under the single-type locomotive fleet criterion, the 2O‘z-EL electric locomotive was recommended for the Marokand–Karshi railway section, with a calculated reduction in daily energy consumption of 4.76% compared with the 2O‘z-ELR electric locomotive. Under the criterion of providing traction services for both passenger and freight trains, a mixed fleet consisting of 2O‘z-EL and O‘z-ELR electric locomotives was recommended. The expected annual economic benefit was estimated at UZS 583.58 million.

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MINIMIZATION OF LOCOMOTIVE IDLE TIME AT TURNAROUND STATIONS THROUGH OPTIMAL LOCOMOTIVE ASSIGNMENT TO FREIGHT TRAINS

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Abstract: This article examines a binary assignment model for providing freight train consists with available locomotives at a turnaround station. The model accounts for locomotive arrival times, completion of technological preparation, train departure times, and imbalances between the available locomotive fleet and the number of train consists awaiting departure. In a simulation example involving 13 trains, total locomotive idle time amounted to 6.54 locomotive-hours. Idle-time indicators are compared for scenarios with 10–40 trains, and the applicability limits of the model results and discrepancies between the original table and graph are discussed.

Keywords: locomotive assignment, turnaround station, freight train, idle time, assignment model.

1. Introduction

Dispatching freight trains according to the established timetable depends on the times at which locomotives and train consists become technically ready. At a turnaround station, assigning a locomotive to its next trip requires not only an available traction unit but also coordination of the technical inspection, crew availability, and the relevant departure window. Consequently, reducing the idle time of one locomotive may increase the waiting times of others.

When developing a rational locomotive assignment plan, the combined effect of individual decisions must be evaluated. By considering all feasible connections between available locomotives and ready train consists at a station simultaneously, the minimum aggregate locomotive idle time can be sought. Although this problem is related to the classical assignment problem in discrete optimization, it must be supplemented with railway-specific time, technical compatibility, and safety constraints.

2. Literature review

A number of researchers have investigated the economic assessment of railway companies' fixed assets, the economic and statistical analysis of railway network performance, and the efficient utilization of rolling stock. In particular, Cordeau J.-F. et al. [1] surveyed optimization models for train routing and scheduling and highlighted the interdependence of resources. In contrast to this broader research direction, the present study focuses on evaluating short-term assignment alternatives based on locomotive readiness and train departure times at a single turnaround station.

Piu F. and Speranza M.G. [2] classified locomotive assignment problems according to their technical constraints, objective functions, and mathematical solution methods. In contrast, the present research evaluates short-term locomotive assignments based on readiness and departure times at a single turnaround station.

Ziarati K. et al. [3] considered traction capabilities and operational requirements in assigning heterogeneous locomotive fleets. In contrast, the present research evaluates short-term locomotive assignments based on readiness and departure times at a single turnaround station.

Ziarati K. et al. [4] applied a branch-and-cut approach to locomotive assignment within an integer optimization framework. In contrast, the present research evaluates short-term locomotive assignments based on readiness and departure times at a single turnaround station.

Cordeau J.-F. et al. [5] used Benders decomposition for the integrated assignment of locomotives and railway cars. In contrast, the present research evaluates short-term locomotive assignments based on readiness and departure times at a single turnaround station.

Cordeau J.-F. et al. [6] investigated a mathematical formulation for the simultaneous assignment of locomotives and cars to passenger trains. In contrast, the present research evaluates short-term locomotive assignments based on readiness and departure times at a single turnaround station.

Ahuja R.K. et al. [7] addressed large-scale, real-life locomotive scheduling problems involving circulation and multiple train services on a railway network. In contrast, the present research evaluates short-term locomotive assignments based on readiness and departure times at a single turnaround station.

Fügenschuh A. et al. [8] modeled locomotive scheduling and car transfers in recurring freight services using time-window constraints. In contrast, the present research evaluates short-term locomotive assignments based on readiness and departure times at a single turnaround station.

Ortiz-Astorquiza C. et al. [9] proposed an extended locomotive assignment model accounting for distributed power. In contrast, the present research evaluates short-term locomotive assignments based on readiness and departure times at a single turnaround station.

Bärmann A. et al. [10] demonstrated the importance of integrating locomotive scheduling with driver assignment. In contrast, the present research evaluates short-term locomotive assignments based on readiness and departure times at a single turnaround station.

The reviewed studies indicate that the mathematical assignment model belongs to a well-established class of optimization problems. The principal aim of this article is not to claim a new universal solution algorithm, but to provide a systematic procedure for converting station

operating data into an assignment matrix and evaluating the limits within which the results can be applied.

3. Mathematical model

One of the principal stages in preparing an operating plan for the locomotive fleet is identifying the most rational assignment of locomotives, crews, and train consists, as well as coordinating these assignments with the scheduled train departures.

The initial data for the problem comprise:

– forecast times at which locomotives and crews become available after completing the TO-1 inspection, and at which train consists of different categories become ready for departure;

– information on priority trains and locomotives for which waiting time before departure must be minimized;

– train timetables for the relevant railway sections;

– the prescribed minimum locomotive turnaround time at the station (t_m).

The problem of assigning freight locomotives to trains is formulated as follows. Let $L = \{L_1, L_2, \ldots, L_i\}$, $i = 1, \ldots, n$, be the set of locomotives available for operation with crews after the TO-1 inspection, and let $S = \{S_1, S_2, \ldots, S_j\}$, $j = 1, \ldots, m$, be the set of freight train consists ready for departure (where n and m denote the numbers of available locomotives with crews and ready train consists, respectively, during the planning period). The idle time t_{ij} depends on the pairing of elements of these sets. If locomotive L_i, ready for operation with its crew, is assigned to train consist S_j, the corresponding decision variable x_{ij} $(i = 1, \ldots, n; j = 1, \ldots, m)$ takes the value 1 ($x_{ij} = 1$); otherwise, it takes the value 0 ($x_{ij} = 0$). The objective is to identify, subject to all constraints and requirements, a combination of locomotive-to-consist assignments that minimizes the total locomotive idle time:

$$T_{ht} = \sum_{i=1}^{n}\sum_{j=1}^{m} t_{ij}x_{ij} \to min \tag{1}$$

The following constraints apply:

$$\sum_{i=1}^{n} x_{ij} = 1, i = 1,\ldots,n \tag{2}$$

$$\sum_{j=1}^{m} x_{ij} = 1, j = 1,\ldots,m \tag{3}$$

$$x_{ij} \in \{0,1\}, i = 1,\ldots,n, j = 1,\ldots,m \tag{4}$$

$$24 \geq t_{ij} \geq t_{м} \tag{5}$$

Constraints (2) require each locomotive to be assigned to one train consist; constraints (3) require each consist to be assigned no more than one locomotive; and constraints (5) specify that the time spent by a locomotive at the turnaround station is at least the prescribed turnaround time and at most one day. During the planning period, the number of locomotives may differ from the number of train consists ($n \neq m$), corresponding to an unbalanced timetable. If $n < m$, dummy locomotives are introduced (representing the arrival of reserve locomotives); if $n > m$, dummy train consists are introduced, allowing the corresponding locomotives to be dispatched as light locomotives.

The procedure for developing an optimal locomotive fleet operating plan for a shift or daily planning period is considered using the assignment problem. The assignment problem is a type of linear programming problem. The Solver function in Microsoft Excel is used to determine t_{ij} for each $\{L_i, S_j\}$ pair. To solve the problem, a locomotive idle-time matrix is constructed from the readiness times of the traction units and train consists (Figure 1).

Train consists / Locomotives	S_1	…	S_j	…	S_m
L_1	t_{11}	…	t_{1j}	…	t_{1m}
…	…	…	…	…	…
L_i	t_{i1}	…	t_{ij}	…	t_{im}
…	…	…	…	…	…
L_n	t_{n1}	…	t_{nj}	…	t_{nm}

Figure 1. Locomotive idle-time matrix constructed from the readiness times of traction units and train consists.

The time difference associated with each cell of the locomotive idle-time matrix, constructed from the readiness times of traction units and train consists, is determined as follows:

$$\Delta t_{st} = L_i - S_i, \text{ hour} \quad (6)$$

Three cases may arise. For each case, the value of t_{ij} is determined as follows:

$$\textit{Case 1: When } \Delta t_{st} \geq t_m \text{ then } t_{ij} = \Delta t_{st} \quad (7)$$

$$\textit{Case 2: When } 0 \leq \Delta t_{st} < t_m \text{ then } t_{ij} = t_m \quad (8)$$

$$\textit{Case 3: When } \Delta t_{st} < 0 \text{ then } t_{ij} = t_m \quad (9)$$

The average idle time of train locomotives at the station where they are assigned to trains is determined as follows:

$$\bar{t}_{avg.loc} = \frac{\sum_{i=1}^{m} t_{ij}}{s}, \text{ hour} \quad (9)$$

Thus, a procedure was developed for calculating the idle times of train locomotives at turnaround stations when preparing an optimal operating plan for traction units over a shift or daily period, using an assignment problem and taking train traffic volumes into account.

4. Results and discussion

Using the procedure described above, consider the calculation of minimum locomotive idle time at a turnaround station where 13 trains are scheduled to depart during a daytime shift (Table 1).

Table 1. Locomotive idle-time matrix for a planning period with 13 trains

			T/r	1	2	3	4	5	6	7	8	9	10	11	12	13
			Train number	2001	2003	2005	2007	2009	2011	2013	2015	2017	2019	2021	2023	2025
			Ready for Departure Time	8:40	9:28	10:11	10:42	11:49	12:25	13:07	13:44	14:59	15:51	16:40	18:59	19:30
T/r	Locomotive number	Time of Readiness for Departure	Numerical value	8,67	9,47	10,18	10,7	11,82	12,42	13,12	13,73	14,98	15,85	16,67	18,98	19,5
1	2002	8:08	8,13	0,54	1,34	2,05	2,57	3,69	4,29	4,99	5,6	6,85	7,72	8,54	10,85	11,37
2	2004	9:15	9,25	0,5	0,5	0,93	1,45	2,57	3,17	3,87	4,48	5,73	6,6	7,42	9,73	10,25
3	2006	10:16	10,27	0,5	0,5	0,5	0,5	1,55	2,15	2,85	3,46	4,71	5,58	6,4	8,71	9,23
4	2008	11:14	11,23	0,5	0,5	0,5	0,5	0,59	1,19	1,89	2,5	3,75	4,62	5,44	7,75	8,27
5	2010	12:38	12,63	0,5	0,5	0,5	0,5	0,5	0,5	0,5	1,1	2,35	3,22	4,04	6,35	6,87

6	2012	12:51	12,85	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,88	2,13	3,0	3,82	6,13	6,65
7	2014	14:19	14,32	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,66	1,53	2,35	4,66	5,18
8	2016	15:07	15,12	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,73	1,55	3,86	4,38
9	2018	15:38	15,63	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	1,04	3,35	3,87
10	2020	16:33	16,55	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	2,43	2,95
11	2022	17:21	17,35	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	1,63	2,15
12	2024	18:43	18,72	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,78
13	2026	19:26	19,43	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5

The value of t_{ij} in each cell of this matrix was calculated using equations (7) – (9). To identify the $\{L_i, S_j\}$ pairs that minimize total locomotive idle time, a matrix of decision variables x_{ij} having the same dimensions as the idle-time matrix is constructed, and the Solver function in Microsoft Excel is applied. The objective function (1) gives a minimum total idle time of 6.54 hours and the following optimal locomotive fleet operating plan for the shift or daily period: $R = \{\{L_1, S_1\}, \{L_2, S_2\}, \{L_3, S_3\}, \{L_4, S_4\}, \{L_5, S_5\}, \{L_6, S_6\}, \{L_7, S_7\}, \{L_8, S_8\}, \{L_9, S_9\}, \{L_{10}, S_{10}\}, \{L_{11}, S_{11}\}, \{L_{12}, S_{12}\}, \{L_{13}, S_{13}\}\}$. At the turnaround station, the maximum locomotive idle time was 0.54 hours (assignment $\{L_1, S_1\}$), the minimum was 0.5 hours, equal to the prescribed turnaround time t_m, and the average was 0.51 hours. Such a situation rarely occurs in practice, since locomotives are assigned on the principle that "a train consist must not wait for a locomotive," which can increase the idle time of traction rolling stock. Using this principle and the method described

above, the maximum and average locomotive idle times were simulated for traffic volumes ranging from 10 to 40 trains in increments of five (Figure 2).

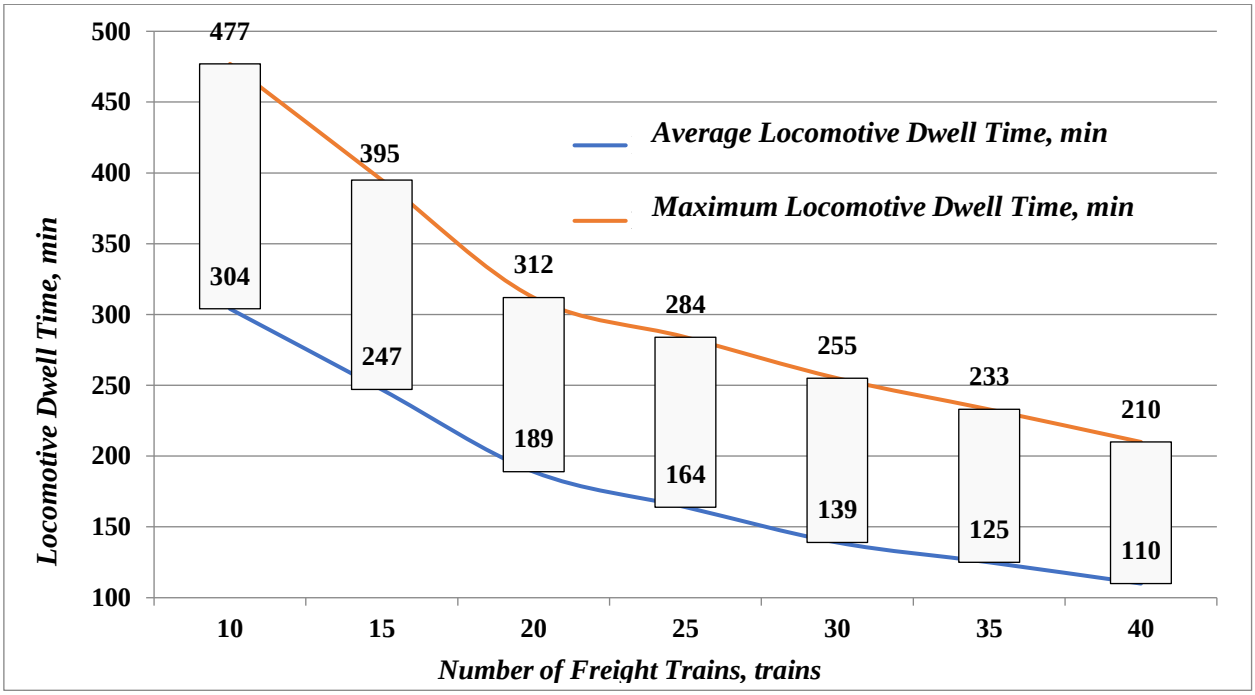


Figure 2. Simulation results for maximum and average locomotive idle times at the turnaround station for traffic volumes ranging from 10 to 40 trains during the planning period.

Thus, traffic volumes representative of JSC Uzbekistan Railways and the existing principles for assigning traction units to trains may reduce the productive operating time of locomotives. Dispatcher-based regulation of locomotives awaiting work could improve their utilization; in particular, dispatcher-controlled locomotives could potentially be used to serve local freight trains.

5. Conclusions

1. A computational framework based on a complete locomotive idle-time matrix and binary assignment variables was systematically presented for assigning locomotives to freight trains. The model makes it possible to evaluate the compatibility of locomotive and train consist readiness times.

2. A method was developed for determining the idle times of train locomotives at turnaround stations when preparing an optimal operating plan for traction units over a shift or daily period. The method uses an assignment problem and accounts for train traffic volumes. The calculated maximum locomotive idle time was 476 minutes for 10 trains and 210 minutes for 40 trains.

3. Before drawing final conclusions for practical application, time references, technical preparation standards, compatibility of locomotive types, crew availability, and the original computational results must be independently verified.

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