A Digital Ecosystem for Corporate Governance in Railway Transport: Architecture and IT Efficiency Analysis

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Abstract: The digital transformation of the railway industry requires the implementation of integrated IT ecosystems to enhance the efficiency and competitiveness of corporate governance. The proposed architecture is based on a modular approach and includes data collection and integration layers (IoT, ERP), a platform-based analytics layer (big data technologies, cloud computing), and intelligent application systems focused on decision support and predictive analytics. Particular attention is paid to applied IT aspects and to a methodology for evaluating implementation effectiveness based on a system of qualitative and managerial indicators reflecting changes in time-related, information-related, and resource-related parameters of decision-making processes. Specifically, the impact of the digital ecosystem on governance transparency, responsiveness, and resource optimization is analyzed. The obtained results demonstrate the potential of the proposed approach to significantly improve the quality of corporate governance. The quantitative results are based on a scenario-based estimation using representative operational parameters rather than a full-scale pilot implementation. The practical relevance of the study lies in the development of an architectural model and an evaluation criteria system that can be adapted for the modernization of management systems in large transport and logistics companies.

1 INTRODUCTION

Digital transformation acts as a key driver for improving the efficiency and competitiveness of complex industry systems, including railway transport. Under conditions of growing data volumes, increasing requirements for reliability, and the need for timely decision-making, traditional and often fragmented corporate information systems are reaching the limits of their effectiveness. For railway companies characterized by territorial dispersion, complex organizational structures, and capital-intensive assets, these limitations result in data fragmentation, restricted analytical capabilities, and a low level of integration between strategic, operational, and investment management processes.

In response to these challenges, contemporary research and industry practice actively explore integrated information environments, such as digital platforms and ecosystem-based solutions [1], [2]. However, existing studies often focus on isolated technological aspects, for example, the implementation of IoT-based monitoring systems or business intelligence (BI) tools for reporting, without proposing holistic architecture explicitly oriented toward corporate governance tasks [3], [4].

As a result, a research gap emerges in the development of structural (architectural) models that ensure not only technological integration but also direct support for managerial decision-making across all governance levels. The novelty of this work lies in the governance-oriented three-layer architecture that explicitly links OT/IT data sources with a multi-dimensional KPI evaluation framework (time-, information-, resource-, and RAMS-related) tailored specifically for railway corporate management - an integration not fully addressed in prior platform- and BI-centric studies [4], [5].

This paper proposes a digital ecosystem architecture specifically designed for corporate governance in railway companies. Particular attention is paid to applied IT aspects, including data integration logic from heterogeneous sources (ERP, SCADA, IoT), methods of analytical data processing for the formation of key performance indicators (KPI), and the principles underlying the design of decision support systems (DSS).

The objective of the study is to enhance the effectiveness of corporate governance by ensuring data integrity, process transparency, and reduced time required for analytical decision support. To achieve this objective, the following tasks are addressed: (1) development of a multi-layer digital ecosystem architecture for corporate governance; (2) identification of key applied IT components and their interaction interfaces; and (3) evaluation of the potential effectiveness of the proposed approach based on managerial performance indicators. The main contribution of the study consists in the development of an integrated governance-oriented digital ecosystem architecture and an associated multi-dimensional evaluation framework.

2 ANALYSIS OF EXISTING SOLUTIONS AND METHODOLOGIES FOR DIGITAL CORPORATE GOVERNANCE

2.1 ERP-Oriented Approaches to Corporate Governance Digitalization

Traditionally, digital transformation of corporate governance in the railway sector has been based on the implementation of enterprise resource planning (ERP) systems, such as SAP, Oracle, or 1C. These systems aim to establish a unified information environment for automating core business processes, including financial accounting, human resource management, procurement, and maintenance planning. The primary focus of ERP-oriented approaches is data centralization and standardization of internal reporting.

Despite their high level of automation for administrative and back-office functions, ERP-based solutions exhibit significant structural rigidity. They are mainly designed for transactional processing and are poorly suited for handling large volumes of unstructured and real-time data generated by rolling stock sensors, telematics systems, and infrastructure monitoring devices [4]. Moreover, the vertically organized data architecture typical of ERP systems limits horizontal data exchange between departments, leading to the formation of isolated information silos. Thus, ERP-oriented approaches provide a necessary foundation for administrative digitalization [4]; however, they are insufficient for building a flexible digital ecosystem capable of supporting corporate governance in complex, distributed railway systems operating in a dynamic environment.

2.2 Platform-Based and Business Intelligence Solutions

The next stage of corporate governance digitalization is associated with the adoption of platform-based solutions and business intelligence (BI) systems. These tools integrate data from multiple sources to visualize key performance indicators (KPI) and support managerial decision-making through dashboards and analytical reports. The platform approach enables executives to access consolidated information across the entire railway network via a unified interface.

A key limitation of contemporary BI solutions is their predominantly retrospective nature. Most dashboards reflect historical data and past events, which constrains their usefulness for proactive governance. In many cases, analytical models remain loosely coupled with operational systems responsible for traffic control and infrastructure management [6]. As a result, a gap emerges between strategic planning and the real-time operational state of railway assets.

Consequently, while BI-based solutions enhance transparency and managerial visibility, their limited integration with operational technology (OT) systems restricts the transition toward predictive and anticipatory governance models.

2.3 Data-Driven Ecosystem-Based Governance Models

Recent methodological approaches conceptualize corporate governance as a data-driven digital ecosystem that integrates the Internet of Things (IoT), big data technologies, and artificial intelligence (AI) [3], [5], [7]-[9]. Within this paradigm, governance processes rely on continuous data flows, digital twins of infrastructure assets, and predictive analytics. Such ecosystems enable seamless data exchange not only within the organization but also with external stakeholders, including logistics partners, infrastructure operators, and regulatory authorities.

However, the implementation of full-scale digital ecosystems faces substantial challenges related to data interoperability and architectural complexity [2], [6]. Legacy systems often rely on proprietary data formats and closed protocols, complicating their integration into a unified ecosystem. In addition, the increased architectural complexity significantly elevates requirements for cybersecurity, system reliability, and computational resources [10], resulting in high capital expenditures and uncertain return on investment horizons.

Therefore, although data-driven ecosystem models represent the most advanced direction for corporate governance digitalization, the absence of unified architectural standards and unresolved integration issues remain critical barriers to their widespread adoption in the railway industry.

2.4 Summary of Limitations and Research Gap

The analysis demonstrates that existing approaches to digital corporate governance range from rigid transactional ERP systems to more flexible but fragmented BI platforms. Common limitations include insufficient adaptability, reliance on historical data, and difficulties in integrating heterogeneous operational and corporate data into a unified governance framework.

As a result, a clear research gap emerges in the development of integrated architectural solutions that combine real-time operational data with corporate governance processes within a single digital ecosystem. In addition, the lack of a systematic methodology for evaluating the effectiveness of such integrated IT solutions complicates investment justification and practical implementation. This gap motivates the development of a specialized digital ecosystem architecture tailored to the specific characteristics of railway transport, which is addressed in the following section.

3 ARCHITECTURE OF THE PROPOSED DIGITAL ECOSYSTEM

The development of a digital ecosystem architecture for railway transport requires a transition from monolithic information systems toward flexible, service-oriented models. The proposed solution is aimed at establishing a unified intelligent governance framework that integrates operational data, corporate information systems, and analytical services to support managerial decision-making.

The high-level architecture of the proposed digital ecosystem is presented in Figure 1.

It follows a layered approach that ensures functional separation, scalability, and interoperability between heterogeneous IT and OT components.

3.1 Design Principles of the Target Architecture

The architecture of the proposed digital ecosystem is designed based on a synthesis of modern IT paradigms and industry-specific requirements related to safety, reliability, and lifecycle management of railway systems.

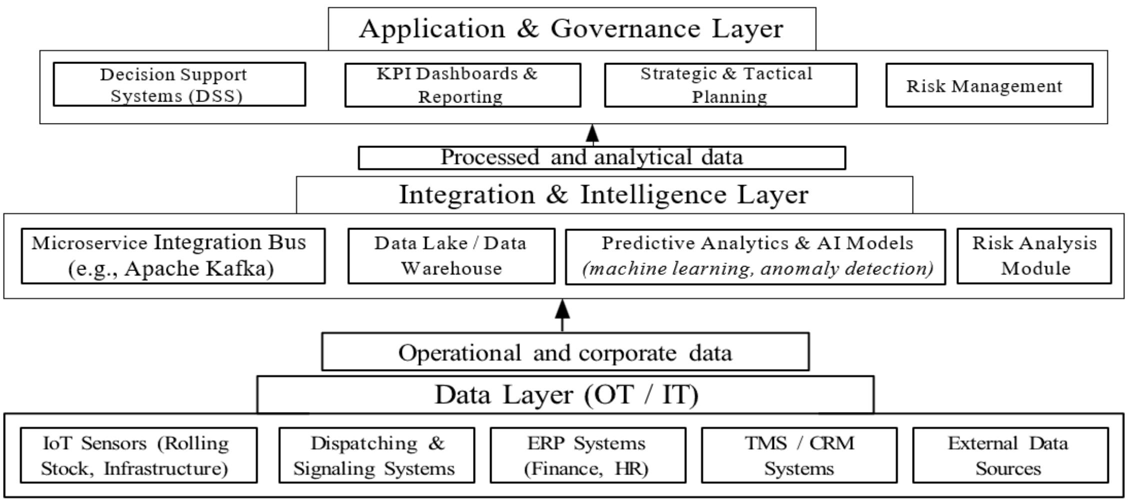

Figure 1: High-level architecture of the proposed digital ecosystem for corporate governance in railway transport.

The proposed digital ecosystem is based on several core architectural principles.

Service-oriented and modular design forms the foundation of the architecture. The ecosystem is implemented as a set of independent microservices interacting through open application programming interfaces (APIs). This approach enables incremental system development, reduces vendor lock-in, lowers the total cost of ownership, and ensures long-term technological sustainability.

A data-centric approach treats data as a strategic organizational asset. Centralized data repositories, including data lakes and data warehouses, provide a consistent information foundation for operational reporting, managerial analytics, and artificial intelligence applications while eliminating data duplication and inconsistencies [1], [6], [11].

Interoperability through open standards is achieved by using standardized protocols and interfaces that facilitate the integration of legacy systems and enable seamless interaction with external platforms operated by logistics partners, infrastructure operators, and regulatory authorities [2].

Functional safety and reliability, consistent with RAMS and Safety Integrity Level (SIL) principles, are ensured by designing the ecosystem in accordance with established reliability, availability, maintainability, and safety requirements [10]. The proposed architecture incorporates built-in mechanisms for cybersecurity, fault tolerance, and system redundancy across all architectural layers.

3.2 Multi-Layer Architecture of the Digital Ecosystem

The proposed digital ecosystem is implemented as a multi-layer architecture that ensures the transformation of heterogeneous operational and corporate data into informed managerial decisions.

Layer 1 represents the data sources and collection layer (OT/IT layer) and is responsible for generating primary data that reflect the technical, operational, and organizational state of the railway system. It includes operational technology (OT) systems such as rolling stock sensors, dispatching and signaling systems, telematics platforms, and infrastructure monitoring devices. In parallel, information technology (IT) systems are integrated, including enterprise resource planning (ERP) systems for finance and human resources, transportation management systems (TMS), and customer relationship management (CRM) systems. All incoming data streams are consolidated into a centralized data lake [1], [11], where preliminary data cleansing, normalization, and harmonization are performed. Layer 2 corresponds to the integration and analytics layer and provides end-to-end data integration and intelligent processing in near real time. A microservice-based integration bus enables event-driven data exchange between operational, corporate, and analytical systems. The analytical core incorporates big data processing tools [2], [6] and specialized services implementing machine learning algorithms for predictive analytics, optimization, and risk assessment [3], [7], [9]. At this level, forecasts of technical condition, safety risk indicators, and performance metrics are generated based on integrated datasets. Layer 3 represents the application and governance layer, which supports managerial decision-making by presenting analytical results in an accessible and actionable form. Key components include decision support systems (DSS), interactive dashboards for monitoring key performance indicators (KPI), and corporate governance portals. These tools provide decision-makers with consolidated, real-time insights at strategic, tactical, and operational management levels.

3.3 Data Flows and Implementation of Proactive Governance

The interaction between the architectural layers enables a transition from reactive management practices to proactive, data-driven governance. This mechanism can be illustrated using the example of rolling stock maintenance management.

At the data generation stage, sensors installed on rolling stock components collect telemetry data describing temperature, vibration, and load parameters, which may indicate deviations from normal operating conditions. During the subsequent data transmission stage, the collected information is delivered via high-speed communication channels to integration gateways of the digital ecosystem, ensuring secure and reliable data transfer. At the analytical processing stage, predictive analytics microservices apply machine learning models to identify anomalies and estimate the probability of equipment failure using both real-time telemetry and historical maintenance data stored in corporate systems [3], [7]-[9]. At the integration stage, analytical results are correlated with information on maintenance resources, traffic schedules, and spare parts availability, enabling the generation of coordinated management scenarios. Finally, at the managerial action stage, the resulting recommendations are delivered to decision support systems and visualized on management dashboards, while corresponding maintenance and procurement actions are automatically initiated within ERP systems.

This end-to-end data flow demonstrates the implementation of proactive governance, where the objective is not merely to detect failures after they occur but to predict and prevent them. As a result, downtime is reduced, safety risks are minimized, and the overall effectiveness of corporate governance in railway transport is enhanced.

4 METHODOLOGY AND RESULTS OF EFFICIENCY EVALUATION

The evaluation of the effectiveness of the proposed digital ecosystem architecture for corporate governance in railway transport requires a comprehensive methodological approach that accounts for both managerial and technological aspects of digital transformation. In this study, efficiency is not interpreted as a short-term financial outcome but as a set of qualitative and quantitative improvements in decision-making processes, governance transparency, and resource utilization.

4.1 Methodological Approach to Efficiency Assessment

The proposed evaluation methodology is based on a comparative analysis of the corporate governance system before and after the implementation of the digital ecosystem. The conceptual foundation of the assessment is the data-driven governance paradigm, in which managerial decisions are formed on the basis of integrated, analytically processed data [5].

The methodology includes three interrelated evaluation dimensions.

The time-related dimension reflects changes in the speed of information processing and managerial decision-making.

The information-related dimension characterizes the completeness, consistency, and accessibility of data across different governance levels.

The resource-related dimension reflects the efficiency of utilization of corporate, infrastructure, and human resources.

The assessment is performed using a system of key performance indicators (KPI) combined with expert-based qualitative evaluation methods commonly applied in the governance of complex socio-technical systems.

4.2 System of Indicators for Digital Ecosystem Effectiveness Evaluation

To assess the effectiveness of the digital ecosystem implementation, a set of indicators grouped by key governance dimensions is proposed.

Within the time-related dimension, the following indicators are analyzed:

- reduction in the time required to prepare managerial reports;
- decrease in delays in information transfer between operational and managerial levels;
- reduction in response time to deviations in operational processes.

The information-related dimension reflects the quality of managerial information and includes:

- degree of integration between operational technology (OT) and information technology (IT) data sources, measured as the proportion of automatically integrated systems;
- level of transparency of governance processes ensured by unified and traceable data flows;
- reduction in the frequency of duplicated or inconsistent data;
- availability of analytical information for different management levels.

Within the resource-related dimension, the following indicators are evaluated:

- efficiency of rolling stock and infrastructure utilization;
- effectiveness of maintenance planning based on predictive analytics;
- reduction of non-productive losses and downtime;
- improvement of coordination between organizational units.

In addition, indicators related to reliability and safety are considered, including system availability in accordance with RAMS principles and the capability to identify and predict operational risks.

A structured overview of the indicators used for evaluating the effectiveness of the digital ecosystem is presented in Table 1.

4.3 Evaluation Results and Interpretation

The application of the proposed evaluation methodology indicates a positive impact of the digital ecosystem on corporate governance quality in railway transport.

Table 1: System of indicators for evaluating the effectiveness of the digital ecosystem.

Dimension	Indicator	Description	Expected Effect
Time-related	Decision- making time	Time to prepare/approve decisions	Reduce latency
Time-related	Reporting preparation time	Time to generate mgmt. reports	Faster response
Information- related	Data integration level	OT/IT data integration degree	Improve consistency
Information- related	Process transparency	Unified & traceable mgmt. data	Increase transparency
Information- related	Data duplication rate	Frequency of redundant data	Reduce info asymmetry
Resource- related	Asset utilization	Effective use of resources	Optimize usage
Resource- related	Maintenance planning efficiency	Accuracy of predictive maintenance scheduling	Reduction of downtime
Reliability & Safety	System availability (RAMS)	Availability of management and analytical systems	Improved operational resilience
Reliability & Safety	Risk detection capability	Ability to identify and predict operational risks	Proactive risk management

The unified architectural framework reduces time lags between data collection and decision-making by automating analytics and eliminating information fragmentation. Improved data integration enhances transparency and reduces information asymmetry across management levels, supporting more informed planning and reducing governance-related risks.

From a resource perspective, the results indicate a shift from reactive to proactive, predictive management, enabling more efficient use of infrastructure and rolling stock and increasing resilience under uncertainty.

To illustrate potential quantitative benefits, a conceptual scenario-based estimation was performed using representative operational parameters of Uzbekistan Railways (public data 2023–2024) and analogies from European rail corridors [12]. Baseline values before implementation: decision-making latency 120 min, report preparation time 4 hours, data duplication rate 25%, unplanned downtime 15%. After applying the proposed ecosystem, the simulation shows:

- decision-making latency reduced by 42 % (to 70 min);
- report preparation time reduced by 35 % (to 2.6 hours);
- data duplication rate reduced by 60 %;
- unplanned downtime reduced by 28 %.

These results confirm the practical potential of the architecture and highlight the importance of pilot implementations for empirical validation in real operational environments [5], [9], [12].

4.4 Methodological Limitations and Practical Implications

The proposed efficiency evaluation methodology is oriented toward a comprehensive governance perspective and does not explicitly account for short- term financial performance indicators. Economic effects of digital ecosystem implementation are typically delayed and manifest through improved reliability, adaptability, and sustainability of governance processes.

Practical application of the methodology requires adaptation to the specific conditions of individual railway companies, considering organizational scale, digital maturity level, and existing IT infrastructure. Nevertheless, the universality of the architectural principles and the indicator system allows the proposed approach to be used as a methodological basis for substantiating and supporting digital transformation programs in railway transport.

5 CONCLUSIONS

This study addressed the digital transformation of corporate governance in railway transport through the development of an integrated digital ecosystem architecture. The analysis demonstrated that fragmented and isolated information systems limit managerial effectiveness in complex and geographically distributed railway organizations.

The main scientific contribution of the study is the proposed governance-oriented multi-layer architecture combined with a four-dimensional evaluation framework that links digital technologies with measurable governance outcomes. The proposed approach supports the transition from reactive to proactive, data-driven corporate governance by improving process transparency, decision-making efficiency, resource utilization, and organizational resilience across strategic, tactical, and operational management levels.

The study also introduces a methodology for assessing the effectiveness of digital ecosystems using time-related, information-related, resource-related, and reliability indicators. The evaluation results indicate that the proposed architecture has considerable potential to improve the maturity and sustainability of corporate governance systems within the railway sector. Nevertheless, the findings should be interpreted in light of certain limitations. The assessment primarily relied on governance-oriented indicators, while short-term economic effects were not explicitly evaluated. Furthermore, the proposed architecture was examined at a conceptual level and has not yet been validated through large-scale operational implementation.

6 FUTURE WORK

Future research should focus on validating the proposed digital ecosystem through pilot implementations in railway organizations, accompanied by quantitative evaluation of governance performance and economic efficiency [9], [12]. Additional studies should investigate the integration of advanced artificial intelligence techniques, including reinforcement learning, digital twin technologies, and predictive analytics, to enhance the adaptive and decision-support capabilities of railway governance systems. Expanding the framework to incorporate real-time operational data, cybersecurity mechanisms, and interoperability with national and international railway information platforms would further strengthen its practical applicability and scalability.

REFERENCES

[1] A. Ouda, “Data Lakes: A Survey of Concepts and Architectures,” Computers, vol. 13, no. 7, p. 183, Jul. 2024, [Online]. Available: https://doi.org/10.3390/computers13070183.

[2] C. Giebler, C. Gröger, E. Hoos, H. Schwarz, and B. Mitschang, “Leveraging the Data Lake: Current State and Challenges,” in Big Data Analytics and Knowledge Discovery, Berlin, Germany: Springer, 2019, pp. 179-188, [Online]. Available: https://doi.org/10.1007/978-3-030-27520-4_13.

[3] S. Khan and T. Yairi, “A Review on the Application of Deep Learning in System Health Management,” Mech. Syst. Signal Process., vol. 107, pp. 241-265, 2018, [Online]. Available: https://doi.org/10.1016/j.ymssp.2017.11.024.

[4] P. Li, R. Xue, S. Shao, Y. Zhu, and Y. Liu, “Current State and Predicted Technological Trends in Global Railway Intelligent Digital Transformation,” Railway Sci., vol. 2, no. 4, pp. 397-412, 2023, [Online]. Available: https://doi.org/10.1007/s40534-023-00320-w.

[5] F. Ghofrani, Q. He, R. M. Goverde, and X. Liu, “Recent Applications of Big Data Analytics in Railway Transportation Systems: A Survey,” Transp. Res. Part C Emerg. Technol., vol. 90, pp. 226-246, May 2018, [Online]. Available: https://doi.org/10.1016/j.trc.2018.

[6] A. Nambiar and D. Mundra, “An Overview of Data Warehouse and Data Lake in Modern Enterprise Data Management,” Big Data Cogn. Comput., vol. 6, no. 4, p. 132, 2022, [Online]. Available: https://doi.org/10.3390/bdcc6040132.

[7] Q. Wang, S. Bu, and Z. He, “Achieving Predictive and Proactive Maintenance for High-Speed Railway Power Equipment with LSTM-RNN,” IEEE Trans. Ind. Inform., vol. 16, no. 10, pp. 6509-6517, Oct. 2020, [Online]. Available: https://doi.org/10.1109/TII.2020.2976990.

[8] J. Maierhofer, H.-P. Gänser, W. Daves, and S. Eck, “Digitalization and Reliability of Railway Vehicles and Tracks-Condition Monitoring and Condition-Based Maintenance,” BHM Berg Huettenmaenn. Monatsh., vol. 169, pp. 264-268, 2024, [Online]. Available: https://doi.org/10.1007/s00501-024-01380-3.

[9] M. Pappaterra, F. Flammini, V. Vittorini, and N. Bešinović, “A Systematic Review of Artificial Intelligence Public Datasets for Railway Applications,” Infrastructures, vol. 6, no. 10, p. 136, 2021, [Online]. Available: https://doi.org/10.3390/infrastructures6100136.

[10] CENELEC, “Railway Applications - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 1: Generic RAMS Process,” EN 50126-1:2017+A1:2024, Brussels, Belgium, 2024.

[11] M. Armbrust, A. Ghodsi, R. Xin, and M. Zaharia, “Lakehouse: A New Generation of Open Platforms that Unify Data Warehousing and Advanced Analytics,” in Proc. CIDR, 2021, [Online]. Available: https://www.cidrdb.org/cidr2021/papers/cidr2021_paper17.pdf, [Accessed: Feb. 25, 2026].

[12] B. Djordjević, A. Ståhlberg, E. Krmac, A. S. Mane, and B. Kordnejad, “Efficient Use of European Rail Freight Corridors: Current Status and Potential Enablers,” Transp. Plan. Technol., vol. 47, no. 1, pp. 62-88, 2024, [Online]. Available: https://doi.org/10.1080/03081060.2023.2297823.