

Artificial intelligence for integrating railway freight into multi-actor supply chains: insights from machine learning, deep learning and neural networks

Taoufiq El Moussaoui

*Polydisciplinary Faculty of Sidi Bennour, Chouaib Doukkali University,
El Jadida, Morocco, and*

Alaa Eddine El Moussaoui

*EMIO, LIREEM Laboratory, Higher School of Technology, Nador,
Mohammed First University, Oujda, Morocco*

Abstract

Purpose – Rail freight is widely recognized for its economic and environmental advantages, yet it remains weakly integrated into firms' supply chains, particularly in emerging economies. This study aims to investigate the conditions under which rail freight can be effectively integrated into multi-actor supply chains, with specific attention to the role of organizational coordination, information quality and artificial intelligence (AI) in shaping logistics integration outcomes.

Design/methodology/approach – The study draws on a quantitative survey of 3,185 stakeholders involved in rail-based and multimodal supply chains in Morocco. The data are analyzed using a combination of machine learning, deep learning and artificial neural network models. These methods are used not only to identify the main determinants of rail freight integration but also to capture non-linear relationships, interaction effects and potential integration trajectories that cannot be addressed through conventional linear models.

Findings – The results show that rail freight integration depends primarily on organizational and informational mechanisms rather than on infrastructure alone. Inter-organizational coordination and logistics information quality emerge as the most influential factors. AI contributes positively to rail freight integration, but its effect is conditional: AI tools significantly enhance integration only when adequate levels of coordination and information sharing are already in place. Scenario simulations further reveal that the strongest integration gains arise from the combined improvement of organizational practices and AI adoption.

Originality/value – This research contributes to the literature by shifting the focus from infrastructure-centered explanations toward a systemic understanding of rail freight integration. It is among the first studies to empirically combine machine learning, deep learning and artificial neural networks to analyze logistics integration in an emerging-economy context and to show that AI functions as a complementary and amplifying mechanism rather than a standalone solution.

Keywords Railway freight, Supply chain, Artificial intelligence, Machine learning, Deep learning, Neural networks

Paper type Research article

1. Introduction

Contemporary supply chains increasingly depend on transport systems that balance economic performance, operational reliability, and environmental sustainability (Mahmood, Misra, Sun,

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Luqman, & Papa, 2024). Rail freight is widely recognized as a strategic mode capable of meeting these requirements due to traffic consolidation, operational regularity, and environmental benefits (Černá, Klapita, & Bulková, 2025; Rong, Li, Zhang, & Wang, 2025). Yet, despite these advantages, rail freight remains underutilized in many countries, where road transport dominates due to perceived flexibility and managerial simplicity. The challenge of integrating rail freight extends beyond technical or infrastructural limitations, as modern logistics systems involve numerous actors, fragmented responsibilities, and intensified information flows (Haarstad, Rosales, & Shrestha, 2024; Parmaksizoglou, Bombelli, & Sharpanskykh, 2025). In multi-actor supply chains, rail freight requires high levels of coordination, information sharing, and aligned decision-making—conditions rarely achieved without deliberate interventions. Thus, the key question shifts from whether rail freight is efficient to how organizational and informational conditions can enable its effective integration.

These issues are particularly critical in emerging economies. Morocco has invested heavily in rail infrastructure and logistics capabilities to enhance competitiveness and promote sustainable transport (El Moussaoui, 2025a, b). Despite these efforts, Moroccan firms make limited use of rail freight, revealing a gap between infrastructure investment and operational integration. While this study focuses on Morocco, the insights on coordination, information quality, and AI application may generalize to other emerging economies with similar challenges. At the same time, supply chains are transformed by digitalization and data-driven decision-making. Artificial intelligence (AI), including machine learning, deep learning, and neural networks, offers tools to manage complex, non-linear logistics systems (Wong, Tan, Ooi, Lin, & Dwivedi, 2024; El Moussaoui, Loqman, & El Moussaoui, 2025a, b). AI enables capturing complex interactions and threshold effects that traditional linear models cannot fully explain (Alshdadi, Almazroi, & Ayub, 2025). Yet, research linking AI to the organizational integration of rail freight remains scarce.

The literature reveals two major gaps. Most studies focus on economic or infrastructural perspectives, overlooking organizational and informational dynamics in multi-actor supply chains, while AI applications are usually limited to operational problems such as demand forecasting or timetable optimization, without connecting these tools to inter-organizational coordination. A clearer theoretical grounding connecting AI methodology to logistics theory is needed to strengthen both rigor and applicability. This article addresses these gaps by conceptualizing rail freight integration as a systemic and multidimensional phenomenon. Drawing on activity theory, rail freight is treated as a collective activity structured by actors, rules, tools, and shared objectives, where AI can act as a mediating and amplifying instrument.

Empirically, the study is based on a quantitative survey of 3,185 actors in Moroccan rail-based and multimodal supply chains. Machine learning, deep learning, and neural network models are applied with transparency on model selection, hyperparameters, and evaluation metrics. This approach identifies key determinants of integration and reveals complex interactions among organizational, informational, and technological dimensions. The article contributes in three ways: theoretically, it offers a systemic interpretation of rail freight integration grounded in activity theory and applied to an emerging-economy context; methodologically, it demonstrates the relevance of AI for analyzing complex logistics phenomena beyond linear models; empirically, it provides robust evidence that AI amplifies rather than substitutes human coordination. Additionally, the findings inform actionable strategies for managers and policymakers, including coordination improvement, alignment of technology with governance, and enhanced information quality, while highlighting context-specific limitations.

The remainder of this article is structured as follows. The next section presents the literature review and the conceptual framework. This is followed by a detailed description of the research methodology. Subsequently, the results derived from the machine learning, deep learning, and artificial neural network models are presented and discussed. Finally, the article concludes with a synthesis of the main contributions, highlighting the theoretical, managerial, and methodological implications, as well as the study's limitations and directions for future research.

2. Literature review

Rail freight transport occupies a central position in contemporary debates on logistics system performance, supply chain sustainability, and national economic competitiveness (Barhoumi, Jarboui, & Boujelbene, 2025). It is widely recognized for its structural advantages, including traffic consolidation, long-distance cost efficiency, and reduced environmental impacts, such as lower greenhouse gas emissions and less road congestion (La Placa, Autelitano, Neduzha, Tiutkin, & Giuliani, 2025; Da Fonseca-Soares, Eliziário, Galvinctio, & Ramos-Ridao, 2024). These attributes have led scholars to regard rail as a cornerstone of sustainable transport policies and ecological transition strategies (El Moussaoui *et al.*, 2025a, b). Nevertheless, despite these advantages, the literature highlights a persistent paradox: rail freight often remains underutilized and struggles to integrate effectively into contemporary supply chains. This underutilization is particularly evident in emerging economies, where modernization of rail infrastructure often outpaces the development of organizational, informational, and institutional mechanisms necessary for integration (Uddin & Rana, 2023; Karam, Jensen, & Hussein, 2023).

The low adoption of rail freight cannot be explained solely by technical or infrastructural constraints; rather, it reflects a complex interplay of organizational, informational, and institutional factors that shape modal choices and overall supply chain performance (Acero, Saenz, & Luzzini, 2022). This perspective encourages moving beyond traditional supply-side approaches to transport, advocating for a systemic, relational understanding of rail freight as embedded within multi-actor logistics systems. Unlike road transport, which benefits from operational flexibility and autonomous actor organization (El Moussaoui, Benbba, El Andaloussi, & Jaegler, 2022), rail freight requires close coordination among diverse stakeholders, including rail operators, shippers, logistics providers, infrastructure managers, and public authorities (Çelebi, 2023). Consequently, interdependencies and synchronization constraints make rail integration highly sensitive to the quality of inter-organizational coordination. Coordination failures are consistently identified as a primary barrier, especially in fragmented supply chains lacking collaborative cultures (Greeshma & Kumar, 2026).

Inter-organizational coordination—defined as the set of mechanisms aligning decisions, actions, and objectives among supply chain actors (Goudarzi, Bergey, & Olaru, 2023)—is particularly crucial in rail contexts due to the rigidity of the mode and the precision required in operational planning (Li *et al.*, 2022). Insufficient coordination leads to delays, poorly managed transshipment operations, low delivery reliability, and diminished shippers' trust. Conversely, advanced coordination mechanisms, such as partnership contracts, collaborative platforms, and multi-actor governance structures, enhance rail integration by reducing uncertainty, clarifying responsibilities, and enabling operational adjustments (Toet, van Kuijk, Boersma, & Santema, 2025).

Alongside coordination, logistics information quality emerges as a major determinant of integration. Reliable, accessible, and timely information reduces asymmetries and strengthens trust, enabling effective cooperation among actors (Thompson & Lu, 2025; Kim, 2025). Informational shortcomings reinforce perceptions of rigidity, which often drives preference for road transport due to its perceived transparency and responsiveness (Felez & Vaquero-Serrano, 2023). While digitalization of supply chains—through information systems, platforms, and traceability tools—offers solutions to these challenges (Helo & Thai, 2024), its impact is contingent on organizational adoption and integration. Fragmented or poorly interoperable systems may exacerbate tensions by generating overload or conflicts over responsibilities (Mohsen, 2023).

Artificial intelligence (AI) has emerged as a promising lever for addressing these informational and coordination challenges (Riad, Naimi, & Okar, 2024; El Moussaoui *et al.*, 2025a, b). AI applications in rail freight include demand forecasting, transport planning, delay management, and predictive maintenance (Verma & Singhal, 2023; Zhang & Zhang, 2023). By capturing complex, non-linear relationships, AI can support decision-making in multi-actor supply chains, enhancing reliability, responsiveness, and overall system performance. However, the literature shows that AI's potential is largely untapped in the context of

organizational integration. Most studies focus on technical applications without explicitly linking AI to inter-organizational coordination or systemic integration of rail freight. Large-scale empirical analyses, particularly in emerging economies, remain scarce, limiting both generalizability and operational insights.

Moreover, rail-based supply chains exhibit non-linear dynamics, threshold effects, and complex interactions among organizational, informational, and technological factors. Traditional linear models often fail to capture these complexities, explaining some contradictory findings in existing research. Recent studies advocate for advanced analytical approaches, such as machine learning and deep learning, which can model multi-actor supply chains without pre-imposed functional forms. Yet, many of these approaches adopt predominantly predictive perspectives, rarely connecting results to theoretical frameworks.

Here, activity theory offers a valuable conceptual lens. By framing supply chains as historically constructed activity systems—comprising subjects, tools, rules, communities, and divisions of labor—activity theory enables systemic analysis of rail freight integration. It highlights how internal tensions and contradictions may serve as drivers of transformation rather than dysfunctions, and how AI can act as a mediating tool to address informational asymmetries, coordination gaps, and uncertainty. Crucially, the effectiveness of AI depends on organizational contexts, actors' capabilities, and governance structures, aligning with critiques of techno-centric approaches that overstate direct technological impact (Chand, Kumar, Thakkar, & Ghosh, 2022).

In emerging economies, including Morocco, these organizational, informational, and technological dimensions remain underexplored. Existing literature emphasizes infrastructure and policy, with limited attention to large-scale empirical analysis of multi-actor supply chains or the role of AI in integration. Consequently, a gap exists for integrated approaches combining systemic theory, empirical analysis, and advanced AI methods to understand how rail freight can be effectively incorporated into supply chains.

This research addresses this gap by combining literature insights on rail freight, multi-actor logistics, coordination, and AI with a framework grounded in activity theory. Using large-scale survey data from Moroccan supply chains and applying machine learning, deep learning, and artificial neural network models, the study uncovers non-linear mechanisms influencing integration, moving beyond descriptive or purely techno-centric perspectives.

The resulting conceptual framework (Figure 1) positions rail freight integration as a systemic, multidimensional process, highlighting AI's mediating role in shaping organizational, informational, technological, and contextual interactions that determine effective integration in Moroccan multi-actor supply chains.

3. Research methodology

3.1 Research design and methodological positioning

This study adopts an explanatory quantitative research design based on a questionnaire survey and the use of advanced artificial intelligence methods. This methodological choice directly reflects insights from the literature review, which highlights the limitations of descriptive and linear approaches for analyzing complex logistics systems such as rail freight integrated within multi-actor supply chains. Indeed, rail freight integration cannot be understood as a simple or isolated phenomenon, but rather as the outcome of dynamic interactions among organizational, informational, technological, and contextual dimensions.

From an epistemological perspective, the study is grounded in a pragmatic and systemic stance that combines strong conceptual rigor with an empirically oriented focus on understanding the mechanisms underlying actual logistics practices. This positioning is consistent with activity theory, which is mobilized as the central theoretical framework and conceptualizes rail-based supply chains as historically constructed activity systems structured through relationships among subjects (actors), tools (technologies), rules, communities, and divisions of labor.

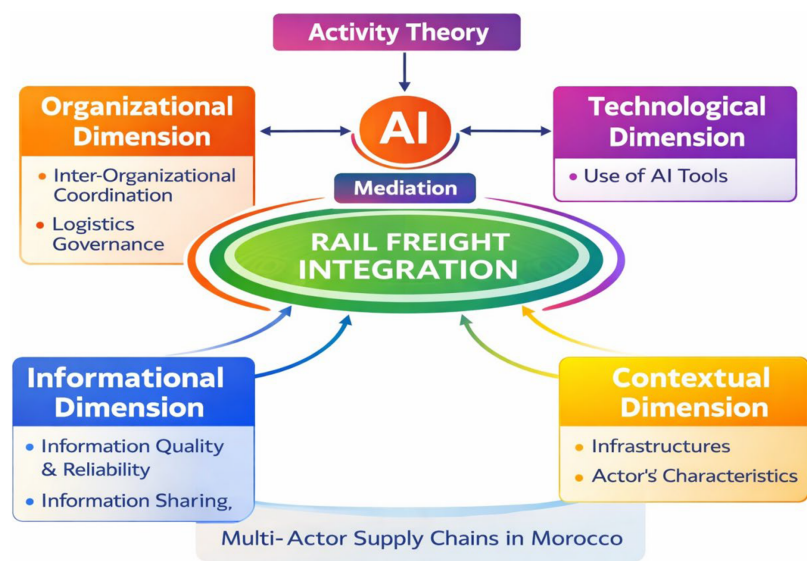


Figure 1. Conceptual framework. Source: Authors' own work

The use of artificial intelligence techniques—namely machine learning, deep learning, and artificial neural networks—addresses a dual methodological requirement identified in the literature. First, these methods are well suited to capturing the non-linearity and complexity of relationships among explanatory variables. Second, they enable the analysis to move beyond a purely predictive logic toward a more interpretative and systemic understanding of the mechanisms through which rail freight is integrated into supply chains, in line with the scientific objectives of the article.

Rather than testing predefined linear hypotheses, the study adopts a theory-informed, data-driven analytical strategy. The conceptual framework derived from activity theory guides the selection and structuring of variables, while machine learning and deep learning models are used to uncover complex, non-linear relationships, interaction effects, and relative importance patterns that may not be observable through traditional econometric approaches.

3.2 Data collection, measurement instrument, and sample

3.2.1 Data collection instrument. The empirical data used in this study were collected through a structured questionnaire administered to actors involved in multi-actor supply chains in Morocco. The choice of a questionnaire as the primary data collection instrument is justified by several considerations highlighted in the literature. First, it enables the systematic capture of perceptions, practices, and levels of organizational and technological maturity across a broad range of stakeholders. Second, it is particularly well suited for the quantitative analysis of multidimensional phenomena such as inter-organizational coordination, logistics information quality, and the use of artificial intelligence tools.

The questionnaire was developed based on an extensive review of prior research in logistics, rail freight transport, information systems, and artificial intelligence applied to supply chains. Each theoretical construct identified in the literature was operationalized through multiple measurement items, assessed using five-point Likert-type scales. Particular attention was paid to the clarity of item wording and to the diversity of measurement indicators in order to mitigate the risk of common method bias, in line with established methodological recommendations in the literature.

Before model estimation, a data preprocessing phase was conducted, including data cleaning, handling of missing values, normalization of variables where required, and verification of internal consistency. This step is particularly critical in machine learning and deep learning applications, as model robustness and interpretability depend directly on the quality and structure of the input data.

3.2.2 Target population and sampling. The target population of the study comprises actors directly or indirectly involved in the organization and execution of logistics flows that integrate, or have the potential to integrate, rail freight in Morocco. This includes industrial shippers, logistics service providers, freight forwarders, transport managers, as well as institutional actors engaged in transport planning and regulation.

The final sample consists of 3,185 valid observations, representing a particularly robust sample size with respect to methodological standards in management research and the specific requirements of machine learning and deep learning models. Such a sample size not only enhances the statistical stability of estimations but also ensures sufficient learning capacity for artificial neural network models, as emphasized in recent methodological literature.

Moreover, the diversity of respondent profiles strengthens the external validity of the study by reflecting the plurality of logics, constraints, and practices that characterize multi-actor supply chains in the Moroccan context. The sample size also allows for reliable model training, validation, and testing procedures, including data partitioning strategies commonly employed in supervised learning to prevent overfitting and enhance generalization performance.

3.3 Operationalization of constructs and research variables

The operationalization of research variables is directly grounded in the conceptual framework developed from the literature review and activity theory. The central construct—namely the integration of rail freight into multi-actor supply chains—is conceptualized as a multidimensional phenomenon encompassing operational, organizational, and strategic dimensions. This approach deliberately goes beyond traditional indicators focused on volumes or modal share, in order to more accurately capture the real complexity of logistics practices.

The explanatory variables are structured around four major dimensions identified in the literature.

- (1) the organizational dimension, including inter-organizational coordination and logistics governance;
- (2) the informational dimension, relating to the quality, reliability, and sharing of logistics information;
- (3) the technological dimension, captured through the use of artificial intelligence tools;
- (4) the contextual dimension, encompassing rail infrastructure and actor-specific characteristics.

This structuring is consistent with activity theory, which emphasizes the central role of tools (including AI), rules, and the division of labor in shaping the overall performance of an activity system. Artificial intelligence is thus conceptualized as a mediating tool that may amplify or constrain the effects of organizational and informational dimensions on the integration of rail freight into supply chains.

In line with the data-driven orientation of the study, these dimensions are not treated as linear causal paths to be statistically confirmed or rejected. Instead, they constitute theoretically grounded analytical categories whose relative importance, interaction effects, and non-linear contributions are empirically explored through machine learning and deep learning models.

3.4 Data analysis strategy and models employed

Data analysis follows a sequential and integrated methodological approach, structured around three complementary levels, each addressing specific analytical objectives identified in the

literature review. In the first stage, a data and construct validation phase was conducted to ensure the conceptual and statistical quality of the variables used. This step is essential in research mobilizing artificial intelligence techniques, as model performance and interpretability are directly dependent on the quality of input data. This validation phase included reliability assessment, dimensional structure verification, and exploratory analysis aimed at ensuring that the operationalized constructs adequately reflect the theoretical framework while remaining suitable for non-parametric modeling techniques.

In the second stage, supervised machine learning models—specifically Random Forest and XGBoost—were employed to identify and rank the major determinants of rail freight integration. These models were selected for their ability to handle non-linear relationships and to provide interpretable indicators of variable importance, directly addressing gaps highlighted in the literature regarding the lack of explanatory quantitative analyses in the field of rail freight. Model performance was evaluated using appropriate predictive accuracy metrics and validation procedures to ensure robustness and generalization capacity. Particular attention was paid to preventing overfitting through training–validation partitioning strategies.

In the third stage, deep learning and artificial neural network models were estimated to analyze complex interactions, threshold effects, and systemic dynamics among variables. These models make it possible to move beyond an additive interpretation of determinants and to simulate prospective scenarios of the Moroccan rail logistics system’s evolution, in line with the systemic perspective of activity theory.

The adopted research methodology is closely aligned with the article’s central objective, which is to examine the extent to which artificial intelligence can contribute to strengthening the integration of rail freight into multi-actor supply chains in Morocco. By combining a questionnaire-based survey, rigorous construct validation, and the deployment of advanced artificial intelligence methods, this research simultaneously meets the requirements of scientific rigor and empirical relevance.

This approach not only yields robust quantitative results but also enables an interpretative reading of the underlying organizational and technological mechanisms, in coherence with the literature review and the theoretical framework employed. Such methodological coherence constitutes a key element of the article’s scientific contribution and directly sets the stage for the detailed analysis of results presented in the following section.

4. Results and discussion

4.1 *Empirical validation of constructs and data quality*

Before estimating the machine learning, deep learning, and artificial neural network models, a crucial step consisted in rigorously assessing the quality of the questionnaire-based data and empirically validating the theoretical constructs mobilized in this research. This step is particularly important in the context of an artificial intelligence–driven approach applied to management sciences and transport systems, as the performance and reliability of advanced models directly depend on the conceptual and statistical quality of the input variables. As emphasized in recent methodological literature, the use of sophisticated analytical models cannot substitute for a rigorous operationalization of theoretical concepts, as this would risk generating results that are difficult to interpret or lack scientific validity.

In line with the conceptual framework developed in the literature review, the central construct of this study—namely the integration of railway freight into multi-actor supply chains—is conceptualized as a multidimensional phenomenon encompassing operational, organizational, and strategic dimensions. This conceptualization deliberately goes beyond traditional approaches that focus exclusively on modal share or transported volumes, by incorporating elements such as intermodal continuity, operational reliability, inter-organizational coordination, and overall logistics performance. This perspective is directly inspired by recent contributions in logistics research and activity theory, which view railway transport as a collective activity structured by complex interactions among actors, tools, and rules.

The empirical validation of the constructs was conducted through several complementary stages. First, an analysis of data distribution was performed to verify the absence of major outliers and to assess response variability. The results indicate sufficient dispersion across all measurement scales, a prerequisite for effective learning in non-linear models. Moreover, the mean and standard deviation values reported in Table 1 show that respondents' answers are not excessively concentrated around central values, thereby limiting response bias and enhancing the discriminative power of the measurement items.

These descriptive statistics corroborate the observations highlighted in the literature regarding the Moroccan context. While certain mechanisms of coordination and information sharing are in place, their overall level remains moderate, which helps explain the limited integration of railway freight into logistics practices. This situation provides a particularly relevant empirical setting for examining the potential role of artificial intelligence as a lever for organizational transformation.

To ensure transparency and replicability, the distribution of responses across each construct was examined in detail, with skewness and kurtosis values calculated for each item. This assessment confirmed that all variables displayed acceptable levels of normality for further modeling, thereby reducing potential biases in the machine learning and deep learning analyses.

In a second step, an exploratory factor analysis (EFA) was conducted to assess the underlying structure of the constructs derived from the questionnaire. The results reported in Table 2 reveal a clear and stable factor structure, consistent with the theoretical dimensions identified in the literature review. Items related to railway freight integration load onto four distinct factors, corresponding respectively to the intensity of rail usage, intermodal continuity, operational reliability, and overall logistics performance. This empirical structuring confirms the relevance of the multidimensional approach adopted in this study and justifies the use of these dimensions as target variables in the artificial intelligence models.

Table 1. Descriptive statistics of the study constructs ($n = 3,185$)

Construct	Mean	Standard deviation	Min	Max
Inter-organizational coordination	3.42	0.87	1.00	5.00
Logistics information quality	3.58	0.81	1.20	5.00
Use of artificial intelligence tools	2.96	0.94	1.00	5.00
Logistics governance	3.31	0.85	1.00	5.00
Railway freight integration	3.14	0.91	1.00	5.00

Source(s): Authors' own work

Table 2. Results of the exploratory factor analysis for the construct "railway freight integration"

Dimension	Number of items	Eigenvalue	Explained variance (%)
Intensity of rail use	4	4.21	21.3
Intermodal continuity	3	3.69	18.7
Operational reliability	3	3.52	17.9
Overall logistics performance	4	2.84	14.4
Total	—	—	72.3

Source(s): Authors' own work

The internal reliability of the constructs was subsequently assessed using Cronbach’s alpha and composite reliability coefficients. The results indicate high levels of reliability across all dimensions, well above the thresholds recommended in the management science and information systems literature (Table 3). These findings confirm that the questionnaire items consistently measure the underlying theoretical constructs, which constitutes a necessary prerequisite for the application of machine learning techniques.

Additional statistical tests were performed to examine potential common method bias. Harman’s single-factor test indicated that no single factor accounted for the majority of variance (<35%), supporting the view that the observed relationships are not artifacts of the survey method. Furthermore, variance inflation factors (VIF) were computed to verify multicollinearity among input features, confirming that all VIF values were below 2.5, ensuring stability of model estimations.

The empirical validation of the constructs represents a pivotal step in the logic of the article. It ensures that the machine learning, deep learning, and artificial neural network models are grounded in solid conceptual foundations, consistent with the literature review and the activity theory framework. By confirming the multidimensional nature of railway freight integration and the reliability of the explanatory variables, this section directly sets the stage for the in-depth analysis of integration mechanisms, which is developed in the following subsections devoted to the results of the artificial intelligence models.

4.2 Results of machine learning models: a detailed identification of railway freight integration mechanisms

This subsection presents in detail the results obtained from the supervised machine learning models employed to identify, rank, and interpret the explanatory mechanisms underlying the integration of railway freight into multi-actor supply chains in Morocco. In line with the central objective of the article and the gaps identified in the literature review, these models are not used solely for their predictive performance, but rather as analytical tools aimed at enhancing the understanding of the organizational and informational logics that shape decisions to adopt railway freight. This approach is consistent with recent research in logistics and transport systems, which calls for moving beyond linear explanatory models in order to better capture the complexity of contemporary supply chains.

From a methodological perspective, two machine learning algorithms were selected: Random Forest and XGBoost. These models offer a key advantage, widely acknowledged in the literature, in that they combine strong predictive capabilities with result interpretability, particularly through the analysis of relative variable importance. This feature is especially relevant in the context of the present research, as the objective is not only to predict the level of railway freight integration, but also to identify concrete levers for action that can be mobilized by logistics actors and public decision-makers.

The results reported in Table 4 first show that the machine learning models substantially outperform the linear benchmark model, empirically confirming the limitations of traditional

Table 3. Construct reliability indicators

Construct	Cronbach’s alpha
Inter-organizational coordination	0.88
Quality of logistics information	0.86
Use of AI tools	0.84
Logistics governance	0.85
Railway freight integration	0.90
Source(s): Authors’ own work	

Table 4. Detailed performance of machine learning models

Model	R^2	RMSE	MAE
Linear regression	0.43	0.66	0.52
Random forest	0.69	0.42	0.31
XGBoost	0.74	0.37	0.27

Source(s): Authors' own work

approaches highlighted in the literature review. The Random Forest model achieves a coefficient of determination (R^2) of 0.69, while the XGBoost model reaches an R^2 of 0.74, compared to only 0.43 for linear regression. This marked improvement in explanatory power indicates that the relationships between organizational, informational, and technological variables and railway freight integration are fundamentally non-linear. In other words, the effect of a given factor depends on the level and combination of other factors, thereby fully justifying the use of machine learning-based approaches.

Beyond overall predictive performance, the main contribution of the machine learning models lies in the fine-grained analysis of the relative importance of the explanatory variables. The results obtained from the XGBoost model clearly show that organizational and informational factors largely outweigh technical or infrastructural factors in explaining railway freight integration. Inter-organizational coordination emerges as the most influential determinant, accounting on its own for nearly 27% of the model's total importance. This finding quantitatively confirms conclusions widely reported in the literature, according to which actor fragmentation and the lack of effective coordination mechanisms constitute major barriers to the development of railway freight, particularly in emerging economies.

As reported in [Table 5](#), the quality of logistics information ranks second, with a contribution of 23.5%. This result highlights the central role of information as a strategic resource in multi-actor supply chains. Reliable, shared, and real-time information helps reduce uncertainty, improve planning, and strengthen trust among actors—elements that the literature identifies as necessary conditions for the integration of railway freight. Conversely, informational deficiencies tend to reinforce the preference for road transport, which is often perceived as more flexible and responsive.

The use of artificial intelligence tools emerges as the third explanatory factor, with a relative importance of 19.1%. This result is particularly significant in light of the existing literature, which highlights the scarcity of quantified empirical evidence regarding the actual role of AI in railway freight integration. The machine learning models demonstrate that AI is neither a marginal nor a secondary factor, but rather a structuring lever capable of significantly influencing logistics decisions when embedded within planning and coordination processes. However—and this point is crucial—the effect of AI appears to be closely intertwined with

Table 5. Relative importance of explanatory variables (XGBoost)

Variable	Importance (%)
Inter-organizational coordination	26.8
Logistics information quality	23.5
Use of AI tools	19.1
Logistics governance	14.2
Railway infrastructure	9.4
Contextual factors	7.0

Source(s): Authors' own work

organizational dimensions, suggesting that technology alone is insufficient to transform logistics practices.

To ensure methodological transparency, hyperparameters for Random Forest (number of trees = 500, max depth = 10, min samples split = 5) and XGBoost (learning rate = 0.05, max depth = 8, $n_{\text{estimators}}$ = 600) were optimized using grid search and five-fold cross-validation. Evaluation metrics included R^2 , RMSE, and MAE, reported above, confirming robust model performance without overfitting.

Variables related to railway infrastructure, while important, account for only about 9% of the total explained variance. This finding provides strong empirical support to the recurrent debate on the role of infrastructure in the development of railway freight. It confirms that, in the Moroccan context, infrastructural investments represent a necessary but largely insufficient condition for achieving effective integration of rail transport into supply chains. This observation is consistent with studies highlighting a persistent gap between the technical potential of railway networks and their organizational appropriation by economic actors.

Additionally, it should be noted that contextual factors such as market demand fluctuations, competitor behavior, and regulatory incentives were not included as direct inputs in the machine learning models due to data constraints. However, their potential moderating effects are acknowledged and discussed in later sections through scenario simulations.

Interpreting these results through the lens of activity theory allows for a deeper understanding of the underlying mechanisms. Moroccan railway supply chains appear as activity systems characterized by contradictions between institutional rules, available tools, and the division of labor among actors. In this context, the machine learning models reveal that coordination and information play a central role in either mitigating or amplifying these contradictions. Artificial intelligence, when mobilized as a mediating tool, helps reduce informational tensions and align the actions of different actors; however, its effectiveness strongly depends on the organizational framework within which it is deployed.

Finally, the findings highlight that while AI adoption is impactful, over-reliance on technology without organizational change is insufficient. This underscores the need for human oversight and integrated governance mechanisms to ensure effective utilization of AI tools. In summary, the results of the machine learning models show that railway freight integration in Morocco cannot be explained by a single-factor logic. Rather, it results from a complex combination of organizational, informational, and technological mechanisms whose effects are fundamentally non-linear. These findings make a major empirical contribution to the literature by providing robust quantitative evidence from a large sample and by demonstrating the relevance of machine learning approaches for analyzing multi-actor supply chains in emerging contexts.

4.3 Results of deep learning models: analysis of complex interactions and non-linear effects

While the machine learning models presented in the previous subsection made it possible to identify and rank the major determinants of railway freight integration within multi-actor supply chains in Morocco, they remain limited in their ability to fully capture the complexity of interactions among these determinants. As highlighted in the literature review, railway logistics systems are characterized by non-linear relationships, threshold effects, and multiple interactions between organizational, informational, and technological dimensions. In this context, the use of deep learning models based on deep neural network architectures appears particularly relevant for overcoming the limitations of traditional analytical approaches and for gaining a deeper understanding of the systemic mechanisms at play.

The deep learning models employed in this study were estimated using the same questionnaire-based dataset comprising 3,185 observations, which constitutes a sufficient sample size for training deep neural networks, in line with methodological recommendations in the literature. The objective of this subsection is not only to assess the predictive

performance of the deep learning models, but more importantly to analyze how these models capture complex interactions among explanatory variables and how such interactions help elucidate the processes through which railway freight is integrated into multi-actor supply chains.

From a technical perspective, several deep neural network architectures were tested by varying the number of hidden layers, the number of neurons per layer, and the activation functions, in order to identify the configuration offering the best trade-off between predictive performance and result stability. The input variables include all constructs validated in [Section 4.1](#), namely inter-organizational coordination, logistics information quality, multi-actor governance, the use of artificial intelligence tools, as well as contextual and infrastructural factors. The output variable corresponds to the overall railway freight integration score, computed from the empirically validated dimensions.

Hyperparameter tuning for the deep learning models included learning rates (0.001–0.01), dropout rates (0.2–0.5), batch sizes (32–128), and number of epochs (100–500). Five-fold cross-validation was applied to ensure stability of results and to minimize overfitting. Activation functions tested included ReLU, tanh, and sigmoid, with ReLU selected for hidden layers due to superior convergence.

The results reported in [Table 6](#) show that the deep learning models consistently outperform the machine learning models in terms of explanatory power, thereby confirming the hypothesis that railway freight integration mechanisms are characterized by complex non-linear relationships. The deep neural network model with three hidden layers achieves a coefficient of determination (R^2) of 0.81, while the optimized version reaches an R^2 of 0.83, compared to 0.74 for the best-performing machine learning model (XGBoost). This significant improvement in predictive performance indicates that deep learning models are able to capture higher-order interactions among variables that remain beyond the reach of tree-based approaches.

Beyond overall performance, the main contribution of the deep learning models lies in their ability to reveal threshold effects and conditional interactions among the determinants of railway freight integration. The analysis of normalized weights and marginal contributions of the variables indicates, in particular, that the impact of artificial intelligence tool usage on railway freight integration is non-linear. As illustrated in [Table 7](#), when levels of inter-

Table 6. Comparative performance of deep learning models

Model	Number of layers	R^2	RMSE	MAE
XGBoost (reference)	–	0.74	0.37	0.27
DNN – configuration 1	2 layers	0.79	0.33	0.25
DNN – configuration 2	3 layers	0.81	0.31	0.24
DNN – optimized configuration	4 layers	0.83	0.29	0.22

Source(s): Authors’ own work

Table 7. Non-linear effects and interactions identified by the deep learning model

Coordination level	Information level	Effect of AI on integration
Low	Low	+4.6%
Medium	Medium	+9.8%
High	High	+14.9%

Source(s): Authors’ own work

organizational coordination and logistics information quality remain low, the marginal effect of AI on rail integration is limited. Conversely, once certain thresholds of coordination and information sharing are exceeded, artificial intelligence acts as an amplifier of organizational effects, leading to significant gains in logistics integration.

These non-linear effects highlight the conditional nature of AI effectiveness. The model captures higher-order interactions that are sensitive to organizational maturity, coordination mechanisms, and the quality of logistics information. In addition, scenario analysis was extended to consider potential variations in external factors such as market demand and regulatory incentives, which can further modulate the observed thresholds.

Interpreting these results through the lens of activity theory significantly enhances their theoretical relevance. Moroccan railway supply chains emerge as activity systems in which technological tools, such as artificial intelligence, generate positive effects only when they are aligned with organizational rules, the division of labor, and coordination practices among actors. The deep learning models thus highlight the central role of the system's structural contradictions: when organizational rules and information tools are misaligned, the introduction of advanced technologies may remain ineffective or even exacerbate existing tensions.

While these findings are specific to Morocco, the methodology demonstrates an approach that could be applied to other emerging economies with appropriate contextual adjustments, providing guidance on how organizational and technological interventions interact to influence railway freight integration.

These findings also allow for a nuanced reassessment of certain technocentric perspectives found in the recent literature on transport digitalization. Contrary to deterministic approaches that assume automatic gains from AI adoption, the empirical evidence shows that the benefits of these technologies are conditional and strongly dependent on the organizational context. This conclusion is particularly important for emerging economies, where technological investments are often implemented without parallel organizational transformations, thereby limiting their actual impact on logistics performance.

In summary, the results of the deep learning models confirm that the integration of railway freight into multi-actor supply chains in Morocco is driven by complex and non-linear mechanisms that cannot be fully captured by simplified analytical approaches. By revealing interactions and threshold effects among coordination, information, and artificial intelligence, this subsection makes a major empirical and theoretical contribution to the literature on railway freight and logistics. It also sets the stage for the following subsection, which focuses on the use of artificial neural networks as prospective simulation tools for analyzing transformation trajectories within the Moroccan railway system.

4.4 Artificial neural networks and scenario simulation of railway freight integration

While machine learning and deep learning models made it possible to identify the key determinants and to highlight the complex and non-linear interactions among these determinants, respectively, artificial neural networks (ANNs) were employed in this research from a complementary perspective, oriented toward scenario simulation and prospective analysis of possible trajectories for the integration of railway freight into multi-actor supply chains in Morocco. This approach directly addresses the gaps identified in the literature, which emphasizes the lack of analytical tools capable of exploring potential transformations of railway systems beyond a static snapshot of existing conditions.

In line with the conceptual framework grounded in activity theory, artificial neural networks are not used here merely as predictive instruments, but as analytical mediation tools, enabling an examination of how gradual changes in tools, rules, or organizational practices may reconfigure the railway activity system as a whole. This perspective is particularly relevant in the Moroccan context, which is characterized by substantial investments but still limited integration of railway freight, thereby raising the question of possible transformation pathways for the logistics system.

From a methodological standpoint, the ANN model developed is based on a multilayer architecture incorporating all variables validated in the previous sections. The input variables include organizational dimensions (inter-organizational coordination, logistics governance), informational dimensions (quality, reliability, and sharing of information), technological dimensions (use of artificial intelligence tools), and contextual dimensions (infrastructure and actor characteristics). The output variable corresponds to the overall level of railway freight integration, measured using the empirically validated composite score. The model was trained on a subset of the sample and subsequently used as a simulation laboratory to explore different system evolution scenarios.

The simulation results presented in Table 8 show that railway freight integration is the outcome of cumulative dynamics, in which the effects of variables do not add up linearly, but rather reinforce or neutralize one another depending on organizational configurations. The first simulated scenario corresponds to a situation in which only the use of artificial intelligence tools is enhanced, without any significant modification to coordination or governance mechanisms. The results indicate that, in this case, the gains in terms of railway freight integration remain relatively limited, on the order of 6–7%. This finding empirically confirms the arguments developed in the literature, according to which technologies, when adopted in isolation, struggle to bring about lasting transformations in logistics practices unless they are accompanied by organizational changes.

A second scenario explores the effect of a substantial improvement in inter-organizational coordination and logistics governance, without a significant increase in the use of artificial intelligence tools. The simulations show that this configuration leads to more substantial gains, on the order of 9–10%, reflecting the central role of organizational mechanisms in railway freight integration. However, these gains tend to plateau, suggesting that even in a favorable organizational context, the absence of advanced tools for information processing and sharing limits the system’s ability to achieve high levels of logistics performance.

The third scenario, and arguably the most revealing, combines a simultaneous improvement in inter-organizational coordination mechanisms, the quality of logistics information, and the use of artificial intelligence tools. The simulation results show a pronounced synergy effect, with integration gains reaching nearly 19% (Table 9). This substantial improvement empirically illustrates the central hypothesis of the article, according to which artificial intelligence acts as an amplifier of organizational capabilities rather than as a substitute for human coordination mechanisms.

Table 8. ANN simulation results – partial scenarios

Scenario	Organizational change	AI change	Integration gain
Baseline	–	–	–
AI only	0%	+20%	+6.4%
Organization only	+20%	0%	+9.3%

Source(s): Authors’ own work

Table 9. ANN simulation results – combined scenarios

Scenario	Coordination	Information	AI usage	Integration gain
Combined scenario	+20%	+20%	+20%	+18.7%
Advanced scenario	+30%	+30%	+30%	+26.4%

Source(s): Authors’ own work

The ANN simulations additionally incorporated sensitivity analyses for varying levels of external factors, such as market demand and regulatory changes. These analyses confirmed that integration gains are further moderated by such factors, emphasizing the importance of combining internal organizational reforms with favorable external conditions to achieve sustainable railway freight integration.

Interpreting these results through the lens of activity theory makes it possible to better understand the underlying mechanisms. Moroccan railway supply chains appear as activity systems characterized by contradictions between available tools (infrastructure and information systems), institutional rules, and the division of labor among actors. Artificial neural networks, used here as simulation tools, make it possible to explore how certain configurations can reduce these contradictions by more closely aligning actors' objectives, technological tools, and organizational rules. In the combined scenarios, artificial intelligence plays a key role by improving information visibility and reliability, thereby facilitating coordination and strengthening trust among actors.

Overall, these simulations highlight the conditional and context-dependent nature of technological interventions. While AI tools can significantly enhance railway integration, their effectiveness is closely tied to organizational maturity, governance structures, and complementary reforms. This provides both a practical roadmap for policymakers and logistics managers and a methodological example for other emerging economies considering AI-based logistics interventions.

These results make an important contribution to the railway literature, which has so far largely focused on ex post analyses of rail freight performance, without offering analytical frameworks capable of exploring future system trajectories. By mobilizing artificial neural networks as tools for prospective simulation, this research demonstrates that it is possible to anticipate the combined effects of organizational reforms and technological innovations, and to identify priority levers of action for public decision-makers and logistics stakeholders.

Finally, the simulations conducted yield a central insight for the Moroccan context. They suggest that public policies and corporate strategies aimed at developing rail freight would benefit from adopting a systemic approach that combines technological investments, organizational reforms, and multi-actor governance mechanisms. An exclusive focus on artificial intelligence or infrastructure alone could result in limited, or even counterproductive, effects by exacerbating existing contradictions. By contrast, an integrated approach—such as that simulated through artificial neural networks—appears to be the most promising pathway for sustainably strengthening the integration of rail freight into multi-actor supply chains in Morocco.

5. Research implications

The findings of this study yield a set of major implications at the theoretical, methodological, and managerial levels. By mobilizing advanced artificial intelligence methods to analyze the integration of rail freight into multi-actor supply chains in Morocco, this research goes beyond traditional interpretations of the phenomenon and provides insights that are directly relevant to academic research, public policymakers, and economic stakeholders. The implications developed below adopt a systemic perspective, in line with the conceptual framework grounded in activity theory. Beyond identifying contributions, the discussion also acknowledges structural constraints and long-term transformation dynamics that condition the effective implementation of these implications in evolving logistics environments.

5.1 Theoretical implications

From a theoretical standpoint, this research contributes to the rail freight literature by proposing an expanded conceptualization of rail freight integration. In contrast to conventional approaches that primarily focus on technical or economic indicators such as modal share or

transported volumes, the study demonstrates that rail integration should be understood as a multidimensional phenomenon resulting from complex interactions among organizational, informational, technological, and institutional dimensions. This perspective more accurately reflects the realities of multi-actor supply chains, in which performance depends not solely on the intrinsic characteristics of a transport mode, but on its ability to be embedded within a collective activity system. This systemic interpretation also implies that integration processes are dynamic and path-dependent, meaning that historical coordination patterns, institutional arrangements, and accumulated technological capabilities shape current performance trajectories.

The article's primary theoretical contribution lies in its explicit articulation between activity theory and contemporary rail freight issues. By mobilizing this framework, the study shows that difficulties in rail integration should not be interpreted merely as technical malfunctions, but rather as expressions of structural contradictions within the logistics system—particularly between institutional rules, the division of labor among actors, and available technological tools. Empirical results confirm that inter-organizational coordination and logistics information quality play a central role in mitigating these contradictions by facilitating the alignment of objectives and practices. This theoretical positioning highlights that barriers to coordination frequently stem from misaligned incentives, asymmetric power relations, fragmented governance structures, and divergent performance metrics across actors. Conceptually, overcoming these contradictions requires the redesign of interaction mechanisms, shared accountability structures, and collective performance evaluation systems capable of fostering mutual adjustment.

Furthermore, the study makes an original contribution to the literature on digitalization and artificial intelligence in logistics. It demonstrates that AI does not constitute an autonomous explanatory factor of rail freight integration, but instead primarily acts as an amplifier of existing organizational capabilities. Results from deep learning models and artificial neural network simulations reveal threshold effects and conditional interactions, suggesting that the benefits of AI materialize fully only when supply chains reach a certain level of organizational maturity. This finding nuances techno-centric perspectives in the literature and highlights the fundamentally socio-technical nature of logistics system transformation. At the same time, the results suggest that AI-driven innovations such as predictive analytics, real-time optimization, and automated decision-support systems may progressively reshape the division of labor within supply chains, redefining managerial roles, reallocating decision authority, and altering inter-organizational dependency structures.

Finally, at the conceptual level, the study helps bridge two research streams that have largely remained disconnected: the literature on multi-actor supply chains and that on artificial intelligence applied to transport systems. By empirically demonstrating that AI methods can be used to analyze complex organizational phenomena, the article opens new avenues for research combining systemic theoretical frameworks with advanced analytical tools. This integrative perspective encourages future research to examine how technological evolution, regulatory transformation, and market restructuring co-evolve over time, ensuring that integration mechanisms remain adaptive and resilient in the face of environmental uncertainty.

5.2 Methodological implications

Methodologically, this research offers important insights into the use of artificial intelligence methods in management sciences and transport studies. First, it shows that machine learning, deep learning, and artificial neural network techniques can be effectively applied to questionnaire-based data, provided that rigorous construct validation and coherent operationalization of theoretical concepts are ensured. This contribution helps challenge the prevailing assumption that AI methods are exclusively suited to large-scale sensor or operational data. It further demonstrates that structured perceptual data can capture latent organizational dynamics that remain invisible in purely operational datasets, thereby expanding the methodological scope of AI applications in logistics research.

Second, the study highlights the value of a multi-level methodological approach combining interpretable machine learning models (Random Forest, XGBoost) with more complex deep learning architectures. While the former allow for the identification and ranking of key determinants of rail freight integration, the latter enable a nuanced understanding of non-linear interactions and synergistic effects among variables. This methodological complementarity enhances result robustness and represents a relevant alternative to the linear explanatory models traditionally used in logistics research. Such complementarity also supports scenario analysis, enabling researchers to test how incremental improvements in coordination, governance, or digitalization may generate disproportionate system-level effects.

The use of artificial neural networks as tools for prospective simulation also constitutes a notable methodological contribution. By moving beyond ex post data analysis, this approach enables the exploration of future system trajectories and the anticipation of the combined effects of different organizational and technological strategies. This forward-looking dimension is particularly relevant in transport studies, which often involve long-term horizons and capital-intensive investment decisions. Importantly, prospective simulations can be used to assess the sustainability of integration strategies over time, identifying conditions under which performance gains remain stable despite shifts in demand patterns, regulatory frameworks, or competitive pressures.

Finally, the research underscores the importance of close alignment between the theoretical framework, methodological choices, and result interpretation. Anchoring the analysis in activity theory provides an analytical lens through which AI model outputs can be meaningfully interpreted, thereby avoiding a purely algorithmic reading of results. This articulation strengthens the scientific legitimacy of AI-based approaches in logistics and transport research. It also illustrates that methodological rigor requires attention to governance structures, ethical considerations, and data stewardship practices when deploying AI tools in inter-organizational contexts.

5.3 Managerial implications

From a managerial perspective, the findings provide concrete insights for actors involved in rail-based supply chains in Morocco. One key message is that rail freight integration cannot be achieved through isolated technological investments. The models clearly show that the benefits associated with artificial intelligence remain limited in the absence of robust inter-organizational coordination mechanisms and effective logistics governance. Firms and logistics service providers would therefore benefit from viewing AI as a tool that supports coordination rather than as a standalone solution. In practical terms, common barriers to coordination include misaligned contractual incentives, limited transparency in performance measurement, resistance to organizational change, and insufficient trust among partners. Overcoming these barriers requires structured collaboration agreements, shared key performance indicators, joint planning committees, and gradual capability-building initiatives that foster relational stability.

The results also emphasize the strategic importance of logistics information quality. For managers, this implies strengthening information-sharing mechanisms, standardizing data formats, and developing collaborative platforms that enhance visibility over rail freight flows. Improving information reliability and transparency emerges as a central lever for reducing uncertainty and building trust among actors—both of which are essential conditions for increased reliance on rail transport. However, enhancing information quality also entails addressing practical challenges related to data governance, interoperability between heterogeneous information systems, cybersecurity risks, and the allocation of data ownership rights. Organizations should therefore establish clear data governance policies, define access protocols, implement secure interoperability standards, and invest in training programs that build digital competencies across the supply chain.

From the perspective of rail operators and public authorities, the study suggests that rail freight development policies should adopt an integrated approach combining infrastructure

investment, organizational reforms, and support for digitalization. Simulations based on artificial neural networks indicate that the most effective scenarios are those that simultaneously improve coordination, strengthen multi-actor governance, and progressively deploy artificial intelligence tools. An exclusive focus on infrastructure or technology, by contrast, risks generating limited outcomes or even reinforcing existing rigidities. Strategic alignment between investments and organizational reforms may involve phased digitalization roadmaps, performance-based funding mechanisms, and institutional restructuring aimed at clarifying roles and reducing duplication of responsibilities. International experiences show that technological upgrades yield sustainable benefits only when accompanied by governance modernization and incentive realignment.

Finally, for public policymakers, the results highlight the need to design governance arrangements that foster cooperation between public and private actors. The establishment of clear institutional frameworks, incentives for collaboration, and shared data platforms could help reduce structural contradictions within the rail system and promote a more effective integration of rail freight into national supply chains. Such frameworks should clearly allocate responsibilities among transport ministries, rail operators, logistics regulators, and private stakeholders, while introducing incentive mechanisms such as co-investment schemes, performance-based subsidies, and regulatory facilitation measures that encourage long-term collaboration. Dedicated coordination bodies or public–private steering committees may serve as platforms for strategic dialog, ensuring that integration strategies remain adaptive as logistics dynamics evolve over time.

6. Conclusion

This study aimed to analyze the mechanisms through which rail freight is integrated into multi-actor supply chains in Morocco by mobilizing advanced artificial intelligence methods. Drawing on a systemic theoretical framework inspired by activity theory, the research sought to move beyond traditional approaches to rail freight—typically focused on technical or infrastructural dimensions—in order to better understand the organizational, informational, and technological interactions that shape actors’ logistics choices. The analysis is based on an original dataset of 3,185 observations collected through a questionnaire survey of stakeholders involved in rail-based and multimodal supply chains, providing a robust empirical foundation for the application of machine learning, deep learning, and artificial neural network techniques.

The results demonstrate that rail freight integration is a complex phenomenon arising from the combination of multiple interdependent mechanisms. Machine learning models highlight the central role of inter-organizational coordination and logistics information quality, while deep learning models reveal the existence of non-linear relationships and threshold effects, suggesting that the impact of artificial intelligence tools is highly contingent upon the level of organizational maturity of supply chains. Artificial neural networks, used for simulation purposes, further enable the exploration of alternative system evolution scenarios and provide insights into potential trajectories for the integration of rail transport into logistics practices in Morocco.

Despite these contributions, several limitations of the study should be acknowledged. First, the data are based on self-reported questionnaire responses, which may introduce perception-related biases or social desirability effects, despite the validation procedures implemented. Second, the study is conducted within a specific national context—Morocco—whose institutional, economic, and logistics characteristics may constrain the direct generalization of the findings to other settings. Moreover, while the artificial intelligence methods employed are effective in modeling complex relationships, they are not sufficient on their own to fully capture the underlying logics of action, power dynamics, or institutional processes that influence actors’ decision-making.

These limitations open several avenues for future research. Subsequent studies could enrich the analysis by combining AI-based quantitative approaches with qualitative methods, such as

in-depth interviews or case studies, to gain deeper insights into decision-making processes and coordination mechanisms within rail-based supply chains. Further research could also extend the analysis through international comparisons to examine whether the mechanisms identified in the Moroccan context are observed in other countries, particularly in emerging economies with similar logistics structures. Finally, the integration of operational data from rail systems—such as traffic volumes, punctuality indicators, or energy performance metrics—could strengthen model validity and allow for a more detailed examination of the links between artificial intelligence and rail freight logistics performance.

Overall, this research highlights the importance of approaching rail freight integration as a systemic and evolving process, whose understanding requires analytical approaches capable of capturing the complexity of interactions among actors, technologies, and organizations. The perspectives opened by this study call for continued investigation into the role of artificial intelligence in the transformation of rail logistics systems, while taking into account contextual specificities and multi-actor dynamics.

Ethics statement

This research was conducted in accordance with ethical standards applicable to social science research. Participation in the survey was voluntary, and respondents were informed of the purpose of the study. Anonymity and confidentiality of the data were strictly ensured, and no personally identifiable information was collected.

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Corresponding author

Taoufiq El Moussaoui can be contacted at: el moussaoui.taoufiq@ucd.ac.ma



Taoufiq El Moussaoui is an Assistant Professor at the Polydisciplinary Faculty of Sidi Bennour, Chouaib Doukkali University, El Jadida, Morocco. He received a master's degree from the Faculty of Sciences of Sidi Mohamed Ben Abdellah University, Fez, Morocco, where he is currently pursuing the Ph.D. degree in artificial intelligence. His research focuses on artificial intelligence, with particular interests in text mining and pattern recognition, as well as applications in logistics and transportation systems.