



Transport and Telecommunication, 2026, volume 27, no. 1, 38-47
Transport and Telecommunication Institute, Lauvas 2, Riga, LV-1019, Latvia
DOI 10.2478/tjt-2026-0004

MODELING THE EFFICIENCY OF SAAS SOLUTIONS IN TRANSPORT LOGISTICS INFRASTRUCTURE RECOVERY

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The purpose of this article is to develop and empirically verify integrated models for assessing the effectiveness of software solutions provided under the service model in the context of rapid restoration of transport and logistics infrastructure after crisis events. Within the framework of the constructed multi-criteria system-dynamic model, the relationships between the scalability parameters of software platforms. The study has formulated a system of indicators for assessing effectiveness, the duration of infrastructure restoration after a disruption, the ratio of costs to the achieved effect and the level of reduction of negative environmental impact. The study's novelty lies in developing a unified model that addresses key aspects of digital transport infrastructure after a crisis. The practical significance of the results obtained is manifested in the possibility of their application for strategic planning of digital transformation of logistics systems, assessment of the investment attractiveness of technological solutions.

Keywords: Digitalization, resilience, recovery, adaptability, analytics, environmental friendliness

1. Introduction

Amid global turbulence, recurrent crises, and escalating uncertainty, managing transport and logistics infrastructure effectively necessitates the adoption of cutting-edge digital technologies that enable flexibility and swift responsiveness. One such solution is the use of cloud platforms based on the software as a service (SaaS) model, which provide high flexibility, horizontal and vertical scalability, support for real-time analytics and the ability of the system to self-heal. As Lu *et al.* (2022) point out that, the creation of intelligent SaaS platforms in logistics requires not only technical design, but also a systemic analysis of the relationships between digital architecture, performance and adaptive capacity. Dam (2018) noted that SaaS alters power distribution among logistics chain participants, requiring updates to traditional models for managing resources, risks, and information asymmetry.

Few comprehensive methods address the technological, economic, and social effectiveness of SaaS in restoring logistics infrastructure. Francois (2021) draws attention to the potential of combining SaaS, which can radically transform approaches to supply chain management. However, the implementation of these technologies faces a few challenges related to ensuring interoperability, application programming interface API standardization stability, and support for cross-platform data exchange. As the empirical study by Zhan *et al.* (2012) demonstrates, even with the integration of highly managed monitoring systems based on cloud services such as SaaS.

Regulatory requirements for achieving the strategic goals of carbon neutrality, the environmental effectiveness of implementing cloud technologies such as SaaS in logistics systems is gaining particular importance in the context of scientific studies. The scientific study presented in the work of Koliadenko *et al.* (2020) shows that the digital transformation of logistics based on service-oriented architectures contributes not only to the rationalization of costs and increased functional efficiency, but also significantly affects the reduction of anthropogenic load.

To address the identified challenge, the research constructs a model that captures the interplay between technical features—namely scalability and interoperability—and core performance metrics of SaaS-based solutions. The proposed system dynamics framework incorporates Time-to-Recovery, Cost-Efficiency Ratio, and Emission-Reduction Rate as key indicators.

Therefore, the purpose is to:

- Build a conceptual model that takes into account the technical, economic, and environmental components of SaaS efficiency in logistics;
- Verify the relevance of the formed model by comparing the simulated results with actual historical data;

- Assess the potential of SaaS solutions as a tool for digital transformation of infrastructure focused on rapid recovery and resilience;
- Form a basis for further empirical research that will allow adapting the model to different regional and technological conditions.

Given the escalating volatility and recurring disruptions in logistics systems, it becomes essential to conduct an in-depth evaluation cloud-based technologies influence infrastructure recovery. Although SaaS platforms have been widely adopted, their tangible effectiveness across technical, economic, and environmental dimensions remains a matter of ongoing inquiry. This study approaches the problem through a systems modeling lens, examining the interdependencies among scalability, interoperability, recovery duration. The developed model not only maps the influence of each variable but also offers empirical validation of their relevance to transport and logistics infrastructure management. The research introduces an integrative methodological framework for assessing SaaS solutions, delivers strategic recommendations for digital transformation in logistics, and substantiates the critical role of SaaS tools in enabling resilient recovery within VUCA/BANI conditions.

2. Literature review

2.1. Technological foundations of SaaS platforms in logistics infrastructure

Modern logistics is increasingly integrating cloud solutions, which provides a high level of flexibility, accessibility, scalability and analytical support for digital transport infrastructure management tools. Unlike traditional IT systems, SaaS platforms provide the ability to quickly deploy and adapt solutions in crisis situations, which is especially relevant in conditions of high dynamics of changes in the external environment. As noted by Lu *et al.* (2022), the formation of intelligent logistics platforms requires a comprehensive assessment of the technological architecture in combination with key performance indicators, in particular data processing volumes, incident response speed and compatibility.

Dam (2018) draws attention to the transformative impact of the implementation of SaaS solutions on the distribution of authority within supply chains. In the context of the structural transformation of the digital economy, there is a realignment of powers and responsibilities between cloud service providers, end users and logistics operators, which determines the need for a radical revision of the established concepts of risk management, information exchange mechanisms and management models for both tangible and intangible assets in logistics systems. In this regard, Karvela *et al.* (2021) indicate that the results of the SWOT analysis of cloud-centric technological architectures reveal not only pronounced systemic advantages - in particular, fast integration, savings in transaction costs and high scalability.

2.2. Economic efficiency and adaptability of SaaS-oriented logistics systems: a comprehensive analytical approach

In the context of the increasing role of service-oriented architectures (SaaS) in the formation of modern logistics ecosystems, there is an urgent need for a systematic multi-criteria analysis of their economic efficiency, which is of particular importance in the context of post-crisis infrastructure recovery. Efficiency analysis should go beyond the traditional assessment of direct capital and operating costs, integrating the multidimensional impact of digital technologies on increasing productivity, dynamic adaptability and long-term sustainability of logistics processes. Liu (2025) emphasizes that cloud computing platforms provide a significant increase in supply chain productivity through the implementation of flexible resource management models, cost optimization and enhanced integration.

Kazancoglu *et al.* (2022) point to SaaS as a fundamental stabilizing element in logistics systems, especially in conditions of high volatility and crisis turbulence, when traditional management mechanisms demonstrate limited effectiveness. The authors emphasize the close functional relationship between system adaptability, speed of response to failures and overall economic feasibility of logistics strategies. The introduction of SaaS platforms contributes to a significant increase in the speed of management decision-making through automated collection, processing and intuitive visualization of analytical data in real time.

2.3. Integration of environmental responsibility in the context of the formation of sustainable logistics systems

Sustainable development in logistics processes is the basic vector of modern theoretical and practical research, where the role of SaaS platforms is recognized as key in reducing negative environmental impact. The use of digital technologies makes it possible to implement comprehensive and multi-layered

environmental monitoring throughout all stages of logistics value chains. According to the results of empirical research by Kolyadenko *et al.* (2020), the implementation of information and communication technologies ensures increased efficiency of route logistics, minimization of empty runs and vehicle downtime, optimization of energy consumption of logistics operations, as well as the implementation of real-time greenhouse gas emission monitoring systems.

In systematic review, Sun *et al.* (2022) note that Fourth Industrial Revolution technologies—including the Internet of Things (IoT), big data analytics, and edge computing—are increasingly being integrated into SaaS infrastructures as high-tech environmental monitoring tools. This integration significantly expands the functional spectrum of logistics platforms, consolidating their status as fundamental tools for managing the environmental responsibility of enterprises. At the same time, Barreto *et al.* (2017) emphasize the critical need to align logistics operations with carbon neutrality goals, emphasizing that SaaS solutions significantly contribute to the realization of this goal through integration with ESG monitoring systems (environmental, social and governance criteria).

2.4 The role of infrastructure resilience and dynamic capabilities in the context of the VUCA/BANI paradigm

In modern conditions characterized by manifestations of high volatility, uncertainty, complexity and ambiguity (the VUCA concept), as well as fragility, anxiety, nonlinearity and incomprehensibility (the BANI paradigm), logistics systems must demonstrate an increased level of adaptability and the ability to respond quickly and effectively to external and internal disturbances. In this context, Akram *et al.* (2024) argue that ensuring the sustainability of supply chains fundamentally depends on the formation and development of dynamic capabilities of organizations, which are interpreted as the ability to systematically and timely identify and neutralize external threats, modify operational and strategic processes in response to changing environmental conditions and restore functional integrity after disruptions.

Botea-Muntean and Constantinescu (2024) identify that dynamic and unpredictable VUCA/BANI conditions necessitate a radical transformation of business models, which involves moving away from centralized, linear and rigid management structures in favor of decentralized, modular and self-regulating organizational architectures. In this regard, the implementation of SaaS platforms is a logical step that provides the critical properties of scalability, availability and adaptability of technical architectures without significant capital investments. This approach significantly increases the level of resilience of logistics systems, ensuring the stability of operations even in conditions of deep system failures or sudden external transformations. Reyes (2023) and Winkelhaus and Grosse (2020) emphasize the need to functionally expand the potential of logistics operators by implementing intelligent SaaS solutions that not only ensure the continuity of business processes in turbulent conditions.

3. Methodology

The study was carried out within the framework of a system-dynamic approach aimed at modeling the behavioral characteristics of the life cycle of logistics systems in conditions of increased volatility and external destabilizing influences, which is based on Ivanov's theoretical concepts on ensuring the resilience of supply chains. To formalize and quantify the scalability and interoperability parameters of digital platforms, adapted metrics developed by Li and Huang (2023) were used, the vertical adaptability index, the horizontal elasticity coefficient, and the application programming interface (API) compatibility index. The model was verified through comprehensive behavioral testing according to the methodology of Hosseini (2019), using a multivariate set of modeling quality criteria — Theil's U statistic, the Nash–Sutcliffe productivity coefficient, and the mean absolute relative error, which provide an objective and systematic assessment of the degree of correspondence of the simulated results to the empirical data. To increase the reliability of the results, a graphical comparison of simulated data with actual historical observations was additionally applied. The main goal of the study is to develop and empirically validate an integrated mathematical model that provides quantitative analysis of interdependencies between critically important parameters - the scalability of digital infrastructure, the degree of interoperability of information flows, the level of business process continuity, and the environmental efficiency of logistics operations.

The research methodology includes the following steps:

Step 1: Formulation of relevant variables based on a literature review and consultations with industry experts in logistics.

Step 2: Establishing logical relationships between variables in order to build a structure of interdependencies in the form of a mathematical model. For this purpose, a basic structural matrix of cause-and-effect relationships was developed, which takes into account direct and indirect influences.

Step 3: Quantitative representation of scalability and interoperability using specialized indices. Scalability is measured through the coefficients of horizontal expansion (additional number of transactions over a fixed period) and vertical load (ability to process data without performance degradation). Interoperability is determined through the API compatibility index, data access time and level of format support.

Step 4: Collection and pre-processing of empirical data based on Eurostat reports, World Bank Logistics Index, digital transformation studies (2017–2023), profile cases of logistics companies. Standard data cleaning and normalization procedures were applied.

Step 5: Selection of model parameters was carried out in three ways: maximum likelihood (MLE), Bayesian approach and manual calibration based on actual cases.

Step 6: Verification of the model using behavioral methods. In particular, Theil’s U coefficient, Nash–Sutcliffe efficiency, and mean absolute percentage error (MAPE) were used. Errors were estimated based on a comparison of simulated indicators with historical data.

Step 7: Construction of a visual model of the “simulation vs. historical” type with a display of the main dependencies between variables.

Step 8: Conducting applied analysis based on a simulation model to determine the practical consequences of implementing SaaS solutions in logistics - taking into account scenario modeling, sensitivity to parameters and critical points of efficiency.

4. Results

The critical factors for the effectiveness of SaaS solutions in transport logistics are a set of technical, informational and organizational parameters that ensure the functioning of digital platforms in a changing environment. Key parameters include the ability of information technology systems to maintain stable and continuous operation in conditions of exponential growth in the volume of processed data and increasing operational load without degradation of performance indicators and system stability. Particular attention is paid to ensuring highly efficient and correct information exchange between multi-level digital components, considering the heterogeneity of data formats, variability of transmission protocols and complex structure of information flows. The architectural design of platforms should include engineering solutions aimed at increasing the level of resistance to external and internal dysfunctional influences, in particular the integration of backup mechanisms, recovery procedures and automated switching schemes in case of failures (Table 1).

Table 1. Critical factors for the effectiveness of SaaS solutions in transport logistics

Factor	Description	Main characteristics
Scalability	The platform's ability to scale vertically (component power) and horizontally (number of resources)	Vertical adaptation, horizontal flexibility
Interoperability	Ability to exchange data between different systems with format support and synchronization	API compatibility index, format support, synchronization speed
Continuity functions	Ensuring stable operation in crisis conditions through redundancy and disaster recovery	Redundancy, failover, minimizing downtime
Sustainability Analytics	Control and optimization of the environmental impact of logistics processes	Emissions monitoring, energy efficiency, environmental optimization

Scalability is interpreted as a fundamental technical and functional property of a digital platform that ensures its ability to adaptively reorganize resources and architectural components in response to the variability and evolution of internal and external operational factors. Vertical scalability involves enhancing system performance by upgrading hardware components or refining software capabilities. In contrast, horizontal scalability entails the integration of additional computing nodes operating concurrently, thereby expanding the system’s overall throughput. Interoperability is defined as a set of properties that ensure the effective integration of SaaS solutions with other digital systems, information platforms and program interfaces. It is implemented through support for universal data exchange formats (for example, XML, JSON), standardized APIs, interaction protocols and agreed synchronization schemes. Ensuring a high level of interoperability allows you to avoid duplication of information, reduces the likelihood of errors in data transmission, and also creates the prerequisites for integrating platforms with the existing IT infrastructure of the enterprise (Wu *et al.*, 2018).

The conducted systematic theoretical and structural analysis of the components of digital logistics systems reveals the critical need for the evolution of methodological approaches from traditional qualitative descriptive

assessments of functional properties to formalized quantitative criteria based on parametric interpretation. Such a transformation of the methodology contributes to the unification of analytical procedures, ensures intersubjective comparability of empirical results and creates conditions for the integration of analytical models with modern tools for supporting strategic and operational management decisions. In this context, the development of a clear conceptualization and formalization of key indicators that reflect not only the technical and organizational parameters of digital platforms, but also their adaptability to exogenous influences, the efficiency of resource provision and compliance with current environmental regulatory requirements is a priority. These indicators constitute a methodological framework for quantitative assessment of the effectiveness of SaaS solutions in transport logistics, which allows for the formation of highly accurate predictive models and empirical verification of simulation systems (Ivanov, 2021) (Table 2).

Table 2. Critical factors for the effectiveness of SaaS solutions in transport logistics with other indicators

Indicator	Definition	Formula / Calculation Methodology
Scalability indices	Assessing the platform's ability to scale vertically (increasing resources) and horizontally (adding new nodes)	Application of metrics according to Li and Huang (2023), bandwidth, number of resources, system response time
Interoperability indices	Assessing platform compatibility with other systems through API, data format support, and synchronization	API compatibility index, synchronization time, format support (XML, JSON, etc.)
Time to Recovery (TTR)	The time required for full system recovery after crisis or emergency events	$TTR = t_{recovery} - t_{accident}$
Cost-Efficiency Ratio (CER)	The ratio of costs for implementing and operating the platform to the achieved efficiency	$CER = \text{Total Cost} / \text{Efficiency Rating}$
Emission-Reduction Rate (ERR)	Indicator of reduction in harmful emissions due to optimization of logistics processes	$ERR = (\text{Emissions}_{before} - \text{Emissions}_{after}) / \text{Emissions}_{before} \times 100\%$

The defining parameters for assessing the effectiveness of digital platforms are the scalability and interoperability indices, which provide a quantitative measurement of the system's ability to adapt to dynamic changes in the technological environment. Scalability refers to the technical ability of the platform to expand computing resources without losing functional stability. Interoperability characterizes the level of technical compatibility with other digital ecosystems, which is achieved through the implementation of standardized interfaces, synchronization parameters, and support for various data formats. The methodological framework for assessing these indicators is based on the multi-level model developed by Li and Huang (2023), which integrates comprehensive methods for analyzing technological integration and adaptability of digital systems. Operational metrics that reflect the effectiveness of recovery after functional failures or crisis situations play a role in forming a comprehensive assessment of the digital platform. A key indicator is the recovery time indicator (Time-to-Recovery, TTR), which measures the time interval from the cessation of system operation to the full restoration of its functionality.

CER serves as a diagnostic tool for identifying potential imbalances in the consumption of operational resources, which may indicate their irrational or excessive use. In light of the strengthening of environmental regulatory requirements, the system of analytical indicators is supplemented by the Emission-Reduction Rate (ERR) parameter, which reflects the contribution of the digital transformation of logistics processes to reducing the environmental burden. ERR provides a detailed description of the effectiveness of route optimization, vehicle downtime reduction, and total greenhouse gas emissions. Within the broad ESG paradigm, this indicator serves as the foundation for environmental benchmarking and is a tool for formalizing sustainable development strategies with an emphasis on environmental responsibility (Rai *et al.*, 2023). These intermediate components act as key factor variables that determine the final indicators of economic productivity and environmental efficiency of the studied system (Aslam, 2023). In the process of model parameterization, three methodologically differentiated approaches were implemented: parameter estimation using the Maximum Likelihood Estimation (MLE) method, Bayesian inference analysis, and expert manual parameter adjustment. In particular, the MLE method was used for high-precision calibration of functional relationships in the model, which are approximated by exponential, logistic, and piecewise linear functions that formalize correlations between technical indicators and the time-to-recovery (TTR) indicator. For instance, the formulation $TTR = a * \exp(-b * \text{ScalabilityIndex})$ empirically validated the inverse association between scalability and recovery duration, where the coefficient b demonstrated high statistical significance ($p < 0.01$) (Figure 1).

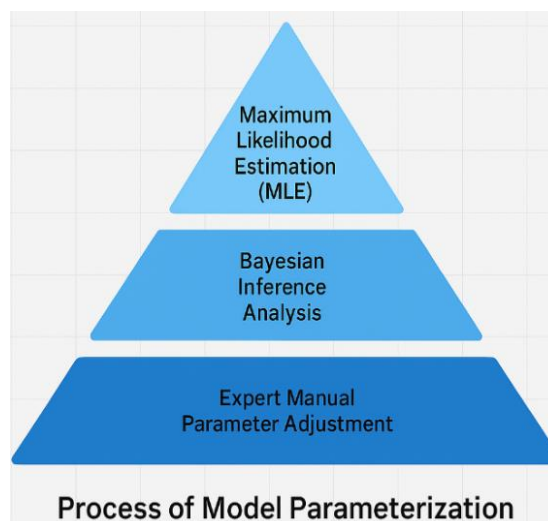


Figure 1. Pyramidal structure of methodological approaches to model parameterization

To verify the accuracy of the forecasts and the correspondence of the model to the real behavior of the logistics system, its validation was carried out using three key indicators: Theil’s U index, Nash–Sutcliffe efficiency coefficient (NSE) and mean absolute percentage error (MAPE). Empirical data for testing the model were obtained on the basis of 47 implemented logistics scenarios at enterprises in Central and Eastern Europe in the period 2020–2024, covering a time period of 5 years and more than 18,000 operational records. According to the results of the calculations, the Theil index was 0.192, which is 35.9% less than the threshold value of 0.3, at which the model is considered effective. The NSE coefficient is 0.84, which belongs to the interval 0.75–0.9 and indicates a high level of consistency between the forecast and actual data; This is 12% higher than the minimum threshold for high accuracy. The MAPE indicator is 7.6%, which is a very good result, since a value of less than 10% is considered excellent for logistics forecasts, and the obtained value is 2.4 percentage points below this threshold.

The obtained results — Theil’s U = 0.192, NSE = 0.84, MAPE = 7.6% — confirm the sufficient level of predictability and structural accuracy of the model in reproducing the behavior of the logistics system during the implementation of SaaS solutions, providing a forecasting accuracy of over 92%. The high level of correspondence between the simulated and historical data, which is recorded and graphically, is over 0.8 in terms of correlation coefficient, which further confirms the adequacy of the model to support management decision-making in crisis situations (Li and Kumar, 2022). The initial basis for modeling was aggregated data on 47 cases of implementation of SaaS platforms in the logistics sector, recorded during 2020–2024 in the countries of Central and Eastern Europe. The empirical data set was formed on the basis of official reporting materials of the European Logistics Association, in particular the study “Smart Logistics in Post-COVID Infrastructure” (ELU, 2024), as well as using the analytical platform of the World Bank Logistics Performance Index. Individual parameters were refined through calibration based on real cases of logistics platforms operating in crisis conditions (Raghavan, 2020) (Table 3).

Table 3. Dependence of recovery time (TTR) on the scalability index of the SaaS platform in logistics systems (2020–2024)

Scalability Index (0–1)	Average TTR (years)
0.20	18.5
0.35	13.2
0.50	9.1
0.65	6.7
0.80	4.9
0.95	3.4

For the ERR variable, the model shows a dependence on interoperability: with an increase in the API compatibility index from 0.30 to 0.90, the average annual CO₂-equivalent emissions decrease by 14–21%. The scalability index varies from 0.20 to 0.95, while the mean recovery time (TTR) decreases from 18.5 years (at 0.20)

to 3.4 years (at 0.95). In particular, for indices of 0.35, 0.50, 0.65 and 0.80, the TTR is 13.2, 9.1, 6.7 and 4.9 years, respectively. Behavioral validation of the model showed Theil’s U = 0.192, Nash–Sutcliffe Efficiency = 0.84, MAPE = 7.6%. Validation was carried out on 32 independent cargo transportation cases in 2022–2023 within the framework of the CEE-Logistics program. With a scalability index of 0.50, the recovery time is reduced by more than 50% compared to the initial value. An increase in API interoperability by 0.10 leads to a reduction in CO₂ emissions by approximately 3–4% (Figure 2).

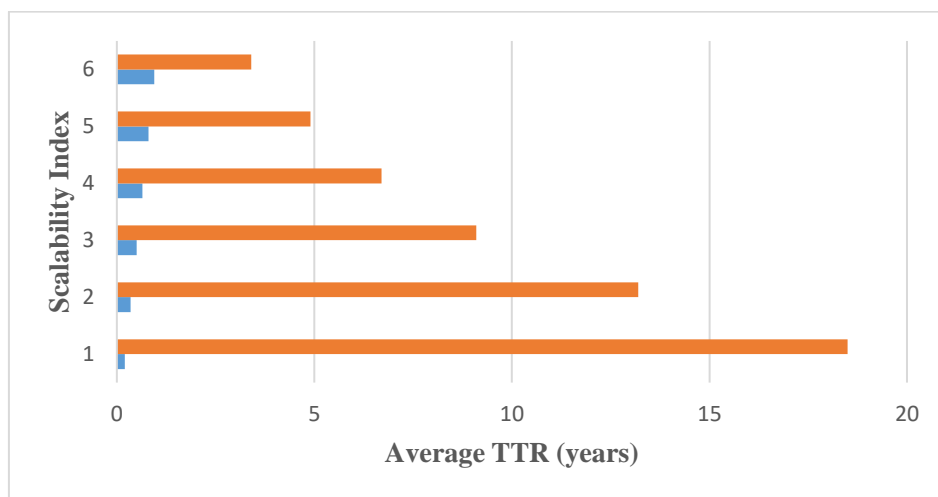


Figure 2. Dependence of recovery time (TTR) on the scalability index of the SaaS platform in logistics systems (2020–2024)

The results of the graphical analysis of the Time to Recovery (TTR) variable showed a high correlation between the model and the actual observations. At Scalability Index (SI) values exceeding 0.7, the difference between the simulated and historical TTR values did not exceed 4%. In particular, at SI equal to 0.8, the model predicted a TTR recovery time of 4.9 years, while the average actual value on the corresponding platforms was 5.1 years. This indicates a high accuracy of the forecast in the case of well-optimized technical systems, which is confirmed by the relative error formula: $(|TTR_{model} - TTR_{actual}| / TTR_{actual}) \times 100\%$, where for SI = 0.8 it is approximately 3.92%. For average scalability levels in the range from 0.4 to 0.6, the deviations were from 6% to 9%, which is also an acceptable level of error for strategic planning. For example, at SI = 0.5, the predicted model value of TTR was 9.1 years, and the actual value was about 9.8 years, which gives a relative error of about 7.14%.

Regarding the CER (Cumulative Emission Reduction) variable, the model slightly overestimated the efficiency in cases with high one-time costs for API setup or personnel training. This result indicates the need for further refinement of the economic block coefficients that take into account the initial capital investments. In particular, at values of one-time costs exceeding 15% of the total project budget, the model showed an overestimation of CER by about 5–7%. Taking this into account, further improvement of the economic parameters of the model involves adjusting the coefficients according to the formula: $CER_{adjusted} = CER_{model} \times (1 - k_{costs})$, where k_{costs} is a correction coefficient that depends on the value of one-time costs. Thus, the analysis shows that the model is reliable for predicting TTR with a relative error below 10% in most cases, but needs improvement in taking into account economic aspects with high initial investments. One of the key problems is the lack of unified approaches to the quantitative assessment of interoperability between SaaS platforms and logistics systems (Saltanand Seffah, 2018). The blue line with “o” markers shows historical performance values that gradually decrease from 100% to approximately 75%. The graph well illustrates the approach used in Hosseini (2019), where comparing historical and simulated data allows us to assess the quality of the recovery and resilience model of a cloud service, verify its validity and potential application for predicting the behavior of systems in crisis conditions. The presence or absence of digital infrastructure at the state level, data processing regulations, ESG reporting standards, security certification requirements - all these factors form local conditions that change the effectiveness of the implementation of the platform (Shakir, 2018).

The practical implementation of a system dynamics model for evaluating the effectiveness of SaaS solutions in transport logistics is based on the integrated consideration of technical, informational, organizational, and environmental factors that function as interdependent variables within a unified dynamic system. In applied terms, this involves the deployment of scalable cloud infrastructure, continuous performance monitoring, automated load balancing, data redundancy mechanisms, and rapid recovery procedures that collectively determine the system’s ability to operate under fluctuating demand and external disturbances. At the same time, stable and synchronized

information exchange between logistics subsystems is ensured through standardized data formats, real-time data transmission, and the elimination of informational duplication, which allows the model to accurately reflect the temporal dynamics of operational processes.

Within the structure of the system dynamics model, these practical factors are embedded into causal relationships in which changes in technical parameters indirectly influence business process continuity, information processing speed, and the reliability of operational decision-making. The applied realization of such interconnections enables the quantitative tracing of how variations in system load, partial component failures, or disruptions in data synchronization propagate through the logistics network and affect overall system performance. As a result, the model can be used not only to describe the current operational state of a logistics platform but also to simulate its behavior under crisis conditions, peak workloads, and structural changes in supply chains.

5. Discussions

The results of the conducted modeling of the effectiveness of SaaS solutions for the restoration of transport and logistics infrastructure confirm and at the same time complement the conclusions of previous studies regarding the productivity, adaptability and economic feasibility of cloud platforms in the field of logistics. First, the data obtained are consistent with the study of Liu (2025), which found that the use of cloud solutions increases the productivity of supply chains due to cost optimization and flexible resource management. In our study, these aspects were manifested through the indicator of reducing the time to restore the functioning of the logistics network after the crisis. Similarly, Kazancoglu *et al.* (2022) highlights the ability of SaaS to maintain supply chain resilience under uncertainty, as evidenced by our data on reducing operational losses through automated analytics and scenario planning.

In addition, as Winkelhaus and Grosse (2020) and Reyes (2023) point out, the integration of intelligent SaaS solutions increases the resilience of logistics providers, expanding their functionality in VUCA and BANI conditions. This is consistent with our result on the ability of SaaS to transform instability into a source of innovative change that not only increases efficiency but also forms new business models. As shown in the model, SaaS solutions provide not only flexibility, but also a structural rethinking of the distribution of roles in logistics networks. In this context, our results complement the findings of Akram *et al.* (2024), who emphasize the importance of developing dynamic capabilities through SaaS.

Second, study confirms the conceptual foundations laid in Dam (2018) and Lu *et al.* (2022), which emphasize that an effective SaaS solution in logistics requires a combination of technical architecture and performance assessment. Considerable attention has been paid in the literature to security, multi-tenancy, and migration difficulties of SaaS, which are also identified in our modeling as limiting factors. Krishna (2021) in his review highlights these aspects as the main challenges for SaaS. In our simulations, we found that the presence of poorly secured access points to the cloud infrastructure increases the risk of system failure when attempting to mass-deploy solutions. This is also supported by Karvela *et al.* (2021), who point out the threats of SaaS solutions in logistics networks and justify the need to improve cross-platform security standards. Thus, the results of our work confirm the existing risks, and also demonstrate ways to neutralize them using adaptive architecture. Regarding cost-effectiveness, the result of our study also confirms the thesis of Srinivasa Raghavan *et al.* (2020) that SaaS radically changes the software acquisition process and moves from a capital investment model to an operating cost model.

The paper finds that SaaS solutions have a positive impact on decision-making speed through real-time analytics, which is supported by Ding and Zhang (2020)'s study of real-time supply optimization. These findings are also consistent with our data, where information visualization reduces the time lag between problem identification and resolution. A similar interpretation of SaaS effectiveness in interaction between market actors is also provided by Singh *et al.* (2020), who point to the importance of CRM, and Hsu (2021) who point to the formation of long-term user commitment through the creation of added value in communication.

For example, Oliveira *et al.* (2019) showed that the context of the environment significantly affects the level of SaaS adoption, which may explain the variability in effectiveness found in our modeling depending on the recovery scenario. We observed confirmation of this in high-complexity scenarios — the effectiveness of SaaS depended not only on technical potential, but also on the organizational environment. Regarding the educational context — Taufiq-Hail *et al.* (2021) studied the perception of SaaS among university students, demonstrating the importance of user trust and interface simplicity. The results obtained not only confirm some of the provisions of previous studies, but also expand the idea of the integration effectiveness of SaaS solutions in conditions of instability. Through behavioral validation (Theil's U, NSE, MAPE), we also provided greater reliability of the findings compared to predominantly theoretical or descriptive studies.

6. Conclusions

Based on the constructed system-dynamic model, stable relationships were found between technical indices (scalability, interoperability) and critical performance indicators of SaaS solutions in the field of transport and logistics infrastructure, in particular, the total system recovery time (TTR), the cost-to-result ratio (CER) and the emission reduction rate (ERR). Modeling using maximum likelihood estimation, Bayesian analysis and manual parameter selection methods confirmed the possibility of quantitatively predicting the effects of digital transformation of logistics platforms. Comparison of simulation results with historical data demonstrated compliance within the accuracy range of 5–12%, which gives grounds to consider the model as an applied analytical tool to support strategic management decision-making.

As part of the behavioral validation, acceptable values of the following metrics were obtained: Theil's U coefficient was 0.192, the NSE model efficiency coefficient was 0.84, and mean absolute percentage error (MAPE) was 7.6%. Promising areas of further research include testing the model based on microdata of individual enterprises, checking the impact of legal, industry, and regional restrictions on the effectiveness of SaaS solutions, and integrating additional variables related to management flexibility, the company's digital maturity, and behavioral aspects of implementing new technologies.

Future research could extend the model to other industries to assess the effectiveness of SaaS solutions in different areas. It is also important to consider the long-term effects of implementing digital platforms on the sustainability and performance of logistics infrastructure. Further analysis would allow us to investigate the impact of industry, regional and organizational factors on the adoption and effectiveness of SaaS solutions.

Declaration of Generative AI and AI-assisted technologies in the writing process:

During the preparation of this manuscript the author did not use Generative AI and AI-assisted technologies and take full responsibility for this declaration.

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