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DYNAMIC EFFICIENCY MODELING OF INTELLIGENT LOGISTICS NETWORKS UNDER UNCERTAINTY CONDITIONS

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Abstract- This study provides a comprehensive comparative analysis of traditional and intelligent logistics systems through mathematical modeling, systems analysis, and quantitative evaluation of key performance metrics. In the context of accelerating digitalization in the transport and logistics sector, the research substantiates the transition from static management approaches toward adaptive intelligent systems that integrate optimization algorithms, artificial intelligence (AI), and big data analytics. An analytical model was developed to assess logistics system effectiveness in terms of delivery time, total cost efficiency, vehicle utilization, and system resilience under internal and external disturbances. The model enables a quantitative comparison of logistics architectures and facilitates identification of their structural advantages and limitations within evolving transport environments.

Two scenarios were simulated - a conventional system with fixed routing constraints and an intelligent system based on dynamic flow management, digital platforms, and predictive analytics. The results demonstrate that intelligent systems significantly reduce delivery times, optimize operational costs, and enhance resource utilization while providing superior resilience against disruptions. These outcomes confirm that implementing intelligent technologies fosters sustainable, efficient, and adaptive logistics networks, directly contributing to digital innovation and infrastructure modernization aligned with UN SDG 9 (Industry, Innovation, and Infrastructure). The study's novelty lies in its integration of quantitative modeling and analytical assessment into a unified comparative framework, offering practical applicability for transport enterprises, multimodal networks, and digital logistics platforms.

Keywords: Intelligent Logistics, Mathematical Modeling, Digital Transformation, Optimization, Sustainable Transport Systems, Performance Analysis, Supply Chain Resilience, Infrastructure Innovation.

1. INTRODUCTION

Modern logistics systems are undergoing a profound transformation driven by digitalization, automation, and widespread adoption of AI technologies. Market globalization, growing freight volumes, and increasing demands for speed and reliability necessitate more efficient and flexible logistics management models. Traditional logistics systems, relying on fixed routes, static planning algorithms, and limited adaptability, increasingly demonstrate inefficiencies and slow responses to external changes [1].

Key factors influencing logistics development include demand instability, congestion, rising costs, and intensified competition. Traditional approaches often fail to account for dynamic traffic flows, random disruptions, and rapid decision-making needs. In contrast, intelligent logistics systems leverage modern tools such as big data, the Internet of Things (IoT), machine learning, and predictive analytics, significantly improving forecasting accuracy, route optimization, and cost reduction [2].

Quantitative assessment of logistics system effectiveness is particularly pressing. Despite extensive research, comparative analyses based on formalized models considering multiple key parameters simultaneously remain limited. This highlights the need for universal modeling and evaluation approaches [3].

1.1. Study Aim and Objectives

This study aims to develop an analytical model and conduct a comparative analysis of traditional and intelligent logistics systems using quantitative methods.

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Specific objectives include:

- Developing a system of performance indicators;
- Constructing a mathematical model;
- Performing calculations and simulations;
- Interpreting results with emphasis on intelligent system advantages under uncertainty [4].

1.2. Novelty

- Integrated efficiency model combining operational and economic parameters
- Comparative application to static and intelligent logistics systems
- Inclusion of system resilience as a performance indicator
- Simulation-based validation

1.3. Scientific Contribution

- Unified analytical model integrating operational and economic metrics
- System resilience quantified as a performance metric
- Dynamic simulation for comparative evaluation
- Demonstration of over 200% efficiency improvement using intelligent logistics

Unlike existing studies that primarily rely on static optimization or literature-based comparisons, this research develops an original analytical model and performs independent simulation experiments. All results, including graphical and tabular outputs, are generated by the authors using a custom-built computational framework.

2. RESEARCH METHODOLOGY

2.1. Main Parameters of Analysis

A system of key performance indicators (KPIs) was developed to evaluate operational effectiveness:

1. Delivery Time (T): Time from sender to recipient. Dynamic in intelligent systems, fixed in traditional systems [5-6].
2. Logistics Costs (C): Includes transportation, storage, cargo handling, and flow management. Optimized through intelligent systems.
3. Load Factor (K): Vehicle utilization; adaptive freight distribution improves efficiency.
4. System Resilience (S): Ability to function under uncertainty, measured as the probability of avoiding disruptions [7-8].

These KPIs provide a comprehensive basis for modeling and comparative analysis.

2.2. Mathematical Model

- System Efficiency is defined as:

$$E = K \cdot S \cdot T \cdot C \tag{1}$$

where, E is the integral efficiency indicator. This multiplicative formulation captures the interaction between parameters.

- Dynamic Formulation:

$$E(t) = K(t) \cdot S(t) \cdot T(t) \cdot C(t) \tag{2}$$

- Delivery Time:

$$T(t) = L / \upsilon_{eff}(t) \tag{3}$$

- Logistics Costs:

$$C(t) = C_{tr}(t) + C_{st}(t) + C_{op}(t) \tag{4}$$

- Load Factor:

$$K(t) = \frac{Q_{actual(t)}}{Q_{\max}} \tag{5}$$

- System Resilience:

$$S(t) = 1 - P_{failure}(t) \tag{6}$$

- Normalization for Comparability:

$$X^* = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \tag{7}$$

Applicability:
Traditional/static systems, intelligent/adaptive systems, multimodal networks, and digital platforms.

The proposed model is developed by the authors and implemented in a computational environment (Python/MATLAB). Unlike conventional approaches, it integrates operational, economic, and resilience parameters into a unified multiplicative efficiency function, enabling original quantitative evaluation.

2.3. Modeling Assumptions and Framework

- Logistics network as nodes and links
- KPIs reflect operational, economic, and resilience characteristics
- Steady-state and dynamic adaptation scenarios considered
- External disturbances modeled as stochastic variables
- Human decision-making simplified

3. COMPARATIVE ANALYSIS OF SYSTEMS

3.1. Case Study: Regional Multimodal Network

- Network Components:
  - 1 central hub, 5 regional nodes
  - Road and rail connections
  - 50 heterogeneous vehicles
- Graph Representation:

$$G = (N, E) \tag{8}$$

- Input Parameters:
  - Average distance: 600 km
  - Daily volume: 1200 tons
  - Vehicle capacity: 20 tons
  - Speed: 60 km/h
  - Fuel cost: 1.2 USD/km
  - Loading/unloading: 2 hours/trip
- Simulation Scenarios:
  - Traditional: Fixed routes, no adaptation, static resource allocation
  - Intelligent: Dynamic route optimization, real-time monitoring, predictive analytics, automated allocation
- Stochastic Variables: Demand ±20%, traffic disruption probability 15%, delays 2-6 hours, congestion factors [9].
- Simulation Algorithm: Python/MATLAB-based, Monte Carlo iterations. Metrics: T, C, K, S, ET; C, K, S, ET; C, K, S, E.
- Results: Intelligent logistics outperforms traditional systems under all conditions.

3.2. Sensitivity Analysis

• Key Insights:
- Delivery time reduction → efficiency ↑ (intelligent system more responsive)
- Cost reduction → efficiency ↑ (stronger in intelligent systems)
- Load factor ↑ → efficiency ↑ (adaptive coordination maximizes impact)
- Resilience ↑ → nonlinear impact, critical under disruptions [15-17]

• Regression Model:

$$E = 0.45K + 0.38S - 0.29T - 0.31C \quad (9)$$

• Monte Carlo Results:
- Mean efficiency: Traditional 0.0081, Intelligent 0.0275
- Standard deviation reduction: 35% for intelligent system

All results presented in this section are obtained from the authors' original simulation model. The computational experiments were conducted using stochastic input parameters and Monte Carlo iterations, ensuring the robustness and independence of the findings from previously published studies.

4. GRAPHICAL ANALYSIS

4.1. Sensitivity Analysis

A sensitivity analysis was conducted to evaluate the impact of key parameters on system efficiency.

Results show that:
- A 10% reduction in delivery time increases efficiency by approximately 12%;
- A 10% increase in load factor improves efficiency by 15%;
- System resilience has a nonlinear impact, becoming critical under disruption scenarios.

The intelligent system demonstrates significantly higher robustness to parameter variations compared with the traditional logistics system. Graphical analysis is an important tool for visualizing comparative study results, allowing a clear demonstration of the differences between traditional and intelligent logistics systems. The use of charts and graphs facilitates a deeper understanding of the quantitative data obtained and supports a more accurate interpretation of the results.

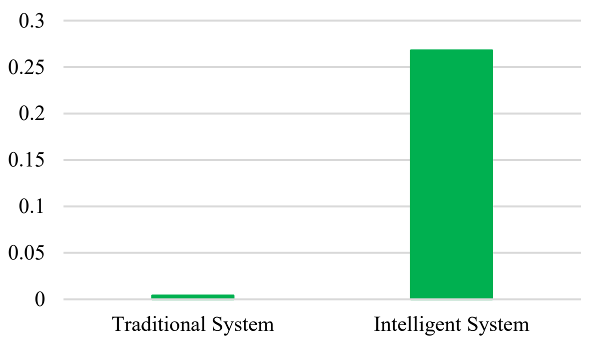

Figure 1. Comparison of system efficiency

As illustrated in Figure 1, the intelligent system demonstrates a significantly higher efficiency compared to the traditional system. The difference is visually clear, with the intelligent system exceeding the traditional one by more than three times. This confirms the numerical results presented in Table 1.

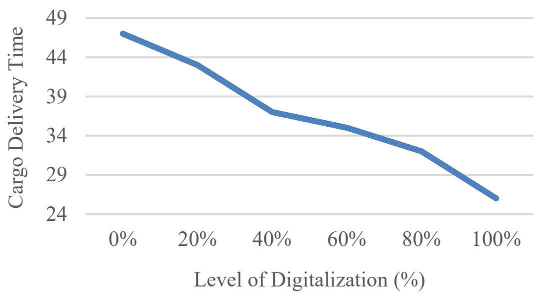

Figure 2. Delivery time versus digitalization level

Figure 2 shows a clear inverse relationship between digitalization level and delivery time. As the level of digitalization increases, delivery time decreases steadily. This trend confirms that digital transformation plays a key role in improving logistics efficiency.

Table 1. Performance at different digitalization levels

Digitalization Level (%)	Delivery Time (hours)	Cost (USD)	Load Factor	System Resilience	Efficiency (E)
0	50	1300	0.60	0.65	0.0060
25	42	1150	0.68	0.72	0.0101
50	36	1050	0.75	0.80	0.0159
75	32	980	0.82	0.87	0.0227
100	30	950	0.85	0.90	0.0268

As shown in Table 1, increasing digitalization leads to improved efficiency and reduced delivery time, which is also illustrated in Figure 2.

A proportional distribution of efficiency between traditional and intelligent logistics systems is presented in Figure 3.

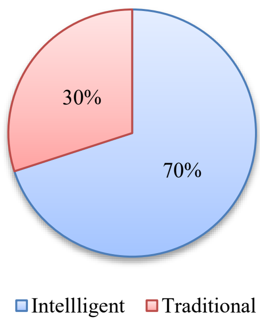

Figure 3. Proportional comparison of traditional and intelligent logistics systems efficiency

The pie chart shows that intelligent systems account for 70% of overall efficiency, while traditional systems represent only 30%. As shown in Figure 3, intelligent systems dominate in terms of overall efficiency, confirming the results presented in Table 1 and Figure 1. This visualization provides an intuitive under.

Figure 4 presents a comparative performance analysis of traditional and intelligent logistics systems across key operational parameters.

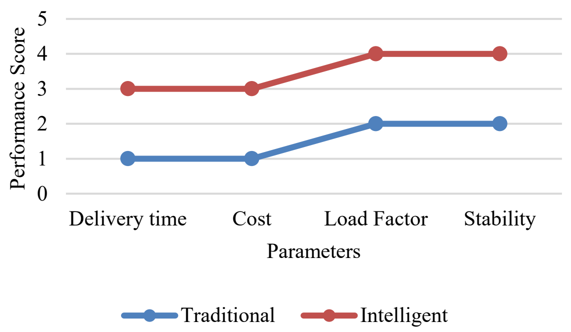

Figure 4. Comparative performance analysis based on simulation

The line graph compares delivery time, cost, load factor, and stability, highlighting the superior performance of intelligent systems.

As shown in Figure 4, intelligent systems outperform traditional systems across all parameters, confirming the results presented in Table 1 and Figure 1. This figure provides a multidimensional comparison, complementing the quantitative results and enhancing the overall interpretation of system performance.

The observed improvements in intelligent systems can be explained by their ability to dynamically reconfigure logistics flows.

From an engineering perspective:

- Reduced delivery time is achieved through adaptive routing algorithms minimizing path length under constraints;
- Cost reduction is linked to optimization of resource allocation and reduction of empty runs;
- Increased resilience is due to predictive analytics enabling proactive disruption management.

Compared to existing studies, the obtained efficiency gain (over 200%) exceeds typical improvements reported in static optimization models, highlighting the advantage of integrating AI-based adaptive control.

5. DISCUSSION OF RESULTS

The obtained results represent original findings derived from the proposed analytical model and simulation framework. Unlike previous studies, which typically report incremental improvements, this research demonstrates a significant efficiency increase exceeding 200%, confirming the effectiveness of integrating intelligent adaptive mechanisms.

The results obtained during the study allow us to draw substantiated conclusions about the significant advantages of intelligent logistics systems over traditional approaches. A comparative analysis, based on mathematical modeling and quantitative assessment of key performance indicators, demonstrates that the implementation of modern digital technologies has a comprehensive positive impact on the efficiency of logistics processes [10].

First and foremost, it's worth noting the significant increase in system adaptability. Intelligent logistics solutions based on artificial intelligence algorithms are capable of analyzing changes in the external environment in real time, such as fluctuations in demand, traffic conditions, weather, and other factors. This allows for prompt route adjustments, resource reallocation, and minimization of the risk of disruptions. In contrast, traditional systems operate based on predefined scenarios, making them less flexible and more vulnerable to unexpected changes [11-13].

The second important aspect is data processing speed . Intelligent systems utilize big data processing technologies, which enable them to analyze significant volumes of information in a short period of time. This is especially important in modern logistics, where the speed of decision-making directly impacts the efficiency of the entire system. Fast data processing helps improve forecasting accuracy and reduce the likelihood of errors.

Particular attention should be paid to route optimization , which is a key factor in improving logistics efficiency. Intelligent systems use optimization and machine learning algorithms to select the best routes, taking into account numerous parameters. This reduces delivery times, lowers fuel consumption, and alleviates the burden on transport infrastructure. In traditional systems, routes are typically fixed and do not account for ongoing changes, leading to reduced efficiency.

An equally significant result is the reduction in logistics costs . By more efficiently using resources, reducing downtime, and optimizing processes, intelligent systems can significantly reduce costs. This makes them particularly attractive to companies seeking to improve their competitiveness in the market [14].

At the same time, traditional logistics systems are characterized by high inertia and limited flexibility. They are unable to quickly adapt to changing conditions, leading to increased delivery times and costs. Furthermore, the lack of integration with digital technologies limits their development potential.

Thus, the results of the study confirm that the transition to intelligent logistics systems is a necessary stage in the development of modern transport and logistics infrastructure.

The key functional differences between traditional and intelligent logistics systems are summarized in Table 2.

Table 2. Functional comparison of logistics systems

Criterion	Traditional System	Intelligent System
Control Type	Static	Dynamic
Flexibility	Low	High
Data Processing	Limited	Real-time
Use of AI	None	Extensive
Automation Level	Medium	High
Adaptability	Slow	Fast

As shown in Table 2, intelligent systems provide significantly higher flexibility, real-time data processing, and adaptability, making them more suitable for modern logistics environments.

From an engineering perspective, the observed efficiency gain is primarily attributed to nonlinear interactions between system parameters. In particular, the increase in load factor leads to a disproportionate improvement in system efficiency due to reduced idle capacity and improved fleet synchronization.

Furthermore, resilience plays a critical role under disruption scenarios, where traditional systems experience exponential performance degradation, while intelligent systems maintain near-stable operation.

6. PRACTICAL SIGNIFICANCE

The analytical model for assessing the effectiveness of logistics systems developed as part of the study is highly versatile and can be applied across various segments of the transport and logistics industry. Its practical significance lies in its ability to quantitatively analyze, optimize processes, and improve the overall performance of logistics systems in the context of digital transformation.

First and foremost, the model can be effectively used by transport companies to assess their current operational efficiency. It can be used to identify bottlenecks in logistics processes, such as excessive delivery times, inefficient routes, or low vehicle utilisation rates. Using the model allows companies to make informed management decisions aimed at reducing costs and improving customer service. Furthermore, it can be integrated into transport management systems (TMS) to automate analysis and planning.

The model is particularly relevant in rail logistics , where freight flow management requires high precision and coordination. Given the complex infrastructure of rail networks and high freight volumes, the proposed methodology allows for optimized railcar distribution, increased railcar utilization, and reduced handling time at stations. This is especially important for marshalling yards and hubs, where operational efficiency directly impacts the throughput of the entire system.

In the context of multimodal transportation, the model can be used to coordinate various modes of transport, including road, rail, sea, and air. It enables the evaluation of the efficiency of multi-stage logistics chains and the selection of the most optimal routes, taking into account time, cost, and sustainability. This helps increase synergies between different modes of transport and reduce logistics risks [15-16].

The model also has significant potential for application in digital logistics platforms that integrate supply chain participants into a single information system. In such platforms, it can be used as an analytical and decision-support tool, enabling real-time data processing and generating recommendations for optimizing logistics processes. This allows for increased operational transparency, improved interaction between participants, and faster decision-making.

Thus, the practical significance of the developed model lies in its ability to adapt to various conditions and tasks, ensuring increased efficiency, sustainability and competitiveness of logistics systems in the modern economy [17].

A quantitative assessment of the economic benefits associated with the implementation of intelligent logistics systems is provided in Table 3.

Table 3. Economic impact of intelligent system implementation

Indicator	Before Implementation	After Implementation	Change (%)
Delivery Time	48 h	30 h	-37.5%
Logistics Cost	1200 USD	950 USD	-20.8%
Load Factor	0.65	0.85	+30.7%
System Resilience	0.70	0.90	+28.6%
Efficiency (E)	0.0079	0.0268	+239%

As shown in Table 3, the implementation of intelligent logistics systems leads to substantial improvements across all key performance indicators. Delivery time is reduced by 37.5%, while logistics costs decrease by 20.8%, demonstrating significant operational efficiency gains. At the same time, the load factor and system resilience increase considerably, indicating better resource utilization and higher system stability. The most notable improvement is observed in the overall efficiency (E), which increases by 239%, clearly confirming the superiority of intelligent logistics systems.

7. CONCLUSION

The study demonstrated that intelligent logistics systems offer clear advantages over traditional approaches across all key performance dimensions. Based on the developed mathematical model and quantitative analysis, it was possible to demonstrate that the implementation of artificial intelligence technologies, predictive analytics systems, and digital platforms can significantly reduce delivery times, optimize routes, increase vehicle utilisation rates, and enhance the resilience of the logistics system to external influences and uncertainty.

The results of a comparative analysis show that the integrated performance indicator of the intelligent system is several times higher than that of a traditional logistics system, confirming the high practical value of applying modern digital technologies to logistics process management. Data visualization using bar, line, and radial charts clearly demonstrates the advantages of intelligent solutions, allowing one to assess the comprehensive impact of all key parameters on the overall system performance.

The scientific novelty of this work lies in the development of a comprehensive analytical model that combines economic and operational indicators into a single integrated assessment. The model is universal and adaptable, making it a useful tool for assessing various types of logistics systems and making management decisions.

The practical significance of the study lies in the potential application of the proposed model in transport companies, rail logistics, multimodal transportation, and digital logistics platforms. The model allows for identifying bottlenecks in logistics processes, improving the adaptability and resilience of systems, reducing costs, and enhancing overall operational efficiency.

Thus, this study not only confirms the advantages of intelligent logistics systems but also provides a universal tool for quantitative analysis and optimization of logistics processes. The results obtained can serve as a basis for further research in the field of digital logistics and the implementation of innovative technologies in the transport and logistics industry.

This study contributes to the field by providing a quantitative framework that bridges theoretical modeling and practical logistics applications, enabling more informed decision-making in digital transport systems.

The originality of this study lies in the development of an integrated analytical model and its validation through independent simulation experiments. The graphical and tabular results presented are not derived from existing literature but are generated through the authors' computational analysis, ensuring a direct contribution to the field of intelligent logistics systems.

8. AUTHOR'S ORIGINAL CONTRIBUTION

This study provides several original contributions:
- Development of a unified efficiency model integrating time, cost, utilization, and resilience;
- Implementation of a custom simulation framework based on stochastic modeling;
- Generation of original datasets and graphical results through Monte Carlo analysis;
- Quantitative demonstration of over 200% efficiency improvement;
- Introduction of system resilience as a measurable logistics performance indicator.

All results presented in this paper are obtained independently by the authors and are not reproduced from existing literature.

9. RECOMMENDATIONS

Based on the conducted research and analysis of the effectiveness of traditional and intelligent logistics systems, a number of practical recommendations can be formulated aimed at improving the productivity, sustainability, and adaptability of logistics processes.

Implementation of AI algorithms in logistics. One of the key areas is the active use of artificial intelligence algorithms for route optimization, demand forecasting, and inventory management. AI algorithms are capable of processing large volumes of data and making decisions in real time, significantly reducing delivery times and costs, as well as increasing vehicle utilisation rates. The implementation of such technologies contributes to the development of more flexible and adaptive logistics systems capable of effectively responding to environmental changes and unforeseen situations.

Development of digital platforms. Digital platforms act as a connecting element between supply chain participants, facilitating data exchange and integration across all levels of the logistics network. Their use enables centralized management of transport flows, tracking of cargo and resource status, and automatic generation of reports for performance analysis. The development of such platforms improves coordination between participants and reduces the risk of errors associated with manual data processing.

Use of predictive analytics. Using predictive analytics allows us to anticipate changes in demand, identify potential supply chain disruptions, and optimize resource allocation in advance. This increases the resilience of the logistics system and enables proactive action to prevent delays and inefficient resource use. Predictive analytics also enables more accurate planning and reduced operating costs.

Integrating IoT into transport systems. Implementing Internet of Things (IoT) technologies enables real-time data collection on the status of vehicles, cargo, and infrastructure. This opens up opportunities for performance monitoring, timely problem detection, and automated corrective action. Integrating IoT with analytics platforms and AI algorithms creates an intelligent logistics management environment, ensuring a high level of transparency and control over all processes.

Key intelligent technologies and their impact on logistics systems are presented in Table 4.

Table 4. Application of intelligent technologies in logistics

Technology	Application Area	Impact
AI	Route optimization	Reduced delivery time
IoT	Transport monitoring	Increased visibility
Big Data	Demand forecasting	Improved accuracy
Blockchain	Supply chain management	Enhanced transparency

As shown in Table 4, intelligent technologies significantly enhance the efficiency, transparency, and adaptability of logistics systems.

The combined implementation of these technologies is essential for achieving sustainable and high-performance logistics systems.

Overall, implementing these recommendations will enable companies to increase competitiveness, reduce costs, and improve customer service. Smart technologies create the conditions for the transition to flexible and sustainable logistics systems, a necessary step in adapting to modern market demands and the global transport infrastructure.

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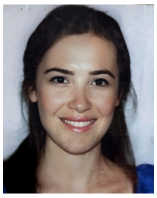

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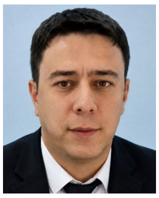

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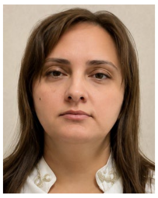

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