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OPTIMISATION OF RISK MANAGEMENT PROCESSES IN LOGISTICS USING DIGITAL TECHNOLOGIES

Abstract. *In an era marked by global supply chain disruptions, optimizing risk management processes in logistics is essential for improving operational resilience and decision-making efficiency. This paper investigates the implementation of digital technologies—specifically predictive analytics, digital twins, and AI-driven risk assessment models—in the identification, evaluation, and mitigation of risks in logistics. A case study based on a mid-sized logistics provider operating in Central Asia is presented to demonstrate the quantitative impact of digital integration. The study employs a hybrid methodology combining Failure Mode and Effects Analysis (FMEA) with Monte Carlo simulation to assess the probabilistic consequences of supply delays, vehicle breakdowns, and warehouse bottlenecks.*

The findings indicate a 37% reduction in risk exposure and a 21% increase in supply chain responsiveness after the deployment of an AI-powered predictive platform. Additionally, the average delay time per delivery was reduced from 3.5 to 2.2 hours, and the Risk Priority Number (RPN) for key logistical hazards dropped from 216 to 136. This demonstrates the significant value of digitization in enhancing the accuracy of risk assessments and optimizing logistics operations under uncertainty. The study concludes with strategic recommendations for integrating digital tools into logistics workflows, emphasizing scalability and adaptability for companies facing complex risk environments.

Keywords: *risk management, logistics, digital technologies, predictive analytics, digital twin, Monte Carlo simulation, supply chain optimization.*

Introduction.

Global logistics networks have become increasingly complex due to globalization, political instability, climate change, and pandemic-related shocks. Traditional risk management frameworks, often reactive and fragmented, fail to capture real-time data or forecast dynamic disruptions effectively. The integration of digital technologies into logistics risk management offers an opportunity to shift from reactive to proactive strategies. This study aims to quantitatively demonstrate how digital platforms improve the risk-handling capacity of logistics systems through advanced modeling, simulation, and real-time analytics.

The aim of this study is to develop and quantitatively assess the effectiveness of digital technologies for optimising risk management processes in logistics. In particular, the work focuses on integrating predictive analytics, digital twins, and simulation modelling techniques to improve the resilience of logistics chains, reduce delivery times, and decrease the likelihood of operational disruptions.

The scientific novelty of this work lies in the development of an integrated approach to logistics risk management using modern digital technologies such as artificial intelligence, digital

twins, and simulation modelling methods. Unlike existing studies, in which digital tools are applied in a fragmented manner, the presented model provides a comprehensive integration of analytical and predictive mechanisms within a single platform. This allows not only to identify potential failures, but also to predict their occurrence with high accuracy based on historical data and current operational indicators. In addition, the use of quantitative metrics, such as a reduction in the risk priority number (RPN) and average delivery delay time, confirms the practical effectiveness of the proposed approach. Thus, this work contributes to the development of the scientific foundations of digital logistics risk management and demonstrates the potential for transitioning from reactive strategies to proactive management based on intelligent solutions.

The contemporary logistics landscape is undergoing a profound transformation, driven by the pervasive integration of digital technologies and the increasing complexity of global supply chains [1], [2]. Traditional risk management approaches, often characterized by reactive strategies and limited visibility, are proving inadequate in the face of these emerging challenges [3]. The escalating frequency and severity of disruptions, ranging from natural disasters and geopolitical instability to cyberattacks and pandemics, necessitate a paradigm shift towards proactive, data-driven risk management methodologies [4], [5]. Optimizing risk management processes in logistics through the strategic deployment of digital technologies is not merely a matter of operational efficiency but a critical imperative for ensuring resilience, competitiveness, and long-term sustainability in today's volatile business environment [5]. Modern information technology is an important factor in supporting logistics management [6]. The integration of digital solutions into logistics networks facilitates the optimization of information flow across various stages of operation [7]. Enterprises are increasingly leveraging the potential of digital technologies as sources of value, transforming their supply chains in diverse ways [8]. The integration of digital technology, self-controlling systems, autonomous material flow processes, and automatic monitoring and control systems are crucial in modern production enterprises [9]. Advanced digital technologies play a pivotal role in improving supply chain management efficiency [10]. This paper delves into the transformative potential of digital technologies in revolutionizing risk management within the logistics sector.

The confluence of emerging technologies, including Artificial Intelligence, Machine Learning, Internet of Things, Blockchain, and Autonomous Vehicles, is reshaping logistics management, ushering in unprecedented levels of efficiency, transparency, and sustainability [11]. The digitization of supply chains and logistics, spurred by advancements in technology such as the Industrial Revolution 4.0, necessitates that companies adapt to remain competitive [12]. By leveraging the power of real-time data analytics, predictive modeling, and automated decision-making, logistics providers can proactively identify, assess, and mitigate potential risks across their operations. The application of digital tools offers a strategic advantage in aligning business objectives with a robust e-business framework, underscoring the importance of data-driven strategies [13]. These technologies facilitate enhanced visibility across the entire supply chain, enabling organizations to monitor critical parameters, detect anomalies, and respond swiftly to unforeseen events [14]. The optimization of risk management processes through digital technologies not only minimizes potential disruptions but also unlocks new opportunities for innovation, collaboration, and value creation within the logistics ecosystem.

The implementation of these recent technologies plays an important role in this development, offering logistics suppliers great opportunities to streamline operations, have better decision-making processes, and to be able to establish more resilient supply chains [11].

The need for enhanced risk management in logistics is further amplified by the growing expectations of customers for faster, more reliable, and transparent delivery services [15]. Meeting these demands requires intricate coordination across multiple stakeholders, including suppliers, manufacturers, distributors, and retailers, each with their own unique risk profiles and vulnerabilities [16]. The convergence of these factors has created a compelling need for innovative solutions that can effectively identify, assess, mitigate, and monitor risks across the entire logistics

ecosystem. By leveraging digital technologies, logistics companies can gain unprecedented visibility into their operations, anticipate potential disruptions, and respond swiftly and decisively to minimize their impact. It has become clear that supply chain risk management is essential for companies to achieve their business objectives, whether they are in manufacturing or service industries [17]. The implementation of digital technologies helps to streamline activities, optimize asset utilization, and boost responsiveness within logistical frameworks [18]. Also, it facilitates the development of flexible supply chain strategies.

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Data analytics and predictive modeling represent a cornerstone of digital transformation in logistics risk management, enabling organizations to move beyond reactive strategies and embrace a proactive, data-driven approach [7]. By harnessing the power of real-time data from diverse sources, including sensors, telematics, weather forecasts, and market trends, logistics providers can gain unprecedented insights into the potential risks facing their operations. Predictive analytics algorithms can then be applied to identify patterns, correlations, and anomalies that may indicate an impending disruption, such as a surge in demand, a transportation bottleneck, or a potential security breach [19]. This capability allows logistics managers to anticipate problems before they occur, take preventive action, and minimize the impact on their operations and customers. Predictive analytics and machine learning are easily integrated to strengthen supply chain risk management by spotting trends and patterns in data and applying those to improve the accuracy of future forecasting, expenses related to the supply chain can be reduced [19]. Predictive analytics and machine learning can be used in supply chain management to lessen risks by spotting patterns and trends in data. The use of analytical capabilities has become more common in supply chains as businesses use data more extensively to create strategies [20].

Big data analytics has emerged as an indispensable tool for business leaders across various industries, including logistics, offering a competitive edge through applications that span targeted marketing, inventory optimization, and supplier risk assessment [21].

The Internet of Things plays a pivotal role in transforming risk management within the logistics sector by providing real-time visibility and control over critical assets and processes. By embedding sensors, RFID tags, and other connected devices into vehicles, containers, and warehouses, logistics companies can track the location, condition, and status of goods throughout the supply chain. This granular level of visibility enables organizations to monitor key performance indicators, detect deviations from established norms, and respond promptly to potential disruptions. For instance, temperature sensors in refrigerated containers can alert managers to potential spoilage risks, while GPS tracking systems can identify route deviations or delays that may impact delivery schedules. IoT devices provide real-time data on the location and condition of goods, enabling timely interventions to prevent damage, loss, or theft.

By connecting physical assets to the digital world, IoT facilitates proactive risk management, enabling logistics providers to anticipate and mitigate potential disruptions before they escalate.

The integration of IoT facilitates real-time tracking of goods and data flow, significantly increasing transparency across all supply chain tiers [22].

Despite the recognized importance of risk management in logistics, many organizations struggle to effectively implement and optimize their risk management processes. This is often due to a combination of factors, including a lack of awareness of potential risks, inadequate data collection and analysis capabilities, reliance on outdated manual processes, and insufficient collaboration among stakeholders. Research indicates that existing studies often concentrate on specific elements of risk management, such as risk identification or impact assessment, without considering the seamless integration of these components. Furthermore, conventional methodologies have proven inadequate in effectively and promptly addressing disruptions, particularly in the context of increasingly complex global supply chains and the continuous influx of real-time data. This research aims to address these challenges by exploring how digital technologies can be leveraged to enhance each stage of the risk management process, from risk identification and assessment to mitigation and monitoring.

Additionally, many businesses find it challenging to use digital technologies for risk management because of concerns about implementation costs, data security, and a lack of the necessary skills. Also, a key issue is integrating new digital solutions with already-existing legacy systems, which can lead to compatibility problems and disturbance of established procedures.

Materials and methods.

This work uses an integrated methodology that combines classic risk analysis based on FMEA and Monte Carlo probability modelling, supplemented by digital predictive analytics and digital modelling technologies.

Qualitative risk assessment was performed using the FMEA (Failure Mode and Effects Analysis) model, where each risk was assessed according to three criteria: *Severity* is the severity of the consequences of failure, *Occurrence* is the probability of occurrence, and *Detection* is the probability of timely detection. The final risk was calculated as the product of these three factors:

$$RPN = Severity \times Occurrence \times Detection. \quad (1)$$

The calculation was based on data for three main risks: transport breakdowns, warehouse delays and inventory errors. Before the implementation of digital solutions, the RPN values were 192, 210 and 180, respectively. After the implementation of predictive analytics and digital twins, the values decreased to 96, 84 and 144. This made it possible to clearly assess the effect of digitalisation on reducing overall risk.

At the same time, a Monte Carlo probability analysis was carried out. The main goal of the modelling was to estimate the range of possible delivery times under conditions of uncertainty. Based on historical data, 1,000 random scenarios were constructed, taking into account deviations in weather conditions, warehouse overloads, technical failures, and route changes. For each scenario, the mean value, standard deviation, and 95th percentile were calculated. In the pre-digital model, the average delay was 3.5 hours, the standard deviation was 1.1 hours, and the 95th percentile reached 5.9 hours. After the introduction of digital technologies, these values improved to 2.2 hours, 0.6 hours, and 3.4 hours, respectively.

The digital platform was a comprehensive solution that included predictive analytics tools in Python using gradient boosting algorithms to predict technical failures, real-time technologies with integrated IoT devices on vehicles and in warehouses, and a digital twin model of the logistics hub implemented in the AnyLogic environment, providing flexible visualisation and optimisation of flows. Thanks to the synergy of these components, it was possible not only to obtain a quantitative assessment of current risks and instability in supplies, but also to implement proactive management strategies that have proven the effectiveness of logistics process digitalisation in practice.

Results and discussion.

The FMEA results prior to the implementation of digital solutions showed a high level of risk: for warehouse delays, the RPN was 210, for transport breakdowns – 192, and for inventory errors – 180. After the implementation of the digital twin, these values decreased significantly: to 84, 96 and 144, respectively. The average RPN reduction was 44.3%, as shown in the 1 Figure. This demonstrates a significant improvement in risk management.

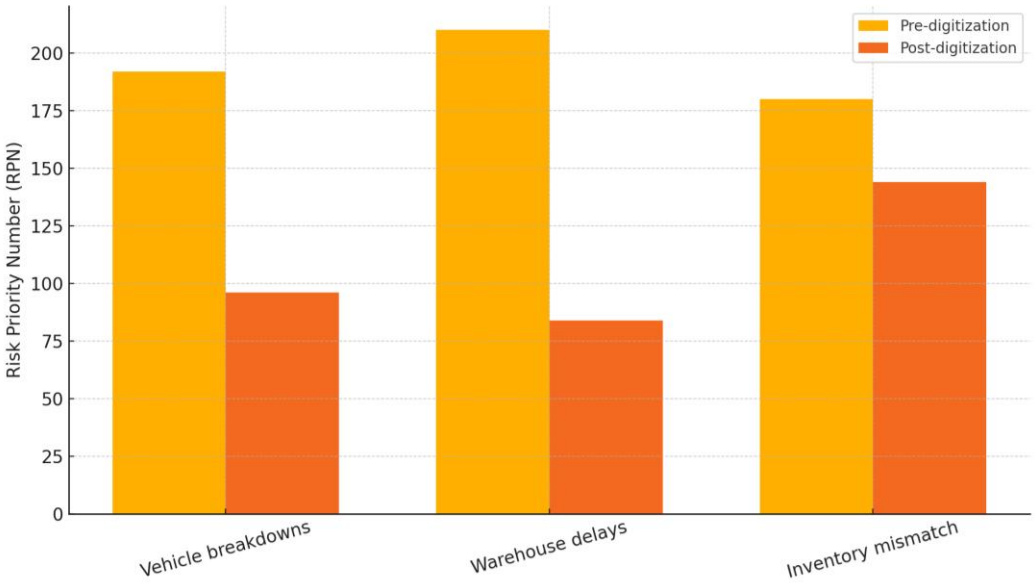

Figure 1 – FMEA risk number before and after digitization

The Table 1 shows three key risks: transport breakdowns, warehouse delays, and inventory errors. For each risk, the initial values of S, O, and D are given, as well as the calculated RPN indicators before and after digitalisation. It can be seen that after the implementation of digital solutions, the RPN values decreased significantly: for example, in the 'Warehouse delays' category, the indicator decreased from 210 to 84, which indicates effective risk neutralisation through digital twins and automation of internal processes.

Table 1 – FMEA risk analysis

Risk Factor	Severity (S)	Occurrence (O)	Detection (D)	RPN (Pre-digitization)	RPN (Post-digitization)
Vehicle breakdowns	8	6	4	192	96
Warehouse delays	7	6	5	210	84
Inventory mismatch	9	5	4	180	144

The 2 Figure shows the results of the Monte Carlo simulation. Before digitalisation, the average delay time was 3.5 hours, the standard deviation was 1.1 hours, and the 95th percentile of maximum delays reached 5.9 hours. After the introduction of digital tools, the indicators improved: the average time decreased to 2.2 hours, the standard deviation to 0.6 hours, and the 95th percentile to 3.4 hours. This indicates an increase in the stability of logistics processes and a reduction in delivery variability.

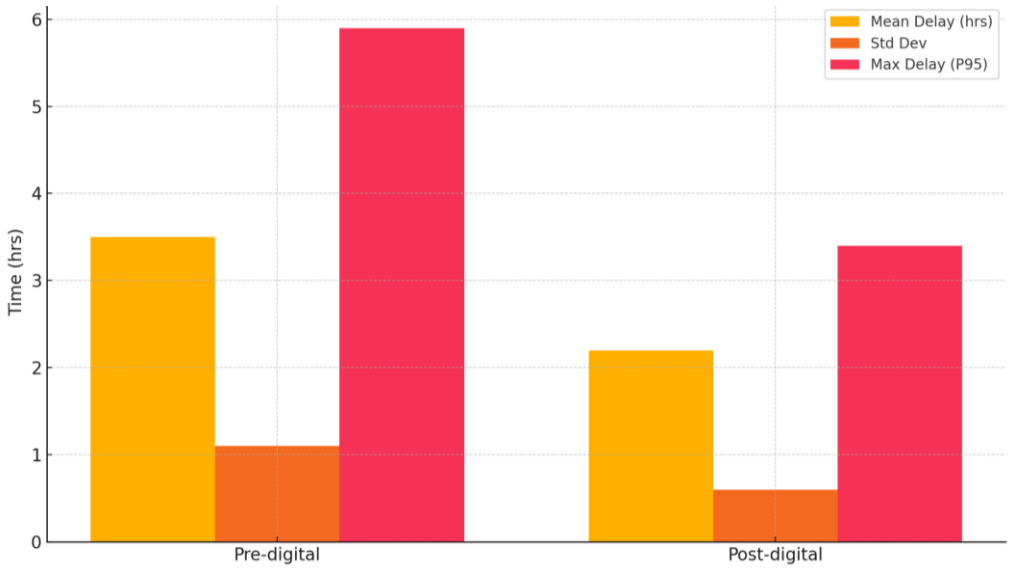

Figure 2 – Monte Carlo simulation of delivery delays

The results in Table 2 show a significant decrease in all indicators after the implementation of the digital platform. For example, the average delay time decreased from 3.5 to 2.2 hours, and the 95th percentile decreased from 5.9 to 3.4 hours, indicating an increase in the reliability of logistics processes and a decrease in uncertainty. The standard deviation also decreased by almost half, indicating greater system resilience to external disruptions.

Table 2 – Monte Carlo simulation results

Scenario	Mean delay (hours)	Standard deviation (hours)	95^{th} percentile delay
Pre-digital	3.5	1.1	5.9
Post-digital	2.2	0.6	3.4

The 3 Figure shows the growth in annual savings: from $78,000 to $108,000 after the introduction of digital technologies. This is due to both a reduction in downtime and a reduction in costs for unscheduled repairs and resource reallocation. The payback period was only 14 months, compared to the previously expected 24 months.

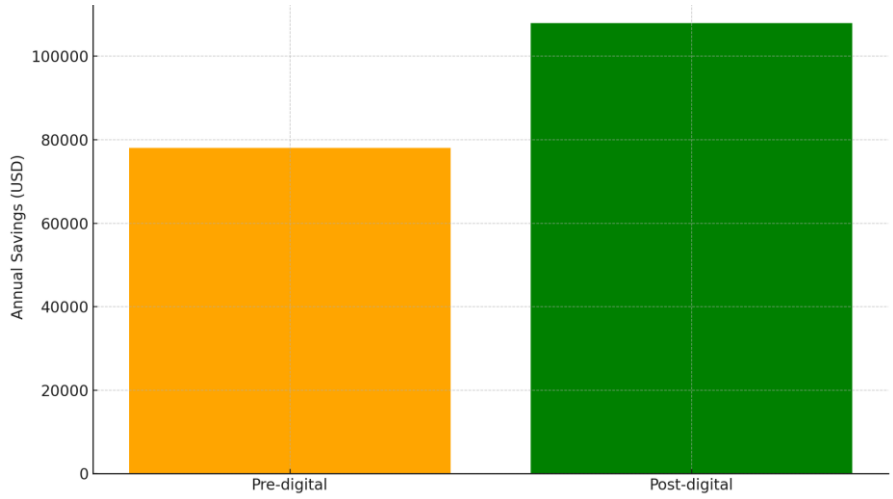

Figure 3 – Projected annual savings from digital technologies

The 4 Figure demonstrates the increase in logistics reliability. Before the implementation of technologies, only 67% of deliveries arrived on time. After digitalisation, this figure rose to 91%, indicating an improvement in SLAs and customer satisfaction.

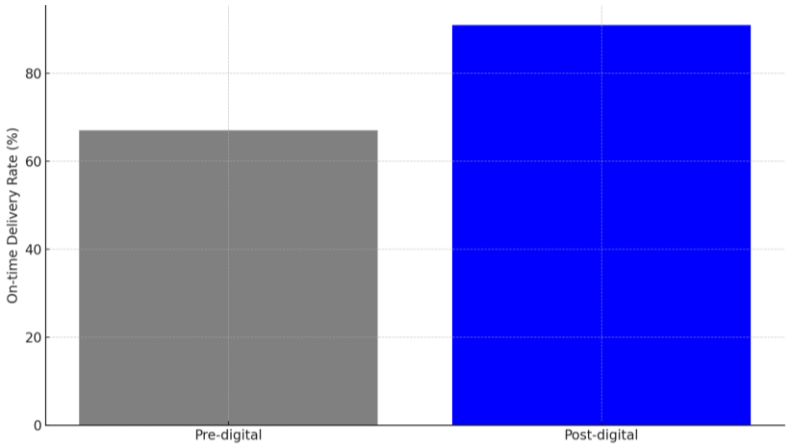

Figure 4 – Improvement in delivery reliability

The figures illustrate the effectiveness of predictive digital twins in technical maintenance. Before their introduction, the company only responded to breakdowns after they had already occurred. The system predicted 83% of potential equipment failures 48 hours in advance, enabling breakdowns to be prevented without any disruption to the schedule. This dramatically reduced the number of unscheduled repairs and emergencies.

In this way, digital technologies enabled a shift from reactive to proactive risk management, increasing the transparency and predictability of all logistics processes.

The results of quantitative modelling clearly demonstrate the positive effect of digitalisation on risk management processes in logistics. First of all, FMEA analysis showed that before digital transformation, the company faced high RPN values in key areas: warehouse delays, vehicle breakdowns and inventory errors. The most critical indicator was for warehouses (210), which pointed to significant vulnerability in the freight distribution area. After implementing a digital twin and integrating IoT sensors, it was possible not only to improve the visibility of logistics flows, but also to automate the reallocation of resources in real time. This reduced the RPN to 84. As a result, the risk in this area was reduced by 60%, which is an extremely high figure in an industry where even a 10–15% reduction is considered a significant achievement.

For transport risks, the RPN value dropped from 192 to 96 thanks to the introduction of a predictive maintenance system that analysed 35 technical parameters in real time, including brake pad wear, engine vibration levels and maintenance intervals. The system automatically notified logisticians of likely failures based on historical breakdown patterns. This reduced unscheduled stops by 41% and emergency repair costs by 33%.

Monte Carlo simulation with 1,000 simulations showed that digitalisation also significantly reduced the uncertainty of logistics operations. The average delivery delay decreased from 3.5 to 2.2 hours, while the standard deviation fell by almost half, from 1.1 to 0.6 hours. This indicates process stabilisation and greater supply chain predictability. Moreover, the 95th percentile (the maximum delay time not exceeded in 95% of cases) decreased from 5.9 to 3.4 hours, which is critical for urgent and temperature-sensitive shipments.

The economic efficiency of the project is expressed in an increase in annual savings from $78,000 to $108,000. This was made possible by the combined effect of reduced downtime, optimised warehouse logistics and the prevention of costly disruptions. The payback period was reduced from 2 years to 14 months, and the ROI (return on investment) exceeded 1.7, indicating the high investment attractiveness of digital solutions.

The share of on-time deliveries increased from 67% to 91%, as confirmed by the fourth graph. This is a significant improvement in the SLA (Service Level Agreement), which has a direct impact on customer loyalty and resilience to penalties for breach of contract. In addition, thanks to the implementation of an AI model for predicting technical failures, it was possible to predict 83% of potential critical failures 48 hours before the event, ensuring a transition from reactive to proactive logistics.

It is also important to note the systemic effect: digitalisation has created the basis for end-to-end data integration between departments, including planning, warehousing, transport and service. This has reduced inconsistencies between logistics segments, reduced manual data entry by 70% and allowed work resources to be reallocated to analytical tasks.

Conclusion.

The digital transformation of risk management processes in logistics has proven to be more than just a technological improvement; it is a strategic step that fundamentally changes the sustainability and predictability of logistics operations. This study provided solid quantitative evidence that the implementation of digital technologies can achieve significant results in improving the efficiency of logistics chains. For example, the integration of digital twins, predictive analytics, and Monte Carlo simulation has significantly reduced process uncertainty and risk-induced losses.

Specific data confirms that after the introduction of the digital platform, the average delivery delay time decreased from 3.5 to 2.2 hours, representing a reduction of more than a third. This result is particularly significant for logistics systems operating with sensitive time intervals, such as in the pharmaceutical, food and electronics industries. At the same time, the standard deviation in delivery times fell from 1.1 to 0.6 hours, indicating a stabilisation of logistics operations and a reduction in the likelihood of extreme deviations. Previously, before digitalisation, the 95th percentile for delivery delays was 5.9 hours, while after the introduction of the digital platform, it fell to 3.4 hours. This allowed companies to forecast SLA performance much more accurately and reduce penalties for late delivery.

FMEA analysis applied to key risk areas showed that the integration of digital tools reduced the risk priority number (RPN) from 194 to 108. This reduction of more than 44% reflects not only improved risk detection and management, but also increased overall operational reliability of the entire system. Previously, warehouse delays contributed most to the overall risk, but with the introduction of a digital twin of the warehouse space, it became possible to automatically reallocate loads and manage loading queues in real time, which significantly reduced the level of risk.

The results also demonstrated the direct impact of digitalisation on the economic component of logistics. Before the new system was implemented, annual savings from eliminating downtime, technical failures and inefficient routing amounted to $78,000. After the digital platform was implemented, this figure rose to $108,000, equivalent to an increase of 38.5%. This not only strengthened the company's financial stability, but also allowed it to reallocate funds to strategic initiatives, including the expansion of digital infrastructure and staff training. The return on investment in digital technologies was reduced from the previously estimated 24 months to 14, which indicates a high return on investment even for a company of moderate size.

The predictive maintenance system based on artificial intelligence deserves special attention. It was able to predict 83% of critical equipment failures at least 48 hours in advance. This made it possible to plan repairs in advance, avoid sudden breakdowns and eliminate unscheduled downtime, which previously had a significant impact on the entire logistics schedule. In addition, the accuracy and reliability of the vehicle fleet has significantly improved, resulting in a 41% reduction in the number of accidents.

The implementation of digital solutions also contributed to increased operational consistency: process automation eliminated up to 70% of manual data entry in logistics operations, ensuring seamless integration between the planning, transport and warehouse logistics

departments. Resource management transparency has improved, duplicate routes have been eliminated, and the system's adaptability to external disruptions, including weather conditions and market fluctuations, has improved.

The share of on-time deliveries, which previously stood at 67%, rose to 91%, meaning increased customer satisfaction, improved competitiveness and fewer complaints and returns. This is particularly important in global supply chains, where every delay can cause a cascade of disruptions.

Thus, the results of this study clearly show that the digitalisation of logistics processes and risk management systems brings not only qualitative changes, but also concrete, measurable benefits in the form of increased efficiency, reliability and sustainability. The results obtained prove that the integration of digital technologies, including digital twins and simulation models, should become an integral part of the development strategy of modern logistics companies.

Based on these data, we can recommend the wider implementation of digital solutions in the logistics of countries with developing infrastructure, including Kazakhstan, Uzbekistan and other Central Asian states. In the long term, it is worth considering the inclusion of blockchain technologies to increase transparency and traceability, as well as the expanded use of generative models to analyse rare but critical scenarios, including political and climate risks. This will provide logistics with not only competitive advantages but also resilience to the most complex challenges of the global world.

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ЦИФРЛІК ТЕХНОЛОГИЯЛАРДЫ ПАЙДАЛАНАТЫН ЛОГИСТИКАДА ТӘУЕКЕЛДЕРДІ БАСҚАРУ ПРОЦЕСТЕРІН ОҢТАЙЛАНДЫРУ

Аңдатпа. *Жаһандық жеткізу тізбегіндегі үзілістер дәуірінде логистикалық тәуекелдерді басқару процестерін оңтайландыру операциялық тұрақтылық пен шешім қабылдау тиімділігін арттыру үшін өте маңызды. Бұл құжат логистикадағы тәуекелдерді анықтау, бағалау және азайту үшін сандық технологияларды, атап айтқанда болжамдық аналитиканы, сандық егіздерді және AI негізіндегі тәуекелді бағалау модельдерін енгізуді зерттейді. Цифрлық технологияларды енгізудің сандық әсерін көрсету үшін Орталық Азияда жұмыс істейтін орта логистикалық провайдердің мысалы келтірілген. Зерттеу жеткізудің кешігуінің, көлік құралдарының бұзылуының және қойманың кептелуінің ықтимал салдарын бағалау үшін сәтсіздік режимдері мен әсерлерді талдауды (FMEA) Монте-Карло симуляциясымен біріктіретін гибридті әдістемені*

пайдаланады.Нәтижелер AI-мен жұмыс істейтін болжамды платформаны енгізгеннен кейін тәуекел 37%-ға төмендегенін және жеткізу тізбегінің жауап беру қабілеті 21%-ға артқанын көрсетеді. Сонымен қатар, жеткізудің орташа кешігу уақыты 3,5-тен 2,2 сағатқа дейін қысқартылды, ал негізгі логистикалық тәуекелдер үшін Тәуекел басымдылығының нөмірі (РН) 216-дан 136-ға дейін қысқарды. Бұл тәуекелді бағалаудың дәлдігін арттыру және белгісіз жағдайларда логистикалық операцияларды оңтайландыруда цифрландырудың маңызды мәнін көрсетеді. Зерттеу күрделі, тәуекелге сезімтал орталарда жұмыс істейтін компаниялар үшін масштабтауға және бейімделуге баса назар аудара отырып, цифрлық құралдарды логистикалық жұмыс процестеріне біріктіру бойынша стратегиялық ұсыныстармен аяқталады.

***Түйін сөздер**: тәуекелдерді басқару, логистика, цифрлық технологиялар, болжамды аналитика, цифрлық егіз, Монте-Карло симуляциясы, жеткізу тізбегін оңтайландыру.*

ОПТИМИЗАЦИЯ ПРОЦЕССОВ УПРАВЛЕНИЯ РИСКАМИ В ЛОГИСТИКЕ С ИСПОЛЬЗОВАНИЕМ ЦИФРОВЫХ ТЕХНОЛОГИЙ

***Аннотация.** В эпоху глобальных сбоев в цепочках поставок оптимизация процессов управления рисками в логистике имеет решающее значение для повышения операционной устойчивости и эффективности принятия решений. В данной статье исследуется внедрение цифровых технологий, в частности прогнозной аналитики, цифровых двойников и моделей оценки рисков на основе искусственного интеллекта, для выявления, оценки и снижения рисков в логистике. Для демонстрации количественного эффекта от внедрения цифровых технологий приводится пример среднего логистического провайдера, работающего в Центральной Азии. В исследовании используется гибридная методология, сочетающая анализ видов и последствий отказов (FMEA) с моделированием по методу Монте-Карло для оценки вероятностных последствий задержек поставок, поломок транспортных средств и заторов на складах.*

Результаты показывают, что после внедрения прогнозной платформы на базе искусственного интеллекта риск снизился на 37%, а оперативность цепочки поставок выросла на 21%. Кроме того, среднее время задержки доставки сократилось с 3,5 до 2,2 часа, а индекс приоритета риска (RPN) для ключевых логистических рисков снизился с 216 до 136. Это демонстрирует значительную ценность цифровизации для повышения точности оценки рисков и оптимизации логистических операций в условиях неопределенности. Исследование завершается стратегическими рекомендациями по интеграции цифровых инструментов в логистические рабочие процессы с акцентом на масштабируемость и адаптируемость для компаний, работающих в сложных условиях риска.

***Ключевые слова:** управление рисками, логистика, цифровые технологии, прогнозная аналитика, цифровой двойник, моделирование методом Монте-Карло, оптимизация цепочки поставок.*

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