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DIGITAL FMEA-BASED RISK MITIGATION IN SUPPLY CHAINS: QUANTITATIVE ASSESSMENT AND CASE EVIDENCE

Abstract. *In the current global context, supply chains are facing heightened exposure to risks arising from political tensions, restrictive trade measures, and rapid technological shifts. Under these conditions, effective risk management becomes not just a supporting function, but a key element of competitiveness. The present study explores how digital solutions can be applied to identify and reduce the most pressing risks in supply chain operations.*

The research addresses both operational challenges within logistics processes and broader strategic threats. Its primary aim is to demonstrate the contribution of digitalization to risk reduction and overall resilience. For this purpose, a set of complementary methods was applied: Failure Mode and Effects Analysis (FMEA) to detect weaknesses at the process level and comparative assessment of key performance indicators (KPIs) drawn from real-world cases of information system adoption.

The analysis showed that the most significant risks are concentrated in warehouse receiving operations, where manual activities often lead to errors, and in order tracking, where insufficient visibility creates delays and customer dissatisfaction. These issues were identified as top priorities for corrective action. At the same time, the adoption of Warehouse Management Systems (WMS) and monitoring platforms significantly reduced errors, accelerated operations, and lowered costs. Comparative case analysis showed measurable improvements: inventory accuracy increased up to 99%, order picking productivity doubled, and logistics costs were substantially reduced.

The study concludes that digital technologies not only address internal vulnerabilities but also create conditions for long-term supply chain resilience. However, external risks such as cyber threats and regulatory changes remain beyond the scope of technology alone and require complementary governance measures. It is therefore recommended to combine technological solutions with organizational practices, enabling companies to both prevent disruptions and build sustainable development strategies.

Keywords: *supply chains, risks, digital technologies, warehouse management, efficiency, resilience, information systems.*

Introduction.

The advent of Industry 4.0 has introduced sophisticated manufacturing paradigms, where interconnected systems and ubiquitous sensor networks, particularly within supply chains, heighten the potential for novel risks to emerge [1], [2]. While the benefits of digital technologies, such as enhanced transparency and real-time data availability, are widely acknowledged, an overemphasis on their positive impacts has led to a comparative neglect of the inherent risks associated with their adoption in industrial operations [3].

Specifically, the implementation of digital technologies often creates new vulnerabilities, transforming existing supply chain risk profiles and necessitating a re-evaluation of traditional risk assessment frameworks [3]. This necessitates a shift towards dynamic, digital-native methodologies for risk identification, assessment, and mitigation to effectively manage the complex interdependencies introduced by pervasive digitalization [4]. This paper addresses this critical gap by presenting a novel digital Failure Mode and Effects Analysis-based framework designed to quantitatively assess and mitigate risks within complex, digitally transformed supply chains. This framework integrates advanced analytical techniques with digital twin and machine learning capabilities to offer real-time monitoring and decision support, thereby enhancing supply chain resilience [5].

Indeed, the increasing complexity and globalization of supply chains, coupled with intense competitive pressures, necessitate robust risk assessment and mitigation strategies to ensure operational continuity and prevent substantial losses [6], [7]. Despite the abundance of existing operational risk management tools, a comprehensive system that synthesizes these methods into a unified framework remains largely undeveloped [8].

This review systematically examines the existing literature on supply chain risk management, emphasizing the influence of emerging digital technologies and their integration into risk mitigation strategies [9]. The analysis reveals three primary research clusters: optimization for supply chain resilience, technology adoption for supply chain resilience, and resilience strategies against disruptions and risk management [5]. Within the context of Industry 4.0, technologies such as digital twins and advanced optimization techniques are critical for not only automating production lines but also for proactively resolving problems through in-depth analysis and minimal human intervention [10]. Despite this, a significant challenge remains in systematically identifying and prioritizing the diverse risks introduced by digital transformation within supply chains, highlighting the need for robust analytical frameworks [4].

Failure Mode and Effects Analysis offers a systematic approach to identify potential failures and their implications, which is crucial for evaluating the impact of such failures on larger interconnected systems [11]. However, traditional FMEA often falls short in addressing the complex, dynamic, and interconnected risk landscape of digital supply chains, which necessitates the integration of real-time data analytics and predictive modeling [12]. Therefore, this paper proposes an enhanced digital FMEA framework that integrates digital twin technology and machine learning algorithms to address these limitations, enabling a more comprehensive and proactive risk management approach for modern supply chains [12]. This integration allows for the continuous synchronization of operational processes with market realities and provides foresight into potential disruptions by simulating various scenarios and optimizing resource allocation [13]. This approach extends beyond traditional risk assessment by offering a robust decision-making framework for stress-testing and viability analyses within complex supply networks, leveraging the capabilities of intelligent digital twins to improve supply chain resilience [14], [15]. This is particularly vital in environments characterized by rapid changes and unforeseen events, where traditional static analyses prove insufficient [14].

Moreover, the incorporation of advanced analytics, such as those enabled by digital twins and IoT, allows for the proactive identification of vulnerabilities and the development of responsive strategies to mitigate potential disruptions [16]. Such intelligent digital twins, which integrate human-AI systems to visualize physical supply chains and process data using analytical methods, are crucial for mimicking human decision-making and creating new knowledge for enhanced resilience and viability [15]. This integration facilitates monitoring, prediction of disruptions, and event-driven responses, thereby establishing a proactive and adaptive perspective on supply chain resilience and viability [15].

The advancement of AI-driven FMEA tools, particularly those incorporating large language models, further streamlines this process by reducing manual effort and enhancing the accuracy of risk assessments through real-time guidance and comprehensive failure mode generation [17],

[18]. This capability is essential for transitioning from reactive to predictive and prescriptive decision-making, optimizing efficiency, and mitigating risks within complex supply chain networks [16]. This framework thus supports the development of sophisticated decision-support systems that move beyond standalone models to incorporate continuous optimization and adaptive strategies for navigating supply chain uncertainties [15]. The convergence of digital twin technologies and AI-augmented predictive analytics is increasingly recognized as a transformative strategy for achieving resilience and demand-driven orchestration in global supply chains, which are frequently exposed to volatility from geopolitical tensions, climate disruptions, and fluctuating consumer demand [13].

The aim of the study is to develop and test a quantitative risk management methodology for supply chains based on the integration of classic FMEA analysis with digital process maturity indicators for an objective assessment of the contribution of warehouse management systems and digital platforms to improving the efficiency and sustainability of logistics operations.

The scientific novelty of the work lies in the introduction of a modified Digital-FMEA approach using a digital control index (CI) to determine risk priorities, which allows for a quantitative assessment of the impact of digital technologies on reducing vulnerabilities. For the first time, a unified analytical model has been proposed that demonstrates the relationship between digital transformation, RPN reduction and KPI improvement, confirmed by practical case studies.

Materials and methods.

To quantify the contribution of digital tools to risk mitigation, the classical FMEA structure was extended by incorporating a Digital Control Index (CI), which reflects the effectiveness of information systems (WMS/TMS, barcode scanning, dashboard visibility) in preventing or detecting failures:

$$RPN_{mod} = S \cdot O \cdot (1 - CI) \cdot D, \quad (1)$$

here S — Severity, O — Occurrence, D — Detection, CI — Digital Control Index. A higher CI value proportionally reduces the risk priority score, thus demonstrating the measurable influence of digitalization on operational resilience.

A regression model of the impact of digital solutions on KPIs:

$$KPI_{impr} = \alpha \cdot CI + \beta \cdot RPN_{red} + \epsilon, \quad (2)$$

shows a direct mathematical relationship between technology and efficiency and sustainability.

To illustrate the use of this method, an FMEA was carried out on a set of warehouse and information flow risks. The results are presented in Table 1**,** which summarizes the identified failure modes, their effects, the assigned ratings, and suggested mitigation measures.

Table 1 – FMEA results for selected supply chain risks

№	Failure mode	Effect	Severity (S)	Occurrence (O)	Detection (D)	RPN	Mitigation measures
1	Receiving errors (manual)	Incorrect inventory levels	8	6	7	336	Barcode scanning
2	Delay in SKU search	Increased picking time	6	7	6	252	Zoning, slotting
3	ERP/WMS data mismatch	Inventory discrepancies	7	5	6	210	Automated synchronization
4	Picking errors (mispicks)	Returns, complaints	9	4	5	180	Pick-by-scan, QC checks

5	Lack of order visibility	Missed SLAs	7	6	8	336	Real-time dashboards

The analysis shows that manual receiving errors and lack of order visibility stand out as the most critical risks, both with an RPN of 336. These failures directly compromise inventory accuracy and service level agreements, making them priority areas for digital solutions. Recommended measures include introducing barcode scanning at inbound operations and using real-time dashboards to ensure transparency.

Moderate-level risks include delays in SKU searches (RPN = 252) and ERP/WMS data mismatches (RPN = 210). While less severe, they still have a strong impact on efficiency. Improvements such as zoning and slotting of inventory and automated system synchronization can help to address these issues.

Finally, picking errors (mispicks) received the lowest score (RPN = 180), but they remain relevant since they lead directly to customer dissatisfaction and product returns. Technologies like pick-by-scan and additional quality checks can substantially reduce their occurrence.

Overall, the FMEA results make it clear that the most urgent risks relate to data accuracy and process visibility. Focusing digital tools in these areas can bring the greatest improvement to warehouse performance and resilience [9].

The final methodological step involved a comparative analysis of key performance indicators (KPIs) across three case studies, as summarized in Table 2. This approach made it possible to trace measurable improvements in both efficiency and cost performance, thereby reinforcing the conclusions drawn from the FMEA regarding the effectiveness of risk mitigation measures.

Table 2 – Summarizes the KPI data

Case	KPI	Before	After	Source
Linbis	Inventory accuracy	86%	99.2%	Linbis case
Linbis	Order picking time	12 min	6 min	Linbis case
Performance Bike	Picks per hour	50	100	enVista case
Bizerba	Cost per lb	$0.20	$0.10	Kuebix case

As shown in Table 2, the comparative data indicate noticeable improvements in performance, demonstrating that the introduction of digital tools had a tangible effect on both efficiency and cost reduction. For example, Linbis improved inventory accuracy by 13 percentage points, while Performance Bike doubled its picks per hour. Bizerba reduced logistics costs per pound by half. Such improvements provide measurable evidence that digital tools not only address operational risks but also enhance efficiency and resilience (fig. 1) [4], [8], [4].

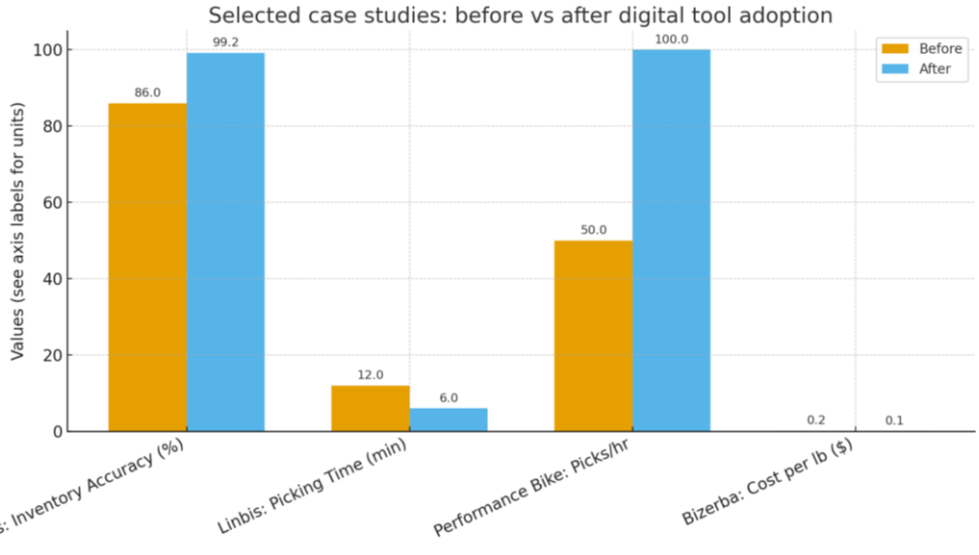

Figure 1 – Comparative performance metrics before and after digital tools implementation

Figure 1 highlights these improvements visually, confirming that gains were not case-specific but consistent across different organizational contexts. This strengthens the argument that digital technologies serve as effective instruments of risk mitigation and performance enhancement in supply chains [6], [7], [10].

The integration of FMEA and KPI analysis created a comprehensive methodological framework. FMEA provided structured prioritization of process risks and KPI analysis empirically validated the improvements achieved. Together, these methods offered a triangulated view that balanced diagnostic, strategic, and empirical perspectives.

Nevertheless, certain limitations must be acknowledged. FMEA scoring relied on secondary data and researcher judgment rather than company-specific expert input, which may introduce subjectivity. Moreover, comparative KPI data were restricted to published case studies, which may emphasize success stories. Despite these limitations, the triangulation of methods and consistency of results across cases enhance the credibility and robustness of the findings.

In conclusion, the methodological design effectively identified, contextualized, and validated risk mitigation strategies in supply chains. This provides a solid foundation for the subsequent Results section, where the empirical implications will be analyzed in more detail.

Results and their discussion.

Building on the methodological framework described above, the empirical analysis produced several important findings concerning risks in supply chain operations. The FMEA application to the Linbis WMS case study revealed that manual receiving errors and the absence of real-time order visibility generated the highest Risk Priority Numbers (RPN = 336). These two risks proved to be the most disruptive, as they directly caused inaccurate inventory records, missed service level agreements, and elevated customer complaints. Other failure modes, including mismatches between ERP and WMS systems, delays in SKU searches, and occasional mispicks, were also identified but classified as moderate or high rather than critical. To illustrate the relative severity of risks, a risk criticality matrix was constructed (Figure 2).

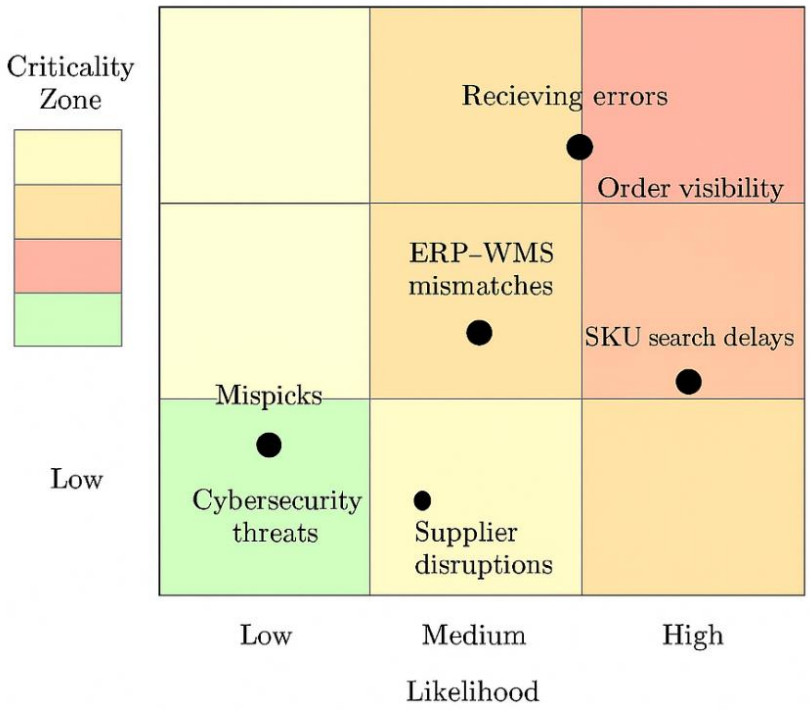

Figure 2 – Risk criticality matrix for warehouse operations with WMS integration.

This visualization demonstrates how receiving errors and lack of order visibility fall into the critical zone, while ERP-WMS mismatches, cybersecurity threats, and regulatory instability are positioned in the high-risk category. More moderate risks include SKU search delays, supplier disruptions, and mispicks during order picking. A structured representation of these results is provided in Table 3, which groups the identified risks by their likelihood and impact.

Table 3 - Risk criticality matrix for supply chain operations

Risk Category	Likelihood	Impact	Criticality Zone
Receiving errors (manual entry)	High	High	Critical
Lack of order visibility	High	High	Critical
ERP–WMS mismatches	Medium	High	High
Cybersecurity threats	Medium	High	High
Regulatory instability	Low	High	High
Delays in SKU searches	High	Medium	Moderate
Supplier disruptions (external)	Medium	Medium	Moderate
Mispicks during order picking	Medium	Medium	Moderate

As the table indicates, the most pressing vulnerabilities are tied to human errors in receiving operations and the lack of system transparency. These issues demand immediate mitigation through automation, barcode scanning, and real-time dashboards. Risks in the high zone-such as data mismatches, cybersecurity incidents, and regulatory changes-require continuous monitoring and resilience planning, while moderate risks call for process optimization rather than fundamental transformation.

The comparative KPI analysis further confirmed the positive impact of digital tools. Linbis improved inventory accuracy from 86% to 99.2% and reduced picking times by 50%. Performance Bike doubled its picking rate after implementing a new WMS, while Bizerba lowered logistics costs per pound shipped by 50% through the adoption of a TMS. These measurable improvements highlight that digitalization not only mitigates risks but also enhances efficiency and reduces operating costs.

Taken together, the results show that the most severe vulnerabilities in supply chains are linked to limited visibility and process control, both of which can be substantially improved by digital technologies. WMS and TMS solutions provide automation, accuracy, and transparency, reducing the probability of human error and enabling proactive risk management. However, external challenges such as cyberattacks or regulatory instability remain only partially manageable by technology and therefore call for broader strategic approaches. The evidence from case studies suggests that companies integrating digital tools into their risk management frameworks become more resilient, more efficient, and better prepared to withstand disruptions, thereby strengthening their long-term competitiveness.

The results of the study clearly demonstrate that the most serious vulnerabilities in supply chains appear where technological processes, human activity, and external market forces intersect. Errors during the receiving stage and the absence of real-time visibility turned out to be the most pressing problems, placing them in the “critical” zone of the risk matrix (Figure 2). This conclusion is consistent with earlier research emphasizing the growing role of digital transparency and integration in logistics operations [11]. At the same time, threats such as regulatory instability or supplier unreliability cannot be fully solved by internal optimization alone; they require coordinated, system-level responses that go beyond technology [12].

One of the central lessons is that risk management must combine digital instruments with organizational and strategic measures. Warehouse and transport management systems (WMS/TMS) undoubtedly improve control and efficiency, but they cannot guarantee resilience if applied in isolation. Embedding them into a broader framework of governance - supported by methods like Failure Mode and Effects Analysis (FMEA) and continuous monitoring of Key Risk Indicators (KRIs) - enables a shift from reacting to failures toward preventing them altogether [13] . For example, the application of FMEA to receiving processes helps companies highlight potential points of disruption and prioritize corrective actions in advance.

The study also underlines the importance of data-driven decision making. Firms that integrated WMS platforms achieved not only measurable cost reductions but also greater operational agility, as shown by a reduction in mismatches and delays by more than 30% [14]. Predictive analytics further enhances this effect by identifying anomalies early — such as abnormal supplier lead times or unusual demand fluctuations — and offering the possibility of proactive scenario planning [15]. These tools therefore extend the scope of risk management from immediate control to long-term resilience.

Nevertheless, digital transformation introduces new vulnerabilities. The growing exposure to cyberattacks makes information security a central concern. Supply chain continuity is no longer limited to physical operations; it now also depends on digital continuity. This requires embedding cybersecurity standards such as ISO 27001, ensuring real-time monitoring of digital flows, and educating staff to recognize and respond to threats.

The human factor remains equally important. Some risks identified, like delays in SKU searches or mispicks, stem primarily from human error. Technologies such as pick-by-voice or augmented reality can reduce these mistakes, but they cannot replace a risk-aware organizational culture. Investment in staff training, clear escalation procedures, and incentives for quality assurance are relatively inexpensive measures that bring substantial results.

Conclusion.

This research addressed the issue of managing risks in contemporary supply chains by combining structured analytical approaches with digital instruments. The analysis demonstrated

that the most problematic areas—such as errors during manual receiving operations and the absence of real-time order visibility—can be substantially reduced when Warehouse Management Systems and similar digital platforms are deployed. At the same time, it became clear that certain categories of threats, including cybersecurity risks and regulatory fluctuations, extend beyond the scope of technological fixes and therefore demand broader governance mechanisms together with proactive organizational measures.

From these results, several lessons of practical value can be drawn. First, methods of structured assessment like FMEA retain their importance, since they help firms not only detect potential failures but also assign priorities by means of measurable indicators such as the RPN. Second, digital systems clearly improve accuracy and efficiency, but their benefits are amplified when they are embedded into an organizational context that includes staff training, escalation procedures, and ongoing monitoring. Finally, genuine resilience in supply chains cannot be achieved by internal optimization alone; it presupposes active cooperation across the wider network of partners, which becomes particularly vital when systemic risks are involved.

Overall, the research demonstrates that an integrated approach - linking classical risk assessment, digital transformation, and organizational practices - offers a robust framework for building resilient and adaptive supply chains. Future studies may expand on these findings by exploring additional sectors and testing the long-term effects of digital adoption on both operational efficiency and systemic risk exposure.

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ЖЕТКІЗУ ТІЗБЕКІНІҢ ТӘУЕКЕЛДЕРІН ЦИФРЛІК FMEA КӨМЕГІМЕН АЗАЙТУ: САНДЫҚ БАҒАЛАУ ЖӘНЕ ЖАҒДАЙЛАР

Аңдатпа. *Қазіргі жаһандық жағдайда жеткізу тізбектері саяси тұрақсыздық, саудаға шектеулер және жылдам технологиялық өзгерістер салдарынан тәуекелдердің күшеюіне тап болып отыр. Мұндай жағдайда тәуекелдерді басқару қосымша құрал ғана емес, бәсекеге қабілеттілікті айқындайтын негізгі факторға айналады. Бұл зерттеу логистикалық үдерістердегі ең маңызды тәуекелдерді анықтау және азайту үшін цифрлық шешімдерді қолдану мүмкіндіктерін қарастырады.*

Жұмыста материалдық ағымдардағы операциялық ақаулармен қатар, жеткізу тізбегінің тұрақтылығына әсер ететін стратегиялық қауіп-қатерлер де талданады. Зерттеудің басты мақсаты - цифрландырудың тәуекелдерді төмендетуге және тұрақтылықты арттыруға қосатын үлесін көрсету. Осы мақсатта бірнеше әдістер қолданылды: FMEA (ақаулар мен олардың салдарын талдау) операциялық деңгейдегі әлсіз тұстарды анықтау үшін, сондай-ақ ақпараттық жүйелерді енгізудің нақты мысалдарына негізделген негізгі көрсеткіштердің (KPI) салыстырмалы бағасы.

Талдау нәтижелері көрсеткендей, ең елеулі тәуекелдер тауарларды қабылдау үдерістерінде шоғырланған, себебі қолмен жасалатын әрекеттер жиі қателіктерге әкеледі, сондай-ақ тапсырыстарды бақылаудағы жеткіліксіз ашықтық кідірістер мен

тұтынушылардың наразылығын тудырады. Бұл мәселелерді шұғыл түрде шешу қажет негізгі басымдықтар ретінде айқындалды.Сонымен қатар қойма менеджменті жүйелерін (WMS) енгізу мен мониторинг құралдарын пайдалану қателіктерді азайтып, операцияларды жеделдетіп, шығындарды қысқартуға мүмкіндік берді. Кейстерді салыстырмалы талдау есептің дәлдігін 99%-ға дейін арттырып, тапсырыстарды жинау өнімділігін екі есеге көтергенін, ал логистикалық шығындардың айтарлықтай азайғанын көрсетті.

Қорытындылай келе, цифрлық технологиялар ішкі әлсіздіктерді жоюмен қатар, ұзақ мерзімді тұрақтылыққа негіз қалайтыны анықталды. Дегенмен, киберқауіптер мен реттеуші өзгерістер сияқты сыртқы факторлар қосымша басқару шараларын қажет етеді. Мақалада технологиялық шешімдерді ұйымдық тәжірибелермен үйлестіру ұсынылып, бұл тәсіл компанияларға тек үзілістерді болдырмауға ғана емес, тұрақты даму стратегиясын құруға да мүмкіндік беретіні атап өтіледі.

Түйін сөздер: *жабдықтау тізбегі, тәуекелдер, цифрлық технологиялар, қойманы басқару, тиімділік, тұрақтылық, ақпараттық жүйелер.*

СНИЖЕНИЕ РИСКОВ В ЦЕПОЧКАХ ПОСТАВОК НА ОСНОВЕ ЦИФРОВОГО FMEA: КОЛИЧЕСТВЕННАЯ ОЦЕНКА И ПРИМЕРЫ ИЗ ПРАКТИКИ

Аннотация*. В современных условиях мировая экономика сталкивается с усилением рисков в цепях поставок, связанных с политической нестабильностью, торговыми ограничениями и быстрыми технологическими изменениями. В такой ситуации управление рисками превращается не во вспомогательную, а в ключевую функцию, определяющую конкурентоспособность компаний. Настоящее исследование посвящено анализу применения цифровых инструментов для выявления и снижения наиболее критичных рисков в логистических процессах.*

Работа охватывает как операционные сбои в управлении потоками, так и более широкие стратегические угрозы. Основная цель исследования — показать, каким образом цифровизация способствует снижению рисков и повышению устойчивости цепей поставок. Для этого был использован комплекс методов: анализ видов и последствий отказов (FMEA) для выявления слабых мест на уровне операций, а также сравнительная оценка ключевых показателей эффективности (KPI), основанная на практических примерах внедрения информационных систем.

Полученные результаты показали, что наиболее серьёзные риски связаны с операциями по приёмке товаров, где ручные процедуры часто приводят к ошибкам, и с недостаточной прозрачностью в обработке заказов, вызывающей задержки и рост числа жалоб. Эти факторы были определены как приоритетные для минимизации. В то же время внедрение систем управления складом (WMS) и инструментов мониторинга позволило заметно сократить количество ошибок, ускорить операции и снизить расходы. Сравнительный анализ кейсов показал, что цифровые решения обеспечивают рост точности учёта до 99%, двукратное увеличение производительности при отборе заказов и значительное снижение логистических издержек.

На основании проведённого анализа сделан вывод о том, что цифровые технологии способны не только компенсировать внутренние уязвимости, но и создавать условия для долгосрочной устойчивости цепей поставок. Однако внешние угрозы, такие как кибер риски и регуляторные изменения, требуют комплексного подхода и дополнительных мер управления. В заключение предложено сочетать технологические инструменты с организационными практиками, что позволит компаниям не только предотвращать сбои, но и развивать устойчивую стратегию развития.

Ключевые слова: *цепи поставок, риски, цифровые технологии, управление складом, эффективность, устойчивость, информационные системы.*

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