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APPLICATION OF RISK PREDICTION SYSTEMS IN THE FOREIGN ECONOMIC ENVIRONMENT: METHODOLOGICAL FOUNDATIONS AND TRANSFORMATION VECTORS IN THE CONTEXT OF INDUSTRY 4.0

ЗАСТОСУВАННЯ СИСТЕМ ПРОГНОЗУВАННЯ РИЗИКІВ У ЗОВНІШНЬОЕКОНОМІЧНОМУ СЕРЕДОВИЩІ: МЕТОДОЛОГІЧНІ ЗАСАДИ ТА ВЕКТОРИ ТРАНСФОРМАЦІЙ В КОНТЕКСТІ ІНДУСТРІЇ 4.0

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The purpose of this study is to analyze the methodological foundations and transformation vectors of risk forecasting systems in the foreign economic environment under the conditions of Industry 4.0. The research highlights existing methodological approaches to risk management from statistical models to hybrid systems that combine artificial intelligence, big data analytics, blockchain, digital twins and foresight technologies turning forecasting into a tool of strategic anticipation. The influence of Industry 4.0 technologies is analyzed, demonstrating that the integration of sensor networks, cloud services, edge analytics and AI forms a multi-level ecosystem in which speed, accuracy and reliability mutually reinforce each other. It is proven that the combination of digital twins and blockchain enables the transition toward an integrated trust infrastructure. The study presents international experience in applying risk forecasting systems in logistics, trade and financial sectors, showing the effectiveness of flexible, self-learning and cross-sector synchronized platforms. Measures have been developed to adapt this experience to Ukraine, combining data centralization, risk monitoring, digital modernization, simulation forecasting and generative intelligence. Such an approach integrates Ukraine into the global risk management ecosystem, enhancing its resilience and transparency. Transformation vectors of risk forecasting systems have been formulated, encompassing generative AI, quantum computing, edge analytics, simulators, the Internet of Everything, hyper-personalized platforms, as well as preventive and ethical models. It is demonstrated that their synergy ensures the transition from local analytics to global cognitive ecosystems capable of adapting to and preventing risks in real time.

Keywords: methodological foundations of risk management, risk prediction systems, foreign economic environment, international experience, Industry 4.0, development vectors, digital transformation.

Метою даного дослідження є поглиблений аналіз методологічних засад та векторів трансформації систем прогнозування ризиків у зовнішньоекономічному середовищі в умовах Індустрії 4.0. У процесі роботи виокремлено основні методологічні підходи до управління ризиками від статистичних моделей до інтегрованих гібридних систем, що поєднують технології Індустрії 4.0 та розширюють межі традиційного прогнозування, перетворюючи його на динамічний інструмент стратегічного випередження. Проаналізовано вплив технологій Індустрії 4.0 на архітектуру систем прогнозування ризиків і доведено, що інтеграція сенсорних мереж, хмарних сервісів, edge-аналітики та систем штучного інтелекту формує багаторівневу екосистему, у якій швидкість обробки, точність моделей і достовірність даних взаємно підсилюють одна одну. Міжнародний досвід використання систем прогнозування ризиків у логістичних, торговельних і фінансових секторах засвідчив, що ключовим чинником успіху є створення гнучких платформ, здатних до самонавчання, обміну даними та міжсекторальної синхронізації, що формує основу стійкої глобальної взаємодії в умовах невизначеності. Розроблено комплекс заходів адаптації міжнародного досвіду до зовнішньоекономічного контексту України, який передбачає поєднання стратегічної централізації даних, оперативного моніторингу ризиків, цифрової модернізації інфраструктури, симуляційного прогнозування у виробничих системах та впровадження генеративного штучного інтелекту у фінансові й державні сервіси. Реалізація запропонованих заходів сприятиме технологічній та інституційній інтеграції України у глобальну екосистему управління ризиками, підвищуючи її стійкість до зовнішніх викликів і прозорість зовнішньоекономічних процесів. Сформовано перспективні вектори трансформації систем прогнозування ризиків, які охоплюють технології генеративного штучного інтелекту, квантових обчислень, периферійної аналітики, комплексних симуляторів, інтернет усього, гіперперсоналізованих платформ, превентивних та етичних моделей. Доведено, що синергія цих напрямів забезпечить перехід від локальних аналітичних моделей до глобальних когнітивних екосистем, здатних адаптуватися, навчатися й запобігати ризикам у режимі реального часу.

Ключові слова: методологічні засади управління ризиками, системи прогнозування ризиків, зовнішньоекономічне середовище, міжнародний досвід, Індустрія 4.0, вектори розвитку, цифрова трансформація.

Formulation of the problem. The system of international economic relations currently functions under conditions of multidimensional turbulence, where the interconnectedness of financial flows, geopolitical tension and asymmetry in access to technologies create preconditions for a constant increase in risks and unpredictable destabilizing influences. Under such circumstances, the question arises regarding the effectiveness of existing approaches to risk management and forecasting. At the same time, traditional approaches to risk management, which are often based on static models and limited data, prove to be ineffective due to their low level of adaptation to new crisis conditions and weak predictive parameters. Therefore, the main problem of this study lies in the effective control of external environment risks, most of which arise independently of the enterprise's actions, requiring the implementation of digital systems for early risk forecasting and preventive risk management capable of processing large volumes of heterogeneous data in real time.

Analysis of recent research and publications. The analysis of scientific research in the context of risk forecasting systems indicates an evolution from the use of statistical models to the formation of hybrid digital systems. Thus, the classical works of Box G., Jenkins G. [1] initiated ARIMA methods for time series analysis, while subsequent studies by Akgün O. B. [2] proved the effectiveness of GARCH approaches combined with machine learning algorithms for assessing financial market volatility. A significant contribution was made by Rumelhart D. E., Hinton G. E., Williams R. J. [3], who laid the foundations of deep learning, later developed in the Transformer (Vaswani A.) [4] and Informer (Zhou H.) [5] models, which made it possible to process long time sequences with high accuracy. The integration of Big Data into forecasting, initiated by the works of Dean J., Ghemawat S. [6] and confirmed by analytical reviews by Tang L. [7], enabled the processing of multidimensional data arrays in real time. A new level of development was ensured by simulation technologies and digital twins (Grieves M., Vickers J. and Qi Q.) [8; 9], which allow modeling risk scenarios in a virtual environment, as well as blockchain technologies (Nakamoto S. and Wang Y.) [10; 11], which ensure data transparency and reliability in international trade. Hybrid forecasting models (Zhang G. and García-Medina A.) [12; 13], which combine neural networks with economic-mathematical approaches, also play an important role, as do foresight Delphi methods (Dalkey N., Helmer O. and Culot G.) [14; 15], which take expert assessments into account when forming development scenarios. As a result, under Industry 4.0 conditions, risk forecasting systems are transforming from retrospective analysis to anticipatory forecasting based on integrated digital technologies. However, issues related to defining the foundations of these methodological approaches, the impact of Industry 4.0 technologies on them, the formation of holistic risk forecasting models based on international cases for further adaptation to the foreign economic context of Ukraine and the development of research directions in the global context have not yet been explored.

Highlighting previously unresolved parts of the overall problem. Despite the existence of a thorough analysis of the methodological foundations and modern approaches to risk forecasting, several key issues remain unresolved in the scientific literature, which are gaining particular relevance under the conditions of Industry 4.0. Firstly, the direct impact of digital technologies on the architecture of risk forecasting systems in the foreign economic environment has not been sufficiently studied, which limits their practical application for improving accuracy and adaptability. Secondly, there are no systematic developments for generalizing and adapting international experience in the use of digital platforms and predictive analytics in the form of practical recommendations for Ukrainian enterprises and state structures, which hinders the formation of an effective model of digital risk management in the national environment. Thirdly, comprehensive vectors of future transformation of risk forecasting systems that would integrate them into a unified development framework have not been formulated. Solving these issues would make it possible to move from descriptive characteristics to the creation of a holistic methodology for risk forecasting, which would ensure improved data standardization, transparency of foreign economic processes and the implementation of adaptive digital models of risk management under conditions of global turbulence.

Formulation of the article's objectives. The purpose work is a comprehensive study of the methodological foundations and transformation vectors of risk forecasting systems in the foreign economic environment, taking into account the development of Industry 4.0 technologies and existing international experience. Within the framework of this study, the following The tasks of the work were identified: 1. To analyze the methodological foundations of risk forecasting systems in the foreign economic environment in the context of Industry 4.0; 2. To study the impact of Industry 4.0 technologies on risk forecasting systems in the foreign economic environment; 3. To analyze international experience in the application of risk forecasting systems in the foreign economic environment in the context of Industry 4.0; 4. To develop measures for adapting international experience in the use of risk forecasting systems in Ukraine in the context of Industry 4.0; 5. To form future transformation vectors of risk forecasting systems in the foreign economic environment in the context of Industry 4.0.

Summary of the main material. The dynamism and unprecedented turbulence of the modern foreign economic environment form a new paradigm of requirements for risk management systems. Traditional forecasting methods, which are mainly based on retrospective analysis, show limited effectiveness under conditions of nonlinear changes and digital transformation of global processes. At the same time, the rapid development of Industry 4.0 technologies not only expands analytical capabilities but also generates new types of risks and uncertainties. This determines both a scientific and practical need to rethink the methodological foundations of risk forecasting and to form adaptive systems capable of effectively responding to the challenges of the new technological order. Therefore, in this context, the systematization and visualization of modern approaches to risk forecasting in foreign economic activity, which are undergoing significant transformations under the influence of Industry 4.0, become relevant. Such an approach will make it possible to form a holistic understanding of the architecture of the modern risk management system and identify its key structural and technological vectors of development, see Figure 1.

Based on the data in Figure 1, a generalization of the methodological foundations of risk forecasting in the foreign economic environment of Industry 4.0 was carried out. It was established that the modern concept is based on the integration of classical economic and mathematical methods with new-generation digital technologies. The work of Box G., Jenkins G. M. [1] initiated ARIMA time series analytics, today, these approaches are evolving into dynamic scenario modeling capable of considering multifactor influences. Akgün O. B. [2] proposed GARCH and VAR methods, which, when combined with machine learning, create a new level of adaptability aimed at effectively analyzing market, currency, or price volatility. Unlike retrospective approaches, modern methodologies are oriented toward risk prediction, which is ensured by big data analytics initiated by Dean J., Ghemawat S. [6] through the MapReduce model, allowing real-time data processing from various sources. As noted by Tang L. [7], big data has become a key resource for intelligent forecasting models, forming the foundation for machine learning, conceptually introduced by Rumelhart D. E., Hinton G. E., Williams R. J. [3] and later developed in modern Transformer and Informer architectures (Vaswani A. [4], Zhou H. [5]), which enable the analysis of long temporal sequences in trade and logistics. A separate group is formed by simulation technologies, particularly digital twins, conceptually justified in the works of Grieves M., Vickers J. [8] and further developed by Qi Q., Tao F., Zuo Y., Zhao D. [9]. They model virtual copies of production processes, logistics chains and predict possible consequences in crisis situations (for example, the blocking of a sea channel). The combination of digital twins with IoT sensors forms cyber-physical systems that correspond to the principles of Industry 4.0, while Blockchain and DLT components, studied in the work of Nakamoto S. [10], transform risk management through decentralization and ensuring data authenticity. For supply chains, this creates transparency and prevents risks (Wang Y., Han J. H., Beynon-Davies P. [11]). The further development of forecasting systems is embodied in hybrid technologies that combine statistics and deep learning, in particular ML methods such as LSTM and GARCH (Zhang G., Patuwo B. E., Hu M. Y. [12], García-Medina A. [13]) confirm their effectiveness in forecasting financial volatility. Within the framework of

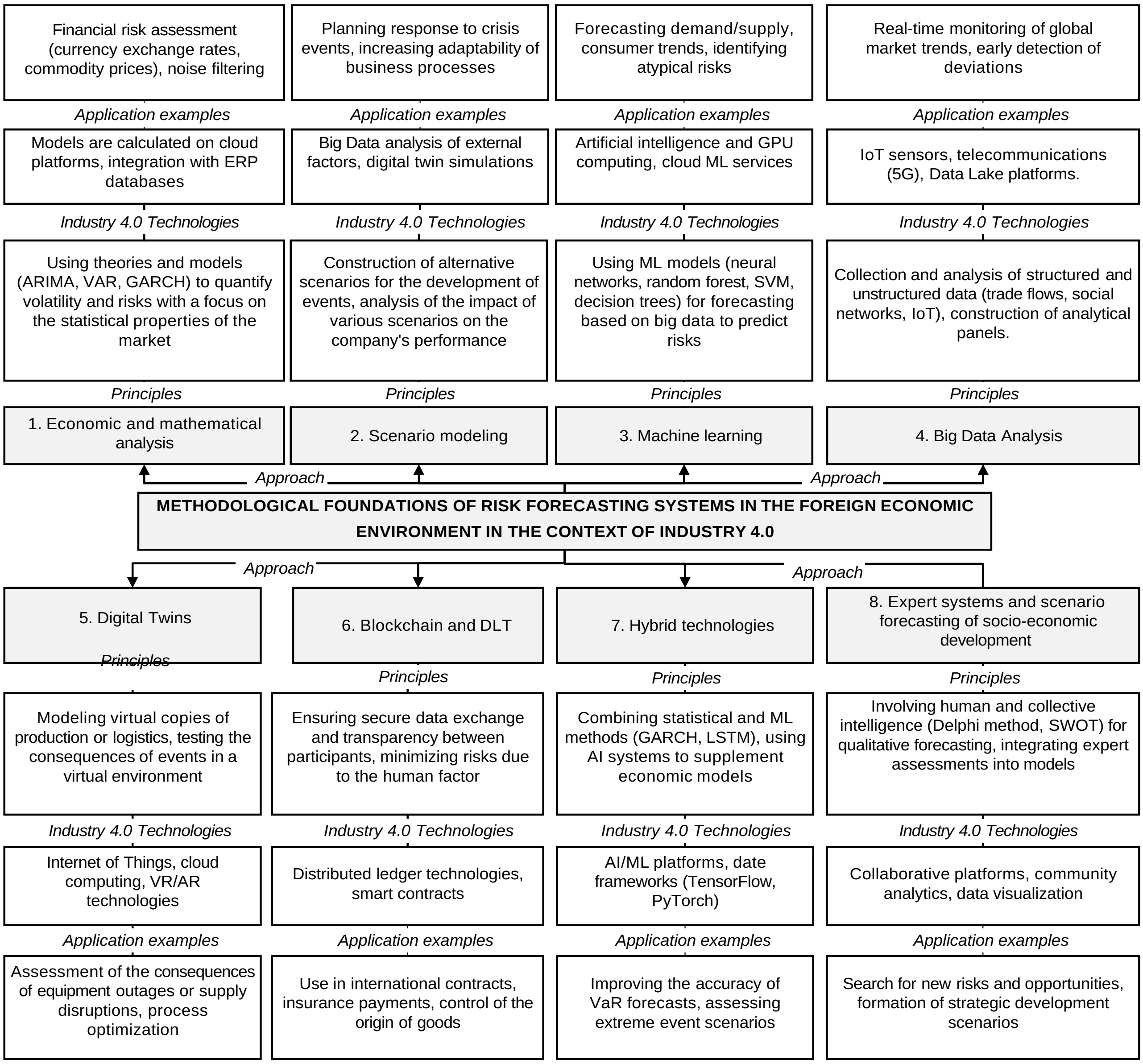

Figure 1. Methodological foundations of risk forecasting systems in the foreign economic environment in the context of Industry 4.0

Source: developed by the author based on the following sources [1; 24; 3; 4; 5; 6; 7; 8; 9; 10; 11; 12; 13; 14; 15] the data in Figure 1, this logic is manifested in the synthesis of economic-mathematical, scenario-based and hybrid approaches, where quantitative models are combined with adaptive algorithms.

The final level consists of expert systems and scenario forecasting of socio-economic development based on the Delphi method (Dalkey N. C., Helmer O. [14]), which take into account human experience and knowledge. As noted by Culot G., Orzes G. [15], they are particularly important under conditions of high turbulence, where analytical models do not always cover geopolitical or behavioral risks.

The next step is to consider the impact of Industry 4.0 technologies on risk forecasting systems in the foreign economic environment, see Figure 2.

Their impact is revealed as a sequential multi-level structure, where sensor networks provide instant and detailed data on the state of processes and objects [16], while big data systems create opportunities for their aggregation and organization (for example, collecting telemetry

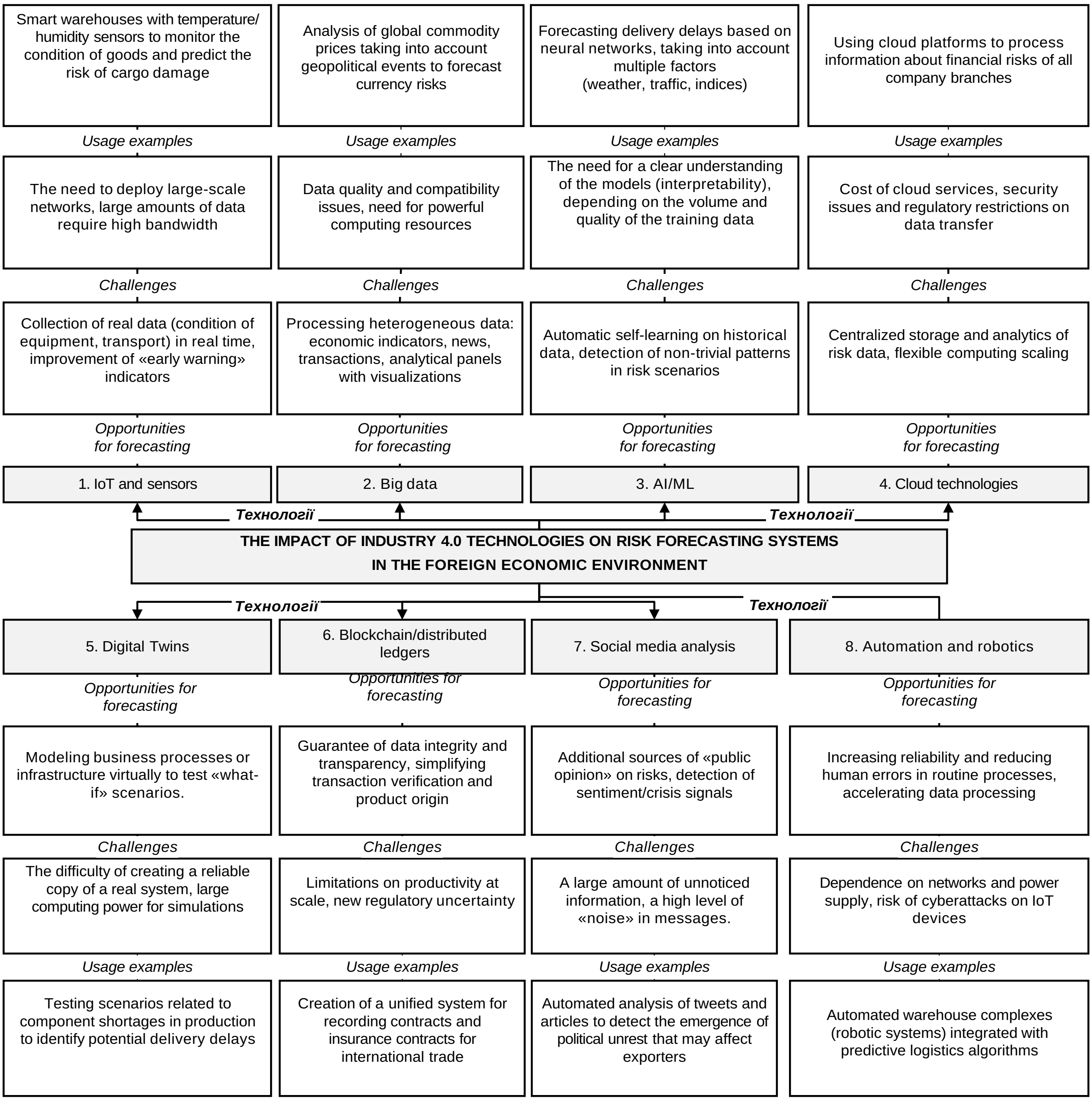

Figure 2. The impact of Industry 4.0 technologies on risk forecasting systems in the foreign economic environment

Source: developed by the author based on the following sources [16; 17; 18; 19; 20; 21; 22] from containers and trucks via Azure IoT Hub or AWS IoT Core, storing streams in Hadoop or Snowflake) [17]. Therefore, the response speed of sensors correlates with the ability of the infrastructure to structure informational chaos and it is at this level that a fundamental balance arises between operational efficiency and system coherence. The analytical layer, represented by artificial intelligence and machine learning, transforms accumulated datasets into predictive models capable of detecting nonlinear and hidden patterns much better than traditional statistics, but these models are less resilient to sudden changes in market conditions and require mechanisms of explainability and validation (training neural networks in TensorFlow followed by interpreting the results using Explainable AI, or applying Watson for supply risk analysis with additional verification on historical cases) [18]. Cloud services provide operational elasticity and orchestration of pipelines, therefore the choice between cloud and edge processing is determined by the requirements for latency, data sovereignty and regulatory context (for example, large-scale model training in AWS or Google Cloud while simultaneously deploying critical analytics elements on edge devices to reduce latency) [19]. Digital twins make it possible to test management decisions in a simulated environment and expand the scenario spaces of analysis, but their accuracy directly depends on the quality of sensor sources and the adequacy of subsystem models (for example, simulating logistics shocks in Siemens Plant Simulation or 3DEXPERIENCE to assess the impact of delays in supply chains) [20], thus they are most effective when closely integrated with real data flows. Distributed ledgers create a trust infrastructure for tracking transactions and product origins and although they contrast with centralized databases due to the immutability of records, under high load the issue of throughput and data tokenization arises (practical options include Hyperledger or R3 Corda for verifying supply chains) [21].

Social network analysis adds a rapid dimension to information risk assessment, as it enables the detection of changes in public sentiment faster than traditional macro indicators, but these signals are often noisy and require filtering and correlation with fundamental metrics (using Brandwatch or Talkwalker for early detection of reputational threats followed by verification through official statistical data) [21]. Automation and robotics transform analytical insights into practical actions; however, their effectiveness depends on the stability of forecasts and the elaboration of exception scenarios (for example, automated RPA processes on UiPath for document processing in supply chains or the use of KUKA robotics to reconfigure production lines under new logistical conditions) [22]. Thus, the forecasting architecture emerges as an ecosystem of mutual compensations, where the speed of sensor data requires structuring of big data [16; 17], the analytical depth of AI demands cloud or hybrid infrastructure [18; 19], the scenario validation of digital twins depends on the quality of input signals [20] and the trust of distributed ledgers must be combined with practical performance [11]. Only under such conditions can the technological ensemble ensure adaptation, loss minimization and well-founded support for management decisions in unstable foreign economic environments.

Let us consider the international experience of applying risk forecasting systems in the foreign economic environment in the context of Industry 4.0 in Figure 3.

The data presented in Figure 3 reflect the international experience in implementing risk forecasting systems in the foreign economic environment in the context of Industry 4.0. The cumulative analysis of the given examples demonstrates that the key development vector is the integration of intelligent technologies into the management of global supply chains, aimed at reducing uncertainty and increasing the adaptability of business processes to fluctuations in the foreign economic situation and the formation of resilient logistical ecosystems. The use of digital platforms such as AWS Supply Chain [24], Maersk Risk Management [25], Pronto PortXchange [26] and Port Digital Twin [27] enables the implementation of predictive recognition and risk prevention. The application of these solutions allows the formation of centralized data repositories that integrate analytical models, flow monitoring and forecasting of potential deviations in transport and logistics processes. Their implementation creates a foundation for systemic interaction among supply chain participants, increasing operational transparency and resilience to external fluctuations.

Particular attention is given to the implementation of predictive analytics algorithms and neural network models capable of identifying complex correlations between economic, infrastructural and natural factors. The cases of FMCG, the Panama Canal and financial markets indicate that artificial intelligence is

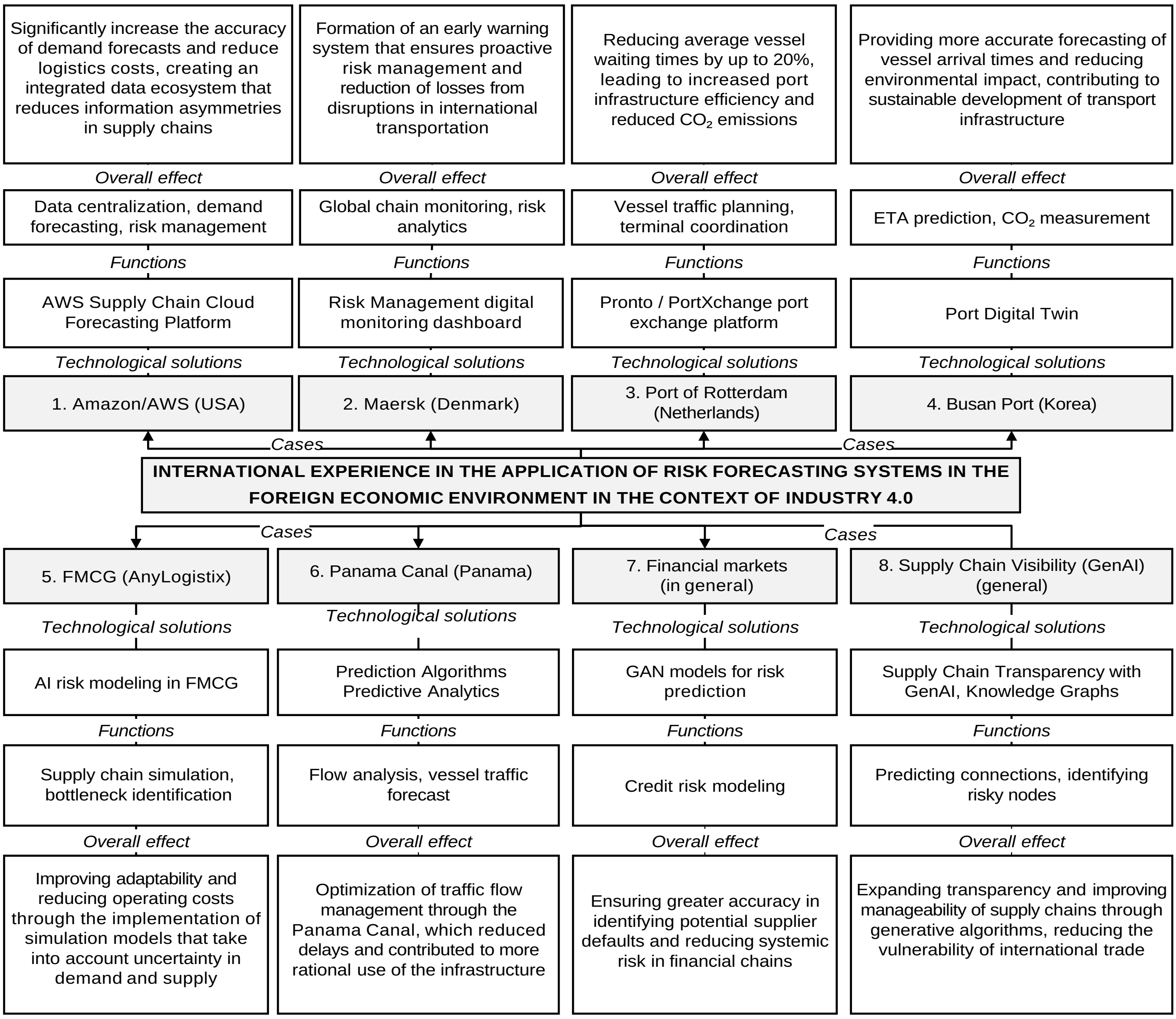

Figure 3. International experience in the application of risk forecasting systems in the foreign economic environment in the context of Industry 4.0

Source: developed by the author based on the following sources [23; 24; 25; 26; 27]

gradually transforming from a conventional analytical tool into a mechanism of strategic forecasting that establishes new standards for risk assessment. The use of GAN models and GenAI solutions [28] with elements of knowledge graphs reflects the evolution from static analytics to cognitive systems capable of self-learning and adaptation under dynamic external influences. The synergistic functioning of digital twins, predictive platforms and intelligent models ensures the transition from fragmented management to a comprehensive ecosystem in which each technological component acts as an interconnected element of a unified logistics network.

The next step is to develop measures for adapting the international experience of using risk forecasting systems in Ukraine in the context of Industry 4.0, see Figure 4.

The first measure involves creating a cloud platform to integrate data from customs, ports and businesses to centralize demand forecasting in global networks, which should improve the accuracy of import and export forecasts and reduce transaction costs through the use of the AWS Supply Chain solution. The second measure focuses on digital monitoring and the introduction of risk panels for exporters and transport companies that will ensure early risk detection and minimization of logistics disruptions, based on CBML, Microsoft Azure machine learning, IoT, GPS, digital twins and big data analytics and unlike the first one, emphasizes responsiveness. The third measure aims at optimizing vessel scheduling and coordinating port operations to reduce downtime and costs, implemented through digital synchronizers such as Pronto or PortXchange within the Port Community System. The fourth measure covers the digital and physical modernization of ports and transport corridors using predictive maintenance, crane monitoring, container stack management and digital twins to improve planning accuracy and reduce environmental risks. Unlike the third measure, it focuses not only on organization but also on eliminating physical bottlenecks. The fifth measure concerns the food industry and proposes simulation-based risk forecasting in FMCG supply chains to minimize supply disruptions and reduce production costs. Compared to the sixth measure, it focuses on internal production processes. The sixth measure targets key foreign economic corridors and applies predictive analytics to forecast vessel movements and manage flows to optimize route capacity, with its technological foundation including IoT sensors, Big Data, cloud computing, digital twins, machine learning, GIS, SCADA, Predictive Maintenance, ERP, MES, blockchain and BI.

Unlike the first and third measures, this approach focuses on international infrastructure coordination. The seventh measure relates to the financial sector and proposes integrating generative algorithms into banking platforms to assess partnership and credit risks using GAN algorithms, Hopsworks, GPU accelerators and anomaly detection tools. Its distinctive feature is its focus not on physical or logistical nodes but on financial risk signals. The eighth measure focuses on public procurement and monitoring through the use of generative AI, knowledge

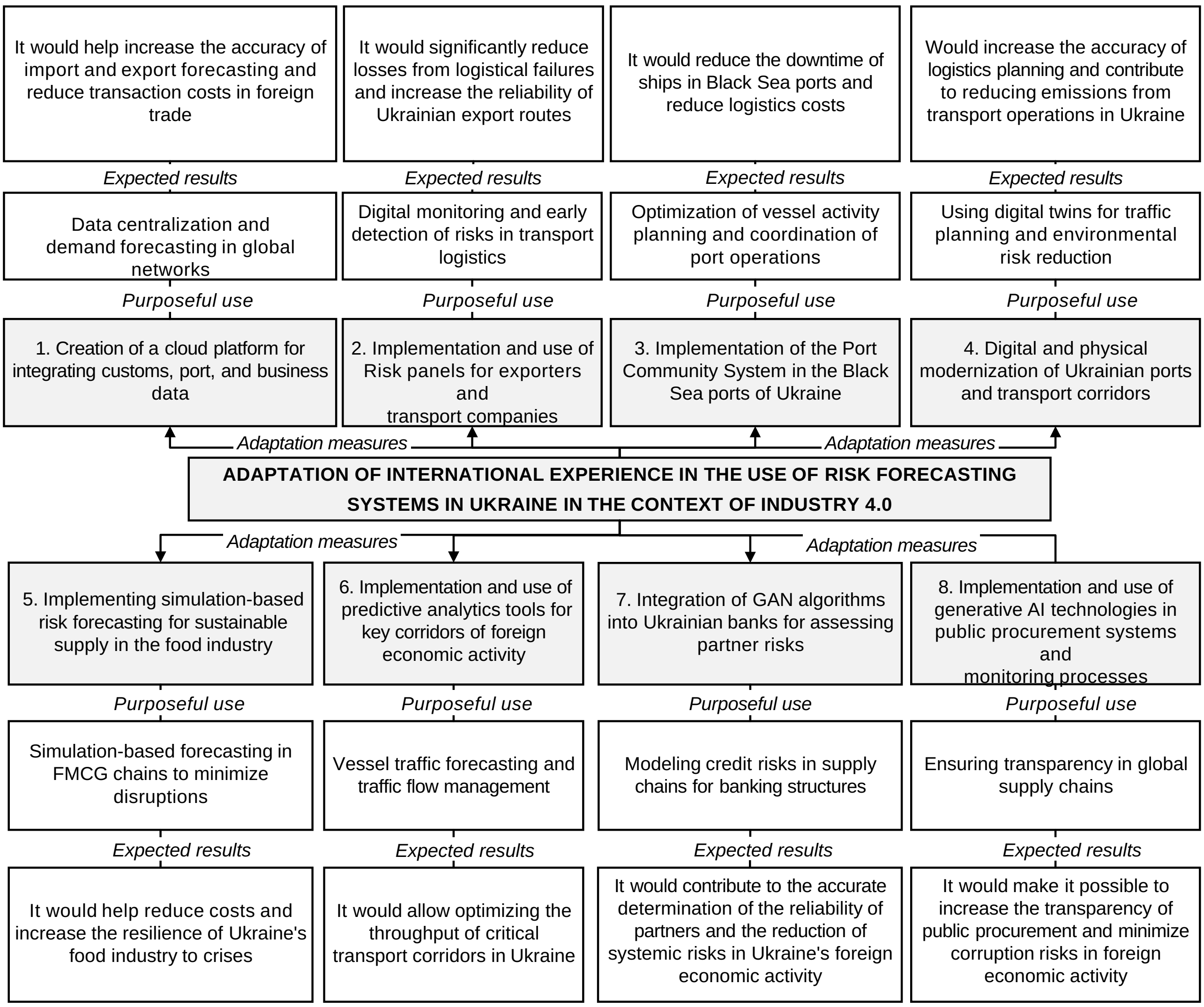

Figure 4. Adaptation of international experience in the use of risk forecasting systems in Ukraine in the context of Industry 4.0

Source: developed by the author himself graph models, ProZorro BI, Dozorro, RPA, LLM, analytics platforms and blockchain, with the expected effect being increased transparency in global supply chains and reduced corruption risks. Compared to conventional audits, this approach ensures scalability and the ability to detect complex interconnections, becoming a tool of strategic prevention. In conclusion, we propose viewing these examples as a complementary synergy of measures for the phased adaptation of international practices. The choice of a specific option should be aligned with operational needs and resource capabilities, while the effectiveness of integration depends on data format unification, cybersecurity assurance and the creation of a regulatory framework.

Based on the data presented in Figures 1–4, we will develop future vectors of transformation for risk forecasting systems in the foreign economic environment in the context of Industry 4.0, see Figure 5.

In our research, we proposed and developed approaches that cover key development trends of each direction, their impact on forecasting and the challenges that arise during implementation. The first vector of generative artificial intelligence

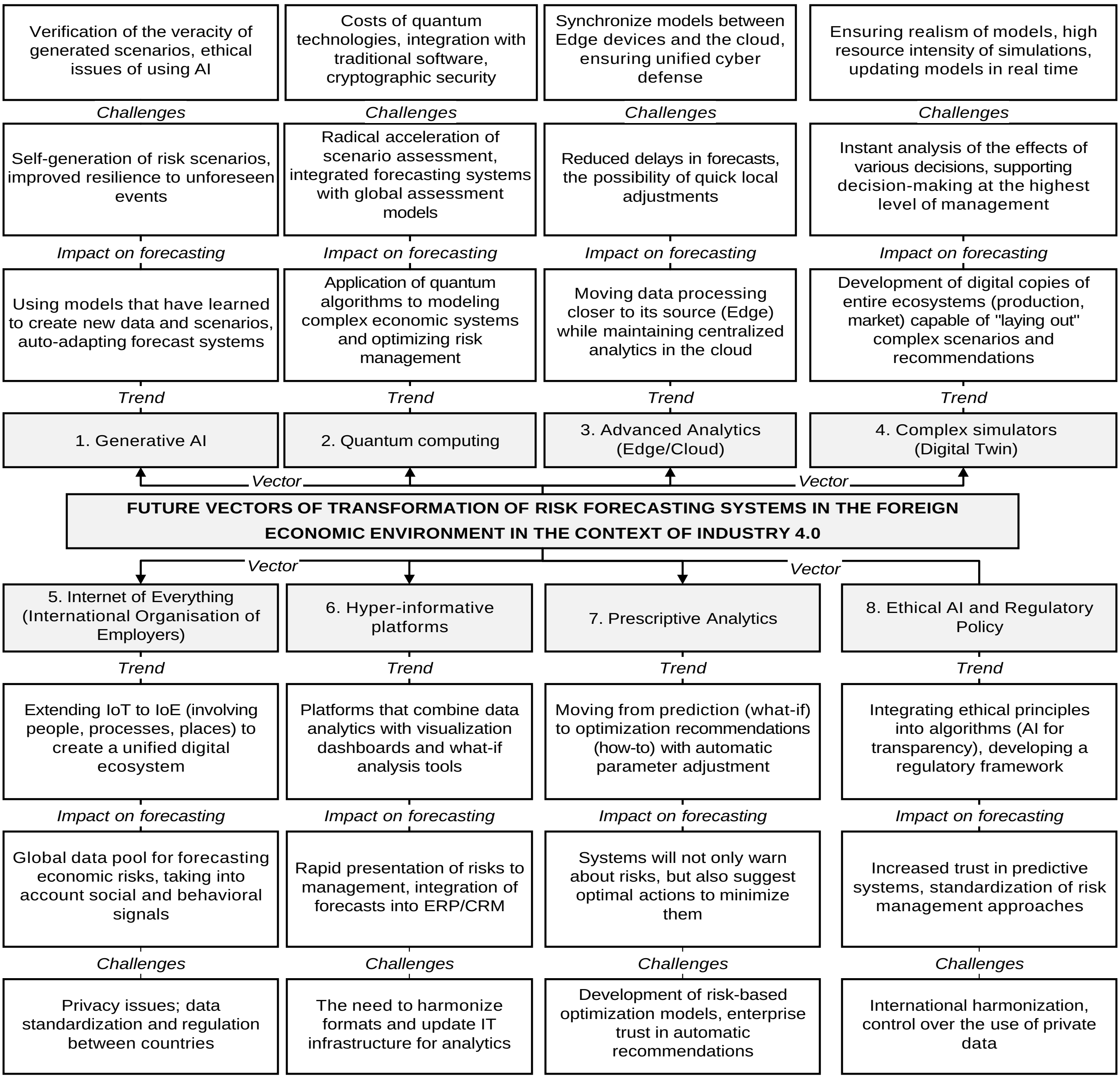

Figure 5. Future vectors of transformation of risk forecasting systems in the foreign economic environment in the context of Industry 4.0

Source: developed by the author himself is distinguished by the ability of models to self-learn and create new data for scenario analysis. Compared to traditional algorithms, this approach opens wider opportunities for automation and the formation of more complex scenarios. Its impact manifests in expanding the range of potential events and increasing preparedness for unpredictable changes; however, this also heightens the risk of false forecasts in the absence of proper control. We identified quantum computing as the next vector, overcoming the limitations of classical analytical methods. Its feature lies in the use of quantum algorithms for modeling complex processes and multifactor interdependencies. While traditional systems are characterized by limited processing speed, quantum technologies provide significantly higher accuracy and scalability. However, their high cost and the need for enhanced data protection form the main challenges of practical use. In the case of advanced analytics based on edge computing, we emphasized bringing data processing closer to the source, as this allows reducing time delays and creating more adaptive models that respond faster than centralized systems.

Compared to them, such an approach enables real-time scenario formation but requires precise synchronization of models across different nodes, otherwise, forecast reliability decreases. We presented the vector of complex simulators (simulations) as a tool for simulating entire ecosystems, differing from models of individual objects. Its advantage lies in reproducing the dynamics of interaction among producers, markets and consumers, providing scenario realism, in contrast to classical models, due to a much higher level of detail. However, this requires significant computational resources and constant data updates, where even minor errors can distort results. The Internet of Everything vector expands the boundaries from IoT to IoE, where devices, processes and people are involved in network integration. Unlike narrow technological systems, this approach forms the basis for multidimensional forecasting, increasing the flexibility of risk models. At the same time, the growing volume of data increases the danger of leaks and privacy violations, which becomes the main challenge of practical implementation. We presented hyper-personalized platforms as a direction combining multichannel analytics and individualization of management decisions. While universal models are focused on standardized scenarios, personalized approaches consider the context of each user or organization, making forecasting more accurate and adaptive. However, integration with existing business systems and high maintenance costs become limitations to their dissemination. In the vector of preventive models, we proposed a transition from «what if» forecasting to «what to do» recommendations. Unlike traditional explanatory models, these systems directly generate managerial decisions. Their impact lies in the fact that managers receive concrete courses of action rather than just probability assessments of scenarios. However, the quality of such recommendations directly depends on the accuracy of input data and errors may lead to negative managerial consequences. The final vector of ethical artificial intelligence and regulatory policy was proposed as a counterbalance to purely technical solutions. While the previous directions focus on efficiency, this one is oriented toward trust and transparency. Its impact lies in incorporating socio-legal factors into risk models, making them more resilient to regulatory changes. At the same time, the difficulty of avoiding discriminatory or manipulative scenarios remains the main challenge of this direction.

Conclusions. Based on the results of the conducted research, a comprehensive analysis of the transformation of risk forecasting systems in the foreign economic environment under the influence of Industry 4.0 technologies was carried out. The theoretical significance of the study lies in the development of methodological foundations for risk forecasting through the integration of classical models and digital technologies, the substantiation of the impact of Industry 4.0 on the architecture of risk management systems and the formation of transformation vectors from local models to global cognitive ecosystems. The practical significance consists in developing a set of measures for adapting international experience to the Ukrainian context, identifying relevant technological solutions for the national risk management system and proving their effectiveness in enhancing transparency, resilience and reducing costs in foreign economic activities. Further scientific research will focus on developing mechanisms for improving digital risk forecasting systems for Ukrainian ports and logistics corridors, creating applied solutions to support exporters and producers in the field of foreign economic activity, developing unified national standards for the use of artificial intelligence in risk management and integrating predictive analytics into public procurement and customs procedures to enhance transparency and reduce corruption risks.

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