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# DIGITAL PLATFORMS AS A MECHANISM FOR ENSURING THE ECONOMIC SECURITY OF ENTERPRISES IN THE CONTEXT OF CORPORATE GOVERNANCE

***Oleh Harmash, Nataliia Trushkina. Olena Khokhlova, Olga Gvozdova. «Digital platforms as a mechanism for ensuring the economic security of enterprises in the context of corporate governance».***

*This study addresses the problem of ensuring the economic security of enterprises operating under conditions of digital transformation, growing uncertainty, and increasing external and internal risks. Modern enterprises function within highly dynamic business environments characterized by operational instability, disruption risks, information asymmetry, cyber threats, and increasing complexity of corporate decision-making processes. Under such conditions, traditional approaches to corporate governance often demonstrate insufficient adaptability to rapidly changing economic and technological conditions.*

*The study substantiates the role of digital platforms as intelligent coordination mechanisms capable of integrating data flows, analytical instruments, risk monitoring procedures, and adaptive decision-making processes within the enterprise management system. Unlike conventional digital infrastructures focused primarily on information exchange and operational support, digital platforms are considered as active mechanisms for strengthening economic security and improving the resilience of enterprises.*

*The aim of the study is to develop a multi-agent coordination model for ensuring the economic security of enterprises in the context of corporate governance, in which the digital platform performs the functions of data integration, risk assessment, adaptive coordination, and optimization of managerial decisions. The proposed model is based on a multi-objective optimization framework integrating operational efficiency, risk minimization, business continuity, and enterprise resilience indicators under uncertainty conditions.*

*A hybrid coordination mechanism is proposed, combining decentralized agent interaction with centralized platform-based optimization. The developed model incorporates scenario-based adaptation, allowing dynamic adjustment of managerial priorities depending on the level of external threats, operational instability, and crisis conditions.*

*The model was validated through a simulation experiment reflecting enterprise operations under stable and crisis scenarios. The obtained results demonstrate that platform-based coordination contributes to improving enterprise resilience, reducing operational risks by 29.79%, decreasing critical disruptions by 66.7%, improving coordination efficiency, and enhancing the continuity of managerial and operational processes under uncertainty conditions.*

*The scientific contribution of the study lies in the formalization of digital platforms as active mechanisms for ensuring economic security within corporate governance systems and in the development of a multi-agent adaptive coordination framework for risk-oriented enterprise management under digital transformation conditions.*

***Keywords**:* economic security, corporate governance, digitalization, enterprise resilience, risk management, digital platforms, threats and risks, adaptive coordination

***Олег Гармаш, Наталія Трушкіна, Олена Хохлова. Ольга Гвоздова. «Цифрові платформи як механізм забезпечення економічної безпеки підприємств у контексті корпоративного управління».*** *У дослідженні розглянуто проблему забезпечення економічної безпеки підприємств, що функціонують в умовах цифрової трансформації, зростаючої невизначеності та посилення зовнішніх і внутрішніх ризиків. Сучасні підприємства працюють у високодинамічному бізнес-середовищі, яке характеризується операційною нестабільністю, ризиками порушення діяльності, інформаційною асиметрією, кіберзагрозами та зростанням складності процесів корпоративного управління. За таких умов традиційні підходи до корпоративного управління часто демонструють недостатню адаптивність до швидкозмінних економічних і технологічних умов.*

*У дослідженні обґрунтовано роль цифрових платформ як інтелектуальних координаційних механізмів, здатних інтегрувати потоки даних, аналітичні інструменти, процедури моніторингу ризиків та адаптивні процеси прийняття управлінських рішень у межах системи управління підприємством. На відміну від традиційних цифрових інфраструктур, орієнтованих переважно на*

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*обмін інформацією та операційну підтримку, цифрові платформи розглядаються як активні механізми зміцнення економічної безпеки та підвищення стійкості підприємств.*

*Метою дослідження є розроблення мультиагентної координаційної моделі забезпечення економічної безпеки підприємств у контексті корпоративного управління, у межах якої цифрова платформа виконує функції інтеграції даних, оцінювання ризиків, адаптивної координації та оптимізації управлінських рішень. Запропонована модель базується на багатокритеріальній оптимізаційній структурі, що інтегрує показники операційної ефективності, мінімізації ризиків, безперервності бізнес-процесів та стійкості підприємства в умовах невизначеності.*

*У роботі запропоновано гібридний механізм координації, який поєднує децентралізовану взаємодію агентів із централізованою платформно-орієнтованою оптимізацією. Розроблена модель включає сценарно-орієнтовану адаптацію, що дозволяє динамічно коригувати управлінські пріоритети залежно від рівня зовнішніх загроз, операційної нестабільності та кризових умов.*

*Валідація моделі здійснювалася шляхом симуляційного експерименту, який відображає функціонування підприємства в умовах стабільних та кризових сценаріїв. Отримані результати демонструють, що платформно-орієнтована координація сприяє підвищенню стійкості підприємства, зниженню операційних ризиків на 29,79%, скороченню критичних порушень на 66,7%, покращенню ефективності координації та забезпеченню безперервності управлінських і операційних процесів в умовах невизначеності.*

*Науковий внесок дослідження полягає у формалізації цифрових платформ як активних механізмів забезпечення економічної безпеки в системах корпоративного управління, а також у розробленні мультиагентної адаптивної координаційної моделі для ризик-орієнтованого управління підприємством в умовах цифрової трансформації.*

***Ключові слова:*** економічна безпека, корпоративне управління, цифровізація, стійкість підприємства, управління ризиками, цифрові платформи, ризики та загрози, адаптивна координація.

**1. Introduction.** The digital transformation of the economy is fundamentally reshaping approaches to enterprise management and creating the foundation for the development of intelligent corporate governance ecosystems. Under conditions of increasing market turbulence, geopolitical instability, technological disruptions, cyber threats, and growing uncertainty, enterprises face a substantial increase in economic risks that directly affect operational continuity, financial stability, competitiveness, and long-term sustainability.

Modern enterprises operate within highly dynamic environments characterized by rapid changes in business conditions, increasing complexity of managerial processes, informational asymmetry, and intensified interdependence among economic actors. Under such conditions, the effectiveness of corporate governance depends not only on the quality of strategic decision-making but also on the ability of enterprises to ensure economic security through adaptive coordination, risk-oriented management, and digital integration of business processes.

Traditional approaches to corporate governance are generally based either on centralized hierarchical management systems or on fragmented decentralized decision-making mechanisms. However, both approaches demonstrate significant limitations under conditions of digital transformation and uncertainty. Centralized models often lack flexibility and responsiveness to rapidly changing external conditions, whereas decentralized approaches frequently generate coordination inefficiencies, inconsistent managerial decisions, operational disruptions, and increased exposure to economic threats due

to the absence of integrated analytical and coordination mechanisms.

An additional level of complexity arises from the necessity to synchronize managerial, operational, informational, and financial processes while simultaneously responding to external and internal threats, including market volatility, cyber risks, operational instability, infrastructure disruptions, and strategic uncertainty. Under such conditions, enterprise resilience depends not only on the efficiency of individual business processes but also on the overall level of coordination among structural units, stakeholders, and decision-making agents within the corporate governance system.

The rapid development of digital platforms creates new opportunities for integrating enterprise management processes and improving transparency, adaptability, and resilience. Digital platforms enable real-time data exchange, monitoring of operational activities, integration of analytical instruments, and synchronization of managerial decisions across multiple organizational levels. Nevertheless, most existing studies primarily consider digital platforms as instruments of information support or operational automation, whereas their role as active mechanisms for ensuring economic security and adaptive corporate governance remains insufficiently explored.

Simultaneously, the development of multi-agent systems, artificial intelligence technologies, and intelligent optimization methods creates new opportunities for modeling complex interactions within enterprise management systems. The multi-agent approach enables the representation of autonomous decision-making entities while accounting for their individual objectives, operational constraints, and behavioral characteristics. This is particularly important under conditions of uncertainty, where enterprises require adaptive coordination mechanisms capable of balancing operational efficiency, risk minimization, and business continuity.

However, current scientific research still lacks integrated models capable of combining multi-agent autonomy, digital platform-based coordination, risk-oriented corporate governance, and multi-objective optimization within a unified adaptive framework for ensuring enterprise economic security under uncertainty conditions.

Therefore, the scientific problem addressed in this study lies in the need to develop adaptive enterprise management models capable of ensuring economic security through coordinated decision-making, integration of digital platforms, incorporation of multi-criteria managerial priorities, and dynamic response to external and internal threats.

The aim of this study is to develop a multi-agent coordination model for ensuring the economic security of enterprises in the context of corporate governance, in which a digital platform acts as an integrating mechanism for data acquisition, risk assessment, adaptive coordination, and optimization of managerial decisions.

To achieve this objective, the study addresses the following tasks:

1. To analyze contemporary approaches to ensuring enterprise economic security under digital transformation conditions;
2. To justify the application of the multi-agent approach for modeling interactions within corporate governance systems;
3. To develop a conceptual model for integrating autonomous agents through a digital platform;
4. To formalize the coordination problem as a multi-objective optimization task considering operational efficiency, risk minimization, and enterprise resilience;
5. To conduct simulation-based validation of the proposed model and evaluate its effectiveness under stable and crisis conditions.

The scientific novelty of the study lies in the formalization of the digital platform as an active mechanism for ensuring economic security within corporate governance

systems, as well as in the development of a multi-agent adaptive coordination model integrating risk-oriented management, multi-objective optimization, and scenario-based adaptation under uncertainty conditions.

The practical significance of the obtained results is associated with the possibility of applying the proposed model to improve enterprise resilience, strengthen economic security mechanisms, optimize managerial coordination, reduce operational risks, and ensure continuity of business processes under conditions of digital transformation and environmental instability.

The paper is structured as follows. Section 2 presents a literature review and identifies the existing research gap. Section 3 develops the conceptual model of the digital ecosystem for enterprise economic security. Section 4 formalizes the proposed multi-agent coordination model. Section 5 presents the results of the simulation experiment and model validation. Section 6 discusses the obtained findings and their theoretical and practical implications. Finally, the concluding section summarizes the main results and outlines directions for future research.

This study addresses the identified research gap by proposing a multi-agent coordination model for enterprise management systems in which a digital platform functions as an active coordination and decision-making mechanism. Unlike existing approaches, the proposed framework integrates multi-objective optimization, platform-based coordination, adaptive risk management, and scenario-driven adaptation within a unified model for ensuring enterprise economic security under conditions of uncertainty and digital transformation.

**2. Scientific Contribution.** This study makes several scientific contributions to the field of enterprise economic security and corporate governance under conditions of digital transformation and increasing environmental uncertainty.

First, the study develops a multi-agent coordination model for ensuring the economic security of enterprises, explicitly considering the dynamic, decentralized, and highly interconnected nature of modern corporate management systems. Unlike traditional management approaches based on static hierarchical coordination, the proposed framework reflects the adaptive interaction among autonomous managerial, operational, analytical, and information agents functioning under conditions of uncertainty and external threats.

Second, the research reconceptualizes the role of digital platforms within corporate governance systems. While existing studies predominantly interpret digital platforms as instruments for information exchange, operational automation, or process monitoring, the proposed approach formalizes the digital platform as an active mechanism for ensuring economic security, adaptive coordination, and risk-oriented managerial decision-making within the enterprise ecosystem.

Third, the study introduces a multi-objective optimization framework integrating operational efficiency, risk minimization, continuity of business processes, and enterprise resilience indicators. Unlike conventional optimization models focused primarily on economic efficiency, the proposed framework incorporates uncertainty factors, operational disruptions, cyber threats, and instability-related risks affecting enterprise sustainability under digital transformation conditions.

Fourth, the research proposes a scenario-based adaptation mechanism enabling dynamic reconfiguration of managerial priorities depending on the level of external and internal threats, operational instability, and crisis conditions. This contributes to the development of adaptive and resilient corporate governance systems capable of maintaining stability and continuity under uncertain business environments.

Fifth, the study develops an integrated adaptive coordination architecture combining decentralized agent autonomy with centralized platform-based optimization. Such an approach enables balancing local managerial objectives with system-wide economic security priorities, thereby reducing coordination inefficiencies and strengthening enterprise resilience.

Finally, the research provides simulation-based validation of the proposed model under stable and crisis scenarios, demonstrating that platform-based coordination contributes to reducing operational risks, improving coordination efficiency, strengthening enterprise resilience, and ensuring continuity of managerial and operational processes under conditions of uncertainty and digital transformation.

The overall scientific contribution of the study lies in the development of a conceptual and methodological framework for integrating digital platforms, adaptive coordination mechanisms, and multi-agent optimization into the system of enterprise economic security and corporate governance.

## 3. LITERATURE REVIEW.

### *3.1. Digital Platforms in Corporate Governance and Enterprise Management*

The digital transformation of the economy has led to the rapid development of digital platforms as key infrastructural elements of modern enterprise management systems [13; 14]. In scientific research, digital platforms are increasingly considered integrated environments that enable coordination among economic agents, facilitate data exchange, improve managerial transparency, and support adaptive decision-making processes within enterprises [3; 18; 20].

Existing studies emphasize the ability of digital platforms to improve operational efficiency, reduce transaction costs, accelerate information exchange, and increase managerial responsiveness under conditions of environmental instability [2; 3; 4]. Digital platforms also contribute to the digital integration of enterprise business processes, strengthening organizational connectivity and supporting real-time monitoring of operational activities [7; 20].

At the same time, the dominant approach in contemporary research still interprets digital platforms primarily as passive infrastructures for information support and process automation rather than as active mechanisms for ensuring economic security and adaptive corporate governance [11; 12]. Consequently, insufficient attention has been paid to the ability of digital platforms to function as intelligent coordination systems capable of integrating risk monitoring, managerial analytics, and adaptive decision-making under conditions of uncertainty and increasing threats [10; 20].

### *3.2. Digitalization, Artificial Intelligence, and Economic Security of Enterprises*

The development of digital technologies, artificial intelligence, big data analytics, and Internet of Things solutions has significantly transformed approaches to enterprise management and economic security formation [5; 17; 23]. Modern intelligent management systems are aimed at increasing enterprise adaptability, operational resilience, responsiveness to threats, and the efficiency of managerial decision-making under unstable business conditions [21; 22].

Scientific studies demonstrate the considerable potential of AI-based technologies in forecasting risks, detecting operational anomalies, optimizing managerial processes, improving resource allocation, and supporting strategic planning [5; 7; 16]. Furthermore, intelligent technologies facilitate the transition from reactive management approaches toward proactive and predictive corporate governance models [9; 21].

However, the majority of existing studies focus mainly on the optimization of separate functional subsystems rather than on the integrated management of enterprise

economic security as a unified adaptive system [16; 21]. Insufficient attention is devoted to the coordination of autonomous managerial agents, integration of digital analytical instruments, and development of adaptive governance mechanisms capable of ensuring enterprise resilience under uncertainty conditions [9; 10]. As a result, the problem of coordinated risk-oriented decision-making within enterprise management systems remains insufficiently explored [11].

### *3.3. Multi-Agent Systems in Enterprise Management*

Multi-agent systems are considered a promising methodological approach for modeling complex decentralized environments in which managerial decisions are generated by interconnected yet autonomous agents [11; 17]. Within enterprise management systems, this approach enables the modeling of interactions among structural units, managerial entities, analytical subsystems, and operational agents while considering their individual objectives, constraints, and behavioral characteristics [3; 21].

Existing studies confirm the effectiveness of multi-agent approaches in coordinating managerial processes, allocating resources, supporting strategic planning, and adapting enterprise operations to changing environmental conditions [1; 16; 21]. In particular, multi-agent systems contribute to decentralized decision-making, operational flexibility, and increased responsiveness to external and internal threats [11].

At the same time, the absence of effective coordination mechanisms among autonomous agents remains one of the key limitations of existing approaches. Most contemporary models either assume complete autonomy of managerial agents, which often leads to suboptimal system-wide decisions, or rely on rigid centralized governance architectures that limit adaptability and responsiveness under uncertainty conditions [4; 11]. Therefore, the problem of integrating agent autonomy with coordinated adaptive decision-making mechanisms remains insufficiently investigated [10; 12].

### *3.4. Coordination and Risk-Oriented Decision-Making in Corporate Governance*

The problem of coordination within enterprise management systems has traditionally been examined through the prism of centralized or hierarchical governance models [4; 15]. Such approaches assume the existence of a unified managerial center responsible for optimizing organizational performance and ensuring strategic stability [15].

An alternative perspective is represented by decentralized governance approaches that account for the interests and autonomy of individual organizational units and stakeholders [2; 19]. Within this framework, coordination mechanisms based on distributed decision-making, game theory, adaptive optimization, and risk-oriented management are increasingly applied [6; 19].

However, existing models demonstrate several important limitations. First, they rarely consider the role of digital platforms as integrated adaptive coordination environments within corporate governance systems [18; 20]. Second, most approaches insufficiently account for the multi-criteria nature of modern managerial decision-making, where operational efficiency, risk minimization, business continuity, and enterprise resilience must be simultaneously optimized [1; 6]. Third, many existing governance models lack adaptability to conditions of high uncertainty, digital disruption, cyber threats, and environmental instability that characterize contemporary enterprise ecosystems [11; 12].

### *3.5. Conceptual Research Streams and Theoretical Positioning*

The conducted literature review demonstrates that contemporary research on digital transformation, enterprise management, and economic security is developing across several interconnected

scientific streams. However, despite the rapid growth of related studies, existing approaches remain highly fragmented and insufficiently integrated within a unified framework of adaptive corporate governance and enterprise economic security.

The first research stream focuses on the relationship between digital platforms and corporate governance systems. Existing studies primarily examine digital platforms as instruments for improving managerial transparency, accelerating information exchange, increasing operational efficiency, and supporting organizational coordination. Within this perspective, digital platforms are interpreted mainly as technological infrastructures facilitating communication and integration among enterprise stakeholders. Nevertheless, significantly less attention is devoted to the role of digital platforms as active adaptive coordination mechanisms capable of influencing enterprise resilience, strategic stability, and economic security under uncertainty conditions.

The second research stream is associated with the interaction between digitalization, artificial intelligence technologies, and enterprise economic security. Existing studies confirm that artificial intelligence, big data analytics, predictive algorithms, and intelligent monitoring systems substantially improve risk detection, operational forecasting, anomaly identification, and managerial responsiveness. However, most existing research concentrates on isolated functional areas of economic security, such as financial security, cybersecurity, operational risk management, or supply chain resilience. Consequently, insufficient attention is devoted to the development of integrated enterprise economic security architectures combining operational, financial, informational, managerial, and strategic security dimensions within a unified adaptive governance system.

The third research stream concerns the application of multi-agent systems for enterprise coordination and adaptive management. Existing approaches demonstrate the effectiveness of multi-agent models for decentralized decision-making, resource allocation, operational coordination, and dynamic adaptation under changing environmental conditions. Nevertheless, most studies focus primarily on local optimization tasks or isolated organizational interactions rather than on system-wide enterprise governance and economic security coordination. As a result, the problem of integrating autonomous agent behavior with centralized adaptive governance mechanisms remains insufficiently explored.

The fourth research stream relates to the development of risk-oriented and resilience-based corporate governance models under conditions of digital transformation. Existing studies increasingly emphasize the importance of organizational resilience, continuity management, adaptive governance, and dynamic response mechanisms for maintaining enterprise stability under uncertainty conditions. In this context, Digital Twin technologies are considered promising instruments for real-time monitoring, simulation modeling, predictive analytics, and adaptive coordination. However, current research still lacks integrated frameworks combining Digital Twin environments, platform-based coordination, multi-agent interaction, and risk-oriented enterprise governance within a unified economic security architecture.

A critical limitation of existing literature is that the majority of studies investigate individual aspects of enterprise economic security separately. Financial risks, operational disruptions, cybersecurity threats, supply chain instability, informational asymmetry, and governance-related vulnerabilities are often examined as isolated management problems rather than interconnected systemic factors affecting enterprise resilience and organizational sustainability.

Furthermore, contemporary research insufficiently addresses the challenges faced by enterprises operating under conditions of elevated environmental turbulence, digital disruption, geopolitical instability, post-crisis recovery, and critical infrastructure vulnerability. Under such conditions, enterprise economic security increasingly depends on the ability to integrate digital coordination mechanisms, adaptive risk-oriented governance, intelligent analytical systems, and continuous feedback-based decision-making processes.

Therefore, the conducted analysis confirms the existence of a significant theoretical and methodological gap associated with the absence of integrated adaptive coordination frameworks capable of combining:

– digital platforms as active governance mechanisms;

– multi-agent adaptive coordination;

– enterprise economic security systems;

– risk-oriented corporate governance;

– Digital Twin technologies;

– resilience-oriented managerial decision-making under uncertainty conditions.

This research gap determines the necessity of developing a unified platform-based multi-agent framework for ensuring enterprise economic security within adaptive corporate governance systems under conditions of digital transformation and environmental instability.

### *3.6. Identification of the Research Gap*

The conducted literature review confirms the existence of a significant scientific gap in the study of digital enterprise management ecosystems operating under conditions of uncertainty and digital transformation.

Despite the active development of research in the fields of digital platforms, enterprise digitalization, economic security, and multi-agent systems [7; 10; 20], there is still no integrated approach capable of:

– combining multi-agent autonomy with platform-based coordination mechanisms;

– integrating operational efficiency, risk minimization, enterprise resilience, and business continuity within a unified management framework;

– ensuring adaptive coordination under conditions of environmental instability and uncertainty;

– formalizing the role of digital platforms as active mechanisms for ensuring enterprise economic security and supporting risk-oriented corporate governance [11; 12].

Therefore, there is a clear need to develop a multi-agent adaptive coordination model in which the digital platform functions not only as an information infrastructure, but also as an intelligent mechanism for optimization, risk-oriented decision-making, and ensuring enterprise economic security within the corporate governance system [10; 20].

## 4. Conceptual model of a digital ecosystem for ensuring enterprise economic security

The formation of effective enterprise economic security systems under conditions of digital transformation requires a transition from fragmented management approaches toward integrated ecosystem-based corporate governance models. In this context, the digital ecosystem of enterprise economic security is considered an adaptive environment of interaction among autonomous managerial, operational, analytical, and informational agents integrated through a digital platform that ensures coordination of enterprise activities within a unified information and analytical space.

The key conceptual element of the proposed framework is the Intelligent Economic Security System (IESS), which is formed through the interaction of managerial processes, data flows, analytical mechanisms, and adaptive decision-making instruments. Within the framework of this study, the IESS is formalized as the following function:

$$IESS = f(S, D, A, U)$$

where: *S (Security Services)* represents the set of managerial, organizational, financial, informational, and risk-management mechanisms aimed at ensuring enterprise economic security; *D (Data)* characterizes information flows generated within the enterprise environment, including operational, financial, analytical, strategic, and risk-related data; *A (Analytics)* defines analytical instruments, including optimization algorithms, forecasting models, risk assessment procedures, and intelligent decision-support systems; *U (Utility)* reflects the value and effectiveness of managerial decisions expressed through enterprise resilience, operational continuity, economic stability, and adaptability under uncertainty conditions.

Unlike traditional approaches in which economic security is primarily interpreted as a protective or control-oriented subsystem, the proposed model considers the Intelligent Economic Security System as an integrated adaptive mechanism combining digital, analytical, organizational, and managerial components within a unified enterprise ecosystem.

Within the proposed framework, the digital platform acts as the central coordination element responsible for transforming the components of the Intelligent Economic Security System into adaptive managerial decisions. The platform integrates data from multiple agents, performs analytical processing, evaluates operational risks, and generates coordinated decisions aimed at maintaining enterprise stability and resilience under changing environmental conditions.

An important extension of the conceptual model is the integration of the Digital Twin approach, which enables the creation of a digital representation of the enterprise management system and its economic security environment. Within the proposed framework, the digital twin functions as a dynamic representation of enterprise processes continuously updated in real time based on operational, financial, analytical, and environmental data.

*The Digital Twin performs three key functions.*

First, it provides real-time visualization of the enterprise state, including operational performance, risk exposure, resource utilization, managerial processes, and external environmental conditions.

Second, it enables simulation of alternative development scenarios, which is critically important for risk-oriented management, forecasting of potential disruptions, and evaluation of enterprise resilience under uncertainty conditions.

Third, it establishes a feedback mechanism between actual enterprise performance and managerial decisions, thereby forming a closed-loop adaptive corporate governance cycle.

Combined with the formalization of the Intelligent Economic Security System, this means that each component of the function: *IESS = f(S, D, A, U)* obtains a dynamic representation within the Digital Twin environment. *Data (D)* are continuously updated in real time, *analytics (A)* evolve through forecasting and optimization procedures, *security mechanisms (S)* are adapted to changing operational conditions, and *utility (U)* is evaluated through enterprise performance and resilience indicators. Consequently, the Digital Twin acts as an operationalization mechanism for the Intelligent Economic Security System concept.

A special role in the proposed model is played by dynamic environmental constraints related to market instability, operational disruptions, cyber threats, resource limitations, and strategic uncertainty. Within the Digital Twin environment, these constraints are integrated into the system as adaptive parameters influencing managerial decision-making and enterprise resilience.

Thus, the proposed conceptual model combines a multi-agent architecture, platform-based coordination, formalization of the Intelligent Economic Security System, and Digital Twin technology into a unified integrated ecosystem. Such an approach enables the transition from static and fragmented governance models toward adaptive and intelligent enterprise management systems capable of operating effectively under conditions of uncertainty and digital transformation.

Within the proposed conceptual framework, a key role is played by the feedback loop mechanism, which ensures system adaptability, self-learning capability, and continuous improvement of managerial decisions. Unlike traditional static governance models, where decisions are based on fixed parameters, the proposed digital ecosystem functions as a dynamic adaptive system in which the results of enterprise activities directly influence subsequent managerial decisions.

Formally, the adaptive management process can be represented as an iterative function:

$$D_{t+1} = F(D_t, S_t, E_t, \varepsilon_t)$$

where: $D_t$ represents the vector of managerial decisions at time *t*; $S_t$ denotes the actual state of the enterprise system; $E_t$ characterizes environmental parameters, including risks, threats, operational constraints, and resource availability; $\varepsilon_t$ reflects stochastic disturbances and uncertainty; $F(\cdot)$ is the adaptive coordination function implemented through the digital platform.

This relationship reflects the fundamental property of the proposed system: each new managerial decision is generated not only on the basis of initial information but also considering the actual outcomes of previous actions and changing environmental conditions. Consequently, enterprise management becomes a continuous adaptive cycle involving monitoring, analytical assessment, optimization, and dynamic refinement of managerial decisions.

Integrating this approach with the Intelligent Economic Security System concept enables extension of the basic model by considering all function components as dynamic variables affected by feedback mechanisms. In particular, *data (D)* are updated according to enterprise performance indicators, *analytics (A)* evolve through refinement of forecasting and optimization procedures, *security mechanisms (S)* adapt to operational threats and instability factors, and *utility (U)* reflects the effectiveness of implemented managerial decisions.

In this context, the Digital Twin serves as the infrastructural foundation for implementing the feedback loop. The digital twin ensures continuous representation of the enterprise state and forms the informational basis for adaptive coordination and updating of managerial decisions.

The interaction between the physical enterprise system and its digital representation creates a closed-loop adaptive management cycle:

*Physical Enterprise System → Data Acquisition → Digital Twin → Analytics & Optimization → Decision Update → Enterprise System*

This cycle can be formalized as a feedback function:

$$D_{t+1} = \Phi(S_t, E_t, R_t)$$

where $\Phi$ is implemented through the digital platform and includes data processing, deviation analysis, risk forecasting, assessment of threats, and generation of corrective managerial decisions.

A specific feature of the proposed model is that feedback possesses not only an operational but also a strategic nature. For example, operational disruptions, cyber threats, financial instability, or managerial inefficiencies affect not only individual business processes but also the overall resilience and economic security of the enterprise. In the proposed framework, these interdependencies are reflected through the Digital Twin, which captures relationships among managerial, operational, financial, and analytical processes within the enterprise ecosystem.

Therefore, the feedback loop mechanism enables the transition from reactive governance toward proactive and adaptive corporate management. The proposed system not only responds to deviations and threats but also accumulates experience and continuously improves managerial coordination and enterprise resilience. This makes it possible to consider the digital ecosystem of enterprise economic security as a cognitive adaptive system capable of self-learning and continuous improvement under conditions of uncertainty and digital transformation.

A specific feature of enterprise economic security systems is that feedback possesses not only an operational but also a strategic and managerial nature. For example, operational disruptions, cyber threats, financial instability, informational asymmetry, or ineffective managerial decisions affect not only individual business processes but also the overall resilience, continuity, and economic stability of the enterprise, requiring dynamic reconfiguration of the corporate governance system. Within the proposed framework, these interdependencies are incorporated through integration with the Digital Twin, which reflects relationships among managerial, operational, analytical, financial, and risk-management processes within the enterprise ecosystem.

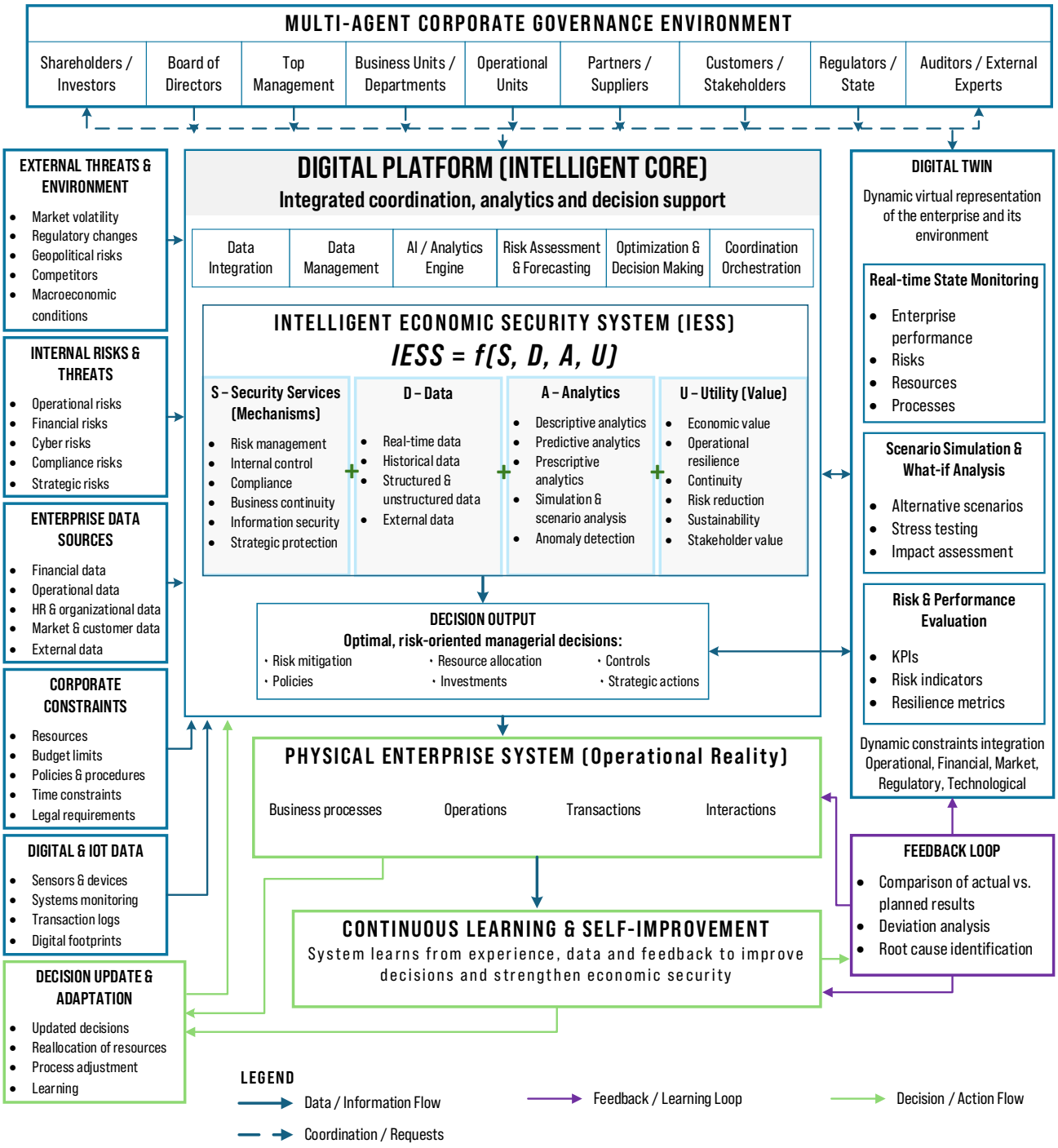


Figure 1. Integrated conceptual framework of a digital platform-enabled multi-agent ecosystem for ensuring enterprise economic security under uncertainty conditions

*Source: developed by the authors.*

Therefore, the feedback loop mechanism enables the transition from reactive corporate governance toward proactive and adaptive enterprise management. The proposed system not only responds to deviations, threats, and operational disturbances but also accumulates experience and continuously improves the effectiveness of managerial coordination and risk-oriented decision-making. This makes it possible to consider the digital ecosystem of enterprise economic security as a cognitive adaptive system capable of self-learning, continuous improvement, and dynamic adaptation under conditions of uncertainty and digital transformation.

## 5. Research methodology: Multi-agent coordination model for ensuring enterprise economic security

***5.1. Methodological framework***. The proposed methodological framework is based on the integration of multi-agent modeling, multi-objective optimization, and simulation-based validation for ensuring enterprise economic security under conditions of uncertainty and digital transformation. The methodological logic of the study is grounded in the assumption that modern enterprise management systems represent decentralized adaptive environments in which multiple autonomous managerial, operational, analytical, and informational agents interact under conditions of environmental instability, operational risks, and dynamic external threats.

Unlike conventional corporate governance models based either on rigid hierarchical coordination or fully decentralized decision-making mechanisms, the proposed approach combines agent autonomy with platform-based adaptive coordination. Within this framework, the digital platform functions as an active coordination mechanism responsible for integrating information flows, synchronizing managerial processes, evaluating risks, and generating adaptive decisions in real time.

The proposed model considers the enterprise ecosystem as a set of interacting autonomous agents operating within a shared digital environment. Let:

$$A = \{a_1, a_2, \ldots, a_n\}$$

be the set of autonomous agents participating in the enterprise ecosystem, including managerial units, operational departments, analytical subsystems, financial structures, risk-management entities, and external stakeholders, and:

$$T = \{t_1, t_2, \ldots, t_m\}$$

be the set of managerial and operational tasks associated with enterprise functioning, strategic coordination, resource allocation, risk management, business continuity, and adaptive response to external and internal threats.

The assignment decision is represented by the binary variable:

$$x_{ij} \in \{0,1\}$$

where:

$$x_{ij} = \begin{cases} 1, & \text{if agent } a_i \text{ performs task } t_j \\ 0, & \text{otherwise} \end{cases}$$

The objective of the model is to determine the optimal allocation of managerial and operational tasks among autonomous agents while simultaneously minimizing operational risks, coordination inefficiencies, resource losses, and disruption impacts under dynamically changing environmental conditions.

The proposed framework follows a computational experiment design in which the model is evaluated through scenario-based simulation reflecting realistic enterprise operating conditions, including operational instability, financial risks, cyber threats, resource constraints, strategic uncertainty, and disruption-related disturbances. Such an approach enables assessment of enterprise resilience, effectiveness of adaptive coordination mechanisms, and stability of corporate governance processes under both stable and crisis scenarios.

***5.2. Multi-objective optimization model***

The coordination problem within the enterprise economic security system is formalized as a multi-objective optimization task:

$$\min Z = \alpha \sum_{i=1}^{n}\sum_{j=1}^{m} C_{ij}x_{ij} + \beta \sum_{i=1}^{n}\sum_{j=1}^{m} T_{ij}x_{ij} + \gamma \sum_{i=1}^{n}\sum_{j=1}^{m} R_{ij}x_{ij}$$

where:

$C_{ij}$ – represents the operational and managerial costs associated with assigning task $t_j$ to agent $a_i$;

$T_{ij}$ – denotes the execution and coordination time required for the implementation of managerial or operational decisions;

$R_{ij}$ – represents the integrated enterprise risk associated with the execution of task $t_j$ to agent $a_i$;

$\alpha$, $\beta$, and $\gamma$ are weighting coefficients reflecting strategic managerial priorities within the enterprise economic security system.

The objective function reflects the multidimensional nature of managerial decision-making under conditions of uncertainty, where enterprise stability simultaneously depends on operational efficiency, coordination speed, and risk minimization. Unlike conventional optimization models focused primarily on economic efficiency or cost reduction, the proposed framework explicitly incorporates enterprise resilience, business continuity, and adaptive risk-oriented governance principles.

The weighting coefficients are dynamically adjusted depending on environmental conditions, threat intensity, operational instability, and strategic priorities. Consequently, the model supports adaptive decision-making under both stable and crisis scenarios.

### *5.3. System constraints*

To ensure the realism and practical applicability of the proposed model, several groups of operational and managerial constraints are introduced.

Agent Capacity Constraints

Each agent possesses limited managerial, analytical, and operational capacity:

$$\sum_{j=1}^{m} x_{ij} \le Cap_i, \quad \forall i$$

where $Cap_i$ represents the maximum number of managerial or operational tasks that can be effectively executed by agent $a_i$.

*Time Constraints*

Enterprise management processes must comply with operational continuity requirements and strategic response limitations:

$$T_{ij}x_{ij} \le T_j^{max}, \quad \forall i,j$$

Where $T_j^{max}$ denotes the maximum allowable execution or response time for task $t_j$.

*Risk Constraints*

The proposed model additionally incorporates threat-oriented and disruption-related limitations:

$$R_{ij} = f(Z_k, Threat_k)$$

where:

$Z_k$ – epresents enterprise vulnerability zones associated with operational, financial, informational, organizational, or cyber-security weaknesses;

$Threat_k$ – characterizes the intensity of external and internal threats, including market instability, cyber risks, financial disruptions, regulatory uncertainty, operational failures, and strategic instability.

The incorporation of risk constraints is particularly important for enterprises operating under conditions of environmental turbulence, digital transformation, geopolitical instability, or post-crisis economic recovery.

### *5.4. Agent behavioral model*

Within the proposed enterprise ecosystem, each autonomous agent acts independently and seeks to maximize its own utility function:

$$U_i = f(P_i, C_i, R_i)$$

where:

$P_i$ – represents operational and managerial performance;

$C_i$ – denotes operational, organizational, or coordination costs;

$R_i$ – reflects the level of individual risk exposure associated with managerial or operational activities.

The behavioral logic of agents reflects the decentralized nature of modern enterprise management systems, where organizational units and managerial entities pursue individual objectives while simultaneously participating in the implementation of collective corporate governance strategies and enterprise economic security mechanisms.

Such conditions create a potential conflict between local optimization and system-wide organizational efficiency. Consequently, the role of the digital platform becomes critically important for coordinating decentralized managerial decisions, reducing systemic inefficiencies, strengthening adaptive governance mechanisms, and ensuring enterprise resilience under uncertainty conditions.

### *5.5. Platform-based coordination mechanism*

Within the proposed framework, the digital platform operates as an intelligent coordination layer integrating information from autonomous managerial, operational, analytical, and informational agents while generating system-level adaptive optimization decisions aimed at ensuring enterprise economic security and organizational resilience.

The platform-based coordination mechanism includes five interconnected stages:

– acquisition and integration of operational, analytical, financial, and risk-related data from enterprise agents and external environments;

– formation of a global adaptive optimization objective considering operational efficiency, enterprise resilience, business continuity, and risk minimization priorities;

– execution of the multi-objective optimization procedure under dynamically changing environmental conditions;

– allocation and coordination of managerial, analytical, and operational tasks among autonomous agents;

– dynamic updating of system parameters through feedback, monitoring, and adaptive learning mechanisms.

Unlike traditional centralized corporate governance models, the proposed framework preserves the autonomy of individual agents while simultaneously enabling platform-based coordination and system-wide optimization at the enterprise ecosystem level. Consequently, the proposed model

represents a hybrid adaptive governance architecture combining decentralized managerial behavior with centralized digital coordination and intelligent optimization mechanisms.

Within this architecture, the digital platform performs not only informational and analytical functions but also acts as an active coordination and decision-support mechanism capable of synchronizing enterprise processes, identifying operational deviations, forecasting risks, and generating adaptive managerial responses under uncertainty conditions.

The conceptual architecture of the proposed platform-based adaptive coordination system is illustrated in Figure 2.

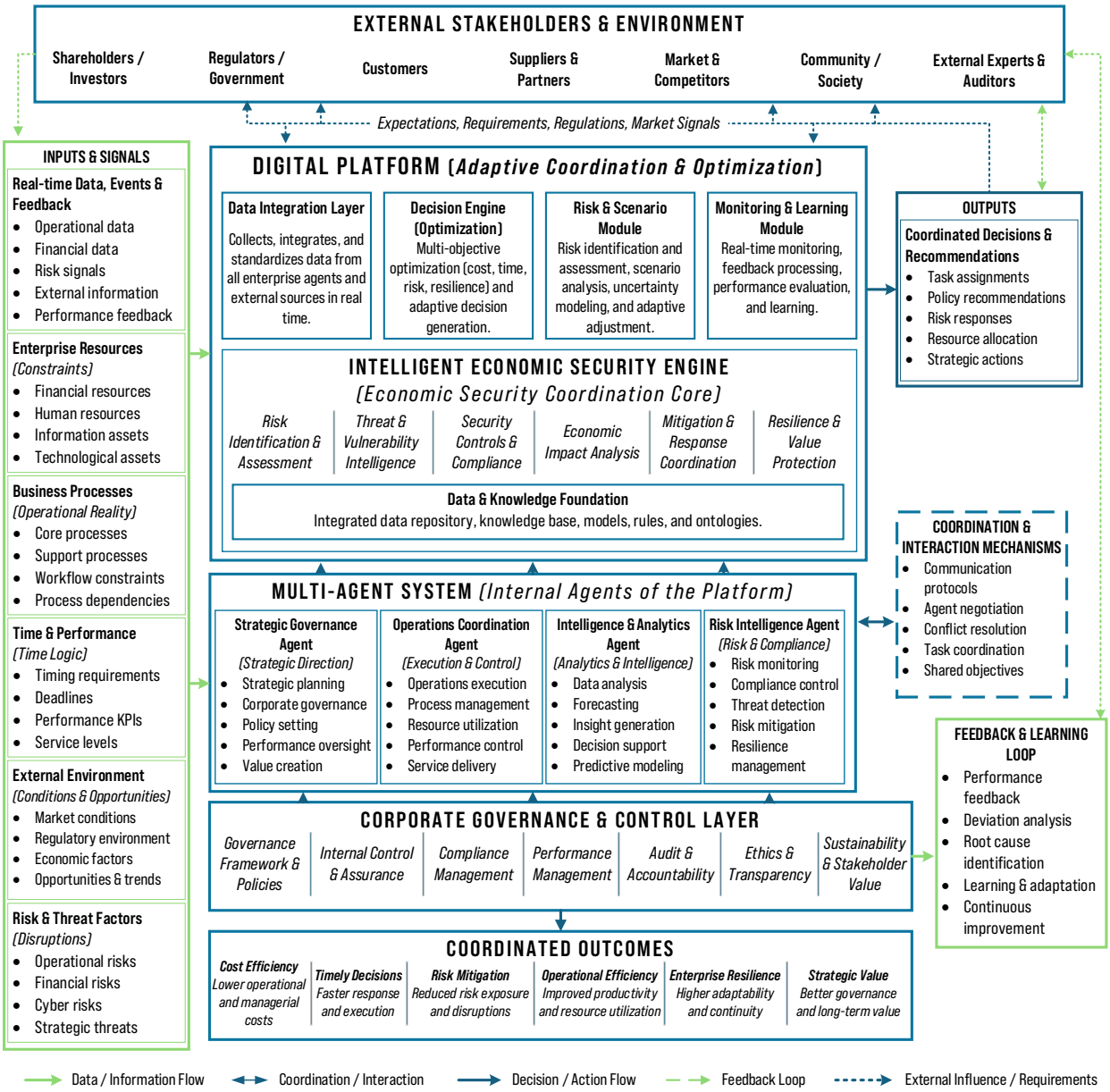


Figure 2. Conceptual architecture of a platform-based multi-agent adaptive coordination system for ensuring enterprise economic security

*Source: developed by the authors.*

Within the proposed architecture, operational processes, enterprise resources, environmental instability, and risk-related factors act as dynamic constraint layers

influencing the feasibility and effectiveness of managerial decisions. This enables synchronization among strategic objectives, operational activities, risk-management mechanisms, and adaptive corporate governance processes within the enterprise ecosystem.

### *5.6. Pareto-based decision logic*

Because the proposed optimization framework simultaneously considers multiple conflicting criteria, the solution cannot be represented by a single universal optimum. Instead, the model generates a set of Pareto-efficient alternatives reflecting different combinations of operational efficiency, risk exposure, managerial responsiveness, and enterprise resilience.

A solution is considered Pareto-optimal if no criterion can be improved without worsening at least one other criterion. This approach enables:

– analysis of trade-offs between operational efficiency, coordination speed, and risk minimization;

– adaptation of managerial decisions to changing strategic priorities and environmental conditions;

– increased flexibility in operational and strategic corporate governance processes;

– balancing enterprise resilience, business continuity, and economic performance under uncertainty conditions.

The application of Pareto-based optimization is particularly important for enterprise economic security systems because the most economically efficient managerial decision is not necessarily the most resilient, sustainable, or risk-resistant under conditions of instability and digital transformation.

Consequently, the proposed framework enables enterprise management systems to identify adaptive decision alternatives capable of balancing economic efficiency with resilience and long-term organizational sustainability.

### *5.7. Scenario-based adaptation*

To account for environmental uncertainty, operational instability, and dynamically changing external and internal threats, the proposed model incorporates a scenario-based adaptation mechanism.

Two generalized operational scenarios are considered.

*Scenario 1: Stable Environment*

– low level of operational disruptions and external threats;

– relatively stable market and institutional conditions;

– priority assigned to operational efficiency, coordination speed, and resource optimization;

– focus on minimizing operational and managerial costs.

*Scenario 2: Crisis Environment*

– elevated levels of uncertainty, disruptions, and strategic instability;

– increased exposure to operational, financial, cyber, and organizational risks;

– priority assigned to enterprise resilience, business continuity, adaptive governance, and risk mitigation;

– focus on preserving organizational stability under adverse conditions.

Scenario adaptation is implemented through dynamic modification of weighting coefficients within the multi-objective optimization framework:

$$\alpha + \beta + \gamma = 1$$

where the relative values of $\alpha$, $\beta$, and $\gamma$ vary depending on the operational scenario, environmental conditions, and strategic managerial priorities.

Under stable conditions, higher weights are assigned to operational efficiency and coordination performance, whereas crisis scenarios prioritize enterprise resilience, continuity of business processes, adaptive responsiveness, and reduction of systemic risks.

This mechanism enables adaptive reconfiguration of managerial coordination logic depending on environmental disturbances, operational instability, threat intensity, and strategic governance objectives. Consequently, the proposed framework supports dynamic balancing between economic efficiency and enterprise economic security under conditions of uncertainty and digital transformation.

### *5.8. Simulation algorithm*

The implementation logic of the proposed multi-agent adaptive coordination model is based on a simulation-driven computational workflow integrating data acquisition, risk assessment, multi-objective optimization, Pareto-based decision analysis, and adaptive feedback mechanisms.

The simulation framework models the functioning of the enterprise management system under varying environmental conditions and operational scenarios. The computational workflow includes continuous monitoring of enterprise processes, dynamic assessment of external and internal threats, generation of adaptive managerial decisions, and iterative updating of system parameters through feedback mechanisms.

The overall structure of the simulation algorithm is presented in Figure 3.

The simulation process begins with the acquisition and integration of input data related to enterprise agents, managerial and operational tasks, risk indicators, and environmental parameters. At this stage, the digital platform integrates heterogeneous information flows originating from managerial units, operational departments, analytical subsystems, financial structures, monitoring systems, and external information sources. The collected data include operational capacities of enterprise agents, resource availability, performance indicators, risk signals, financial constraints, organizational parameters, and external environmental factors affecting enterprise stability and economic security.

Based on the acquired information, the model generates cost, time, risk, and performance matrices representing the operational characteristics of each possible assignment alternative within the enterprise management system. These matrices form the analytical foundation for subsequent optimization procedures. The risk matrix additionally incorporates disruption-related parameters associated with operational instability, cyber threats, financial uncertainty, organizational vulnerabilities, and environmental turbulence affecting enterprise resilience.

At the next stage, the weighting coefficients of the objective function are initialized according to the selected operational scenario. The simulation framework distinguishes between stable and crisis environments. Under stable conditions, the model prioritizes operational efficiency, coordination speed, and resource optimization, whereas crisis scenarios increase the importance of enterprise resilience, business continuity, adaptive governance, and risk minimization. This adaptive weighting mechanism enables dynamic reconfiguration of managerial priorities depending on environmental conditions and threat intensity.

After parameter initialization, the digital platform executes the multi-objective optimization procedure. The optimization engine processes the integrated dataset and generates feasible allocation alternatives while simultaneously minimizing operational costs, coordination inefficiencies, execution time, and systemic risks. The optimization process operates under the system constraints introduced in Equations (2)–(4), thereby ensuring the realism, adaptability, and feasibility of generated managerial decisions.

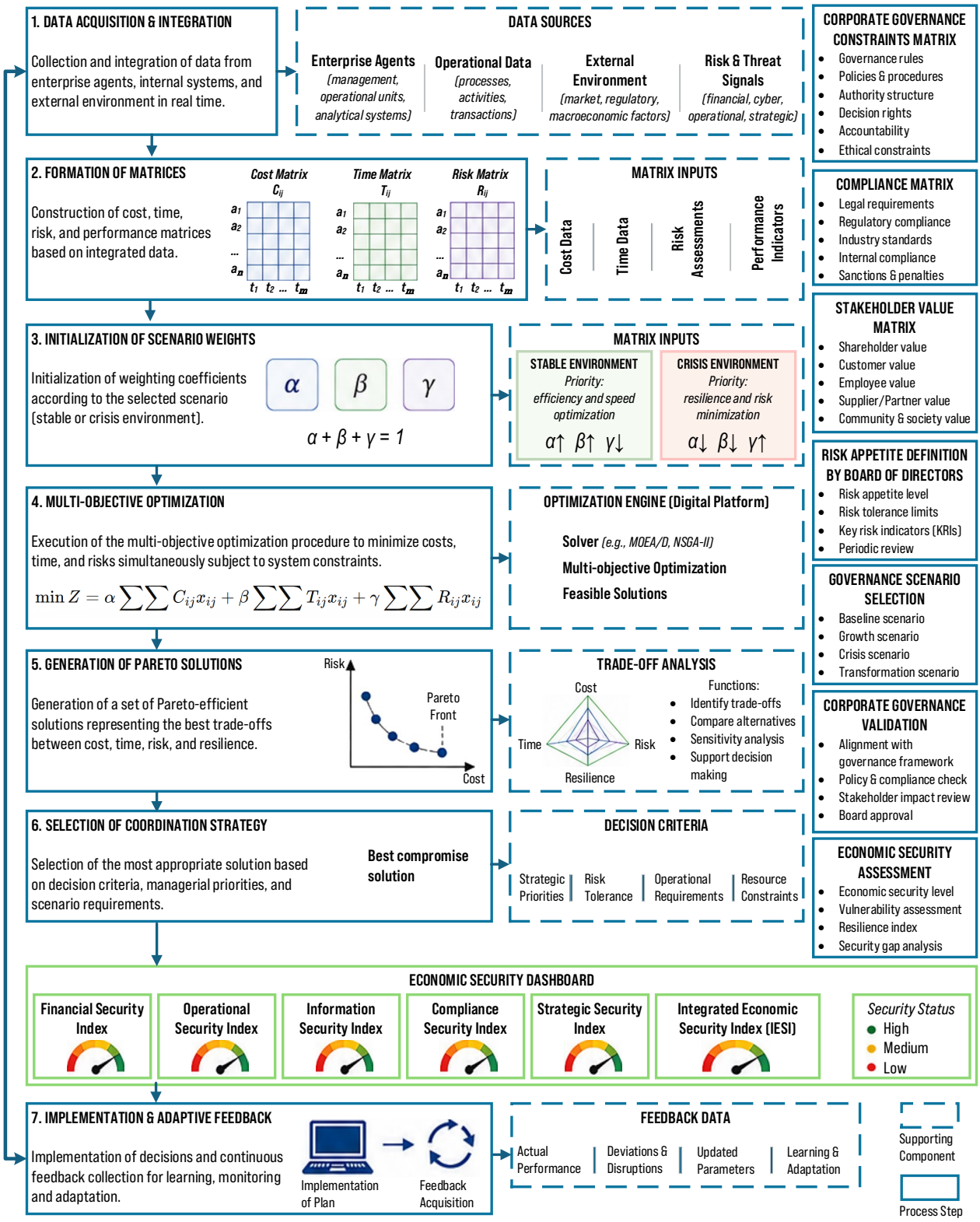


Figure 3. Simulation algorithm for the platform-based multi-agent adaptive coordination model for ensuring enterprise economic security
*Source: developed by the authors.*

Because the optimization problem includes multiple conflicting objectives, the solution is represented as a set of Pareto-efficient alternatives rather than a single

deterministic optimum. The Pareto frontier enables the analysis of trade-offs among operational efficiency, enterprise resilience, managerial responsiveness, and risk exposure indicators. This allows decision-makers to evaluate alternative coordination strategies depending on strategic priorities, acceptable risk levels, operational constraints, and environmental conditions.

The next stage involves selecting the most appropriate coordination strategy from the generated Pareto-efficient solutions. The selection process considers strategic priorities of enterprise development, acceptable levels of risk exposure, business continuity requirements, operational constraints, and long-term sustainability objectives. In this context, the digital platform functions not only as an optimization instrument but also as an intelligent decision-support mechanism facilitating adaptive coordination among autonomous enterprise agents.

Following the selection of the coordination strategy, the generated solution is implemented within the operational environment of the enterprise ecosystem. Real-time monitoring data generated during implementation are continuously collected by the digital platform and incorporated into the adaptive feedback loop mechanism. This feedback process enables dynamic updating of model parameters, identification of operational deviations, detection of emerging threats, and adaptive refinement of future managerial decisions.

The integration of feedback mechanisms transforms the proposed simulation framework into a continuously learning adaptive system capable of responding to environmental changes, operational instability, and uncertainty conditions. Consequently, the simulation algorithm supports not only operational optimization but also the long-term resilience, sustainability, and economic security of enterprise management systems.

The proposed computational workflow therefore combines multi-agent autonomy, platform-based coordination, adaptive optimization, risk-oriented governance, and continuous feedback integration within a unified simulation environment. Such an approach enables realistic modeling of complex enterprise management processes and provides a methodological basis for evaluating coordination efficiency, enterprise resilience, and economic security under varying operational scenarios and uncertainty conditions.

## 6. Model validation and research results

To validate the proposed multi-agent adaptive coordination model, a simulation environment representing the functioning of an enterprise management system under conditions of uncertainty and digital transformation was developed. The simulation framework was designed to evaluate the effectiveness of the digital platform as an active coordination mechanism for synchronizing managerial, operational, analytical, and risk-management processes within the enterprise ecosystem under varying environmental conditions.

The simulation environment included five groups of autonomous enterprise agents, twenty managerial and operational tasks, and two generalized operational scenarios: a stable environment and a crisis environment. Under the stable scenario, managerial priorities were primarily focused on operational efficiency, coordination speed, and optimization of enterprise resources. Under the crisis scenario, greater importance was assigned to enterprise resilience, business continuity, adaptive governance, and mitigation of operational, financial, cyber, and organizational risks.

To evaluate the effectiveness of the proposed coordination mechanism, the study employed a multidimensional performance assessment framework integrating economic, operational, risk-related, and resilience-oriented indicators. Such an approach avoids oversimplified evaluation based exclusively

on economic efficiency or cost minimization and reflects the inherently multi-criteria nature of enterprise economic security systems operating under uncertainty conditions.

The simulation parameters were calibrated to reproduce realistic enterprise operating conditions, including operational constraints, resource limitations, uncertainty-related disruptions, external environmental instability, organizational vulnerabilities, and dynamically changing threat factors. The computational experiment additionally incorporated adaptive feedback mechanisms and scenario-based parameter modification, enabling evaluation of the stability and responsiveness of the proposed coordination model under different operational environments.

The digital platform continuously integrated data generated by enterprise agents and external information sources, performed analytical processing, executed the multi-objective optimization procedure, and generated adaptive managerial decisions in real time. This enabled assessment not only of operational coordination efficiency but also of the ability of the proposed framework to strengthen enterprise resilience, improve continuity of business processes, and reduce systemic risk exposure.

The obtained simulation results demonstrate that the platform-based adaptive coordination mechanism significantly improves enterprise management efficiency under both stable and crisis conditions. In stable environments, the proposed model contributes to optimization of operational coordination, reduction of managerial inefficiencies, and improvement of decision responsiveness. Under crisis conditions, the framework demonstrates increased adaptability, improved continuity of enterprise operations, and enhanced capability to mitigate disruption-related risks and environmental instability.

Consequently, the proposed simulation framework confirms the effectiveness of integrating multi-agent coordination, adaptive optimization, digital platforms, and feedback-based governance mechanisms into a unified enterprise economic security system capable of functioning under conditions of uncertainty and digital transformation.

### *6.1. Performance evaluation framework*

To compare the traditional decentralized enterprise management model with the proposed platform-based adaptive coordination mechanism, six groups of performance indicators were employed:

– total operational and managerial costs *(C)*;

– average decision execution and coordination time *(T)*;

– number of operational disruptions and delays *(D)*;

– deviation from planned operational performance indicators *(S)*;

– integrated enterprise risk index *(R)*;

– number of critical operational failures *(F)*.

All indicators were formulated as minimization criteria. The relative improvement of each indicator after implementation of the digital platform was calculated as:

$$\Delta X = \frac{X_{platform} - X_{traditional}}{X_{traditional}} \times 100\%$$

where $X_{traditional}$ – represents the value of the indicator under traditional decentralized coordination; $X_{platform}$ – denotes the corresponding value under platform-based adaptive coordination.

The proposed evaluation framework enables simultaneous assessment of operational efficiency, managerial coordination quality, enterprise resilience, and the effectiveness of economic security mechanisms under uncertainty conditions.

### *6.2. Scenario parameterization*

Different weighting structures were applied depending on the operational scenario. In the stable environment, the optimization logic prioritized operational efficiency, coordination responsiveness, and resource optimization. Conversely, in the crisis scenario, higher weights were assigned to enterprise resilience, business continuity, adaptive governance, and systemic risk minimization.

This parameterization reflects the logic of adaptive enterprise management under uncertainty conditions. Under stable environments, the primary objective is optimization of enterprise performance, whereas crisis conditions require preservation of organizational stability, continuity of operations, and mitigation of disruption-related impacts.

The weighting coefficients of the objective function were dynamically adjusted according to scenario conditions:

$$\alpha + \beta + \gamma = 1$$

where:

$\alpha$ represents the weight of operational and managerial costs;

$\beta$ denotes the weight of coordination and execution time;

$\gamma$ characterizes the weight of risk-related and resilience-oriented factors.

### *6.3. Results of the stable scenario*

The simulation results for the stable operational environment demonstrate that platform-based adaptive coordination produces consistent improvements across all key enterprise performance indicators.

Total operational and managerial costs decreased from 4,820 thousand UAH to 4,320 thousand UAH, representing a 10.37% reduction. The average coordination and execution time decreased by 13.04%, while the number of operational disruptions and delays decreased from six to two cases, corresponding to a 66.67% improvement. Furthermore, deviation from planned operational performance indicators was reduced from 14% to 6%, while the integrated enterprise risk index decreased by 22.58%.

The most significant effect was observed in the reduction of operational disruptions and coordination delays, indicating that the primary advantage of platform-based adaptive coordination lies not only in cost reduction but also in improving synchronization among enterprise processes, managerial decisions, and operational activities. Under modern enterprise conditions, even minor operational disruptions may create cascading effects influencing organizational performance, resource utilization, and managerial stability. Therefore, improved coordination represents a critical organizational benefit.

The reduction in operational costs can be explained by more balanced allocation of managerial and operational tasks among enterprise agents and improved resource coordination. Similarly, the decrease in coordination time reflects the ability of the digital platform to minimize operational conflicts, improve decision synchronization, and optimize adaptive managerial interaction.

### *6.4. Results of the crisis scenario*

The impact of platform-based adaptive coordination becomes even more significant under crisis conditions characterized by elevated uncertainty, disruption risks, and environmental instability.

In the crisis scenario, total operational costs decreased by 7.25%, while the average coordination time decreased by 12.04%. More importantly, the number of operational

disruptions was reduced by 63.64%, and deviation from planned enterprise performance indicators decreased from 27% to 12%. The integrated enterprise risk index decreased by 29.79%, while the number of critical operational failures decreased from three to one event, corresponding to a 66.67% reduction.

These results confirm the central hypothesis of the study: under uncertainty conditions, the primary value of the digital platform is not limited to operational efficiency but extends to strengthening enterprise resilience and ensuring continuity of business processes. The proposed coordination mechanism significantly improves the ability of the enterprise management system to maintain operational stability despite disruptions and environmental instability.

The reduction in critical operational failures is particularly important because modern enterprise systems are highly sensitive to cascading disruptions. Operational delays, coordination failures, cyber incidents, or resource instability may directly affect organizational continuity, financial stability, and managerial performance. Therefore, resilience-oriented adaptive coordination becomes strategically more important than pure operational efficiency under crisis conditions.

### *6.5. Normalized efficiency assessment*

To compare performance across heterogeneous indicators, a normalized efficiency framework was introduced.

Because all indicators represent minimization criteria, the normalized value for each indicator was calculated as:

$$N_i = \frac{X_{platform}}{X_{traditional}}$$

where: $N_i < 1$ indicates performance improvement; $N_i > 1$ indicates deterioration.

Based on normalized indicators, the integrated Platform Efficiency Index (PEI) was calculated as:

$$PEI = \sum_{i=1}^{n} w_i N_i$$

where: $w_i$ – denotes the weighting coefficient of the corresponding criterion; $N_i$ – represents the normalized value of the indicator.

For the stable scenario, the weighting structure was defined as: $w_C = 0{,}40$, $w_T = 0{,}40$, $w_R = 0{,}20$. For the crisis scenario: $w_C = 0{,}25$, $w_T = 0{,}25$, $w_R = 0{,}50$.

The obtained results indicate that the integrated efficiency effect of platform-based adaptive coordination reached 13.9% in the stable scenario and 19.7% in the crisis scenario. These findings demonstrate that the digital platform exhibits greater systemic utility under elevated uncertainty conditions because it more effectively compensates for disruptions, operational instability, and systemic risks.

### *6.6. Coordination effect assessment*

To evaluate the impact of the digital platform on synchronization quality among enterprise agents and organizational processes, a Coordination Effect Index (CEI) was introduced:

$$CEI = \frac{\Delta D + \Delta S}{2}$$

where:

$\Delta D$ – represents the relative reduction in operational disruptions and delays;

$\Delta S$ – denotes the relative reduction in deviations from planned enterprise performance indicators.

The calculated CEI values reached 61.91% in the stable scenario and 59.60% in the crisis scenario. These results demonstrate that the digital platform ensures a consistently high coordination effect regardless of environmental conditions.

This finding is critically important because synchronization among managerial decisions, operational activities, analytical subsystems, and risk-management processes represents one of the key determinants of enterprise resilience and economic security under uncertainty conditions.

### *6.7. Resilience assessment*

To evaluate the resilience capacity of the proposed coordination mechanism under crisis conditions, a Resilience Index *(RI)* was calculated:

$$RI = \frac{F_{traditional} - F_{platform}}{F_{traditional}}$$

where: $F-$ denotes the number of critical operational failures or disruption events.

The obtained resilience index reached 0.667, indicating that platform-based adaptive coordination reduced the frequency of critical disruptions by approximately two-thirds compared with the traditional decentralized management model.

This result confirms the ability of the proposed framework to support continuity, operational stability, and enterprise economic security under uncertainty conditions.

### *6.8. Agent load balancing analysis*

An additional effect of platform-based adaptive coordination is the balancing of managerial and operational workload among enterprise agents.

To evaluate the unevenness of task allocation, the coefficient of variation was calculated:

$$CV = \frac{\sigma}{\bar{x}} \times 100\%$$

where:

$\sigma$ – represents the standard deviation of task distribution among enterprise agents;

$\mathrm{x}$ – denotes the average number of assigned tasks per agent.

The results demonstrate a reduction in the coefficient of variation from 44.7% under traditional decentralized coordination to 15.8% under platform-based adaptive coordination.

This confirms that the digital platform substantially improves workload balancing across enterprise agents, thereby reducing bottleneck formation, preventing overload concentration, and improving organizational stability.

### *6.9. Pareto analysis of alternative coordination strategies*

Because enterprise management decisions are inherently multi-objective, the proposed framework generates a set of Pareto-efficient alternatives rather than a single deterministic solution.

Four alternative coordination strategies were generated for the crisis scenario. Alternative ***P1*** prioritized operational efficiency and cost minimization, whereas ***P4*** focused on maximum enterprise resilience and risk reduction. Alternatives ***P2*** and ***P3*** represented intermediate trade-offs among operational efficiency, coordination responsiveness, and systemic risk minimization.

To identify the most balanced coordination strategy, a Weighted Sum Model ***(WSM)*** was applied:

$$WSM_k = \sum_{i=1}^{n} w_i N_{ik}$$

where:

$WSM_k -$ represents the integrated score of alternative $k$;

$N_{ik}$ – denotes the normalized value of criterion $i$;

$w_i$ – is the weighting coefficient.

Because all criteria are minimized, the optimal alternative corresponds to the lowest WSM value.

The results indicate that alternative ***P4*** achieved the best integrated performance under crisis conditions despite having the highest operational costs. This result confirms that under high uncertainty, optimization logic shifts toward resilience-oriented and risk-adaptive managerial decision-making.

### *6.10. Sensitivity analysis*

To evaluate the stability of the proposed framework, a sensitivity analysis was conducted by varying the weight assigned to the risk criterion ($w_R$).

The results demonstrate that increasing the importance of risk-related factors gradually shifts the optimal coordination strategy toward more resilient, although operationally more expensive, alternatives. Under low risk weights, alternative ***P2*** remains preferable due to its balanced efficiency profile. However, as ($w_R$) increases, the model increasingly favors alternatives ***P3*** and ***P4***, which prioritize enterprise resilience, continuity of operations, and disruption resistance.

The sensitivity analysis therefore confirms the adaptive nature of the proposed coordination framework and its ability to dynamically respond to changing managerial priorities and environmental conditions.

### *6.11. Monte Carlo simulation and probabilistic risk assessment*

To increase the reliability of risk evaluation, the study additionally employed Monte Carlo simulation methods. The probabilistic simulation framework enables consideration of stochastic fluctuations in operational costs, coordination time, disruption probabilities, and uncertainty-related factors within the enterprise management ecosystem.

Within the simulation model, each managerial and operational task was represented as a stochastic process characterized by three random variables:

– operational cost;

– coordination and execution time;

– disruption-related risk.

The objective function for each simulation iteration was represented as:

$$Z^{(k)} = \alpha C^{(k)} + \beta T^{(k)} + \gamma R^{(k)}$$

where $k$ denotes the simulation iteration.

The study employed 10,000 simulation iterations for both traditional decentralized coordination and platform-based adaptive coordination scenarios.

The following probability distributions were used:

– normal distribution for operational costs;

– lognormal distribution for coordination and execution time;

– beta distribution for disruption-related risk;

– Bernoulli distribution for critical operational failures.

The simulation results confirm the robustness of the proposed coordination framework. Compared with traditional decentralized coordination, platform-based adaptive coordination reduced:

– total operational costs by 7.03%;

– average coordination time by 13.76%;

– integrated enterprise risk by 29.17%;

– operational disruptions and delays by 61.11%;

– probability of critical operational failures by 61.29%.

The probabilistic analysis additionally demonstrated a substantial reduction in the likelihood of critical operational states. The probability of coordination time exceeding 11 hours decreased from 42% to 18%, while the

probability of risk values exceeding 0.45 decreased from 47% to 16%. Similarly, the probability of at least one critical operational disruption occurring decreased from 31% to 12%.

These results indicate that the digital platform improves not only average operational performance but also the probabilistic stability profile of the entire enterprise management system.

### *6.12. Generalization of results*

The obtained simulation results confirm that platform-based adaptive coordination produces both operational and systemic effects within enterprise economic security systems.

Under stable conditions, the proposed framework improves operational efficiency through reductions in costs, coordination time, disruptions, and deviations from planned enterprise performance indicators. Under crisis conditions, the strongest effect is observed in resilience-related indicators, including risk reduction, disruption prevention, continuity preservation, and adaptive responsiveness.

The most important result of the study is that the digital platform fundamentally transforms the coordination logic of enterprise management systems. Traditional decentralized management approaches rely primarily on local decision-making by individual organizational units, whereas the proposed platform-based mechanism enables system-level optimization, adaptive synchronization, and coordinated risk-oriented governance across the entire enterprise ecosystem.

This systemic coordination effect explains the substantial reduction in workload imbalance among enterprise agents, the significant decrease in operational disruptions, and the increased resilience of enterprise management systems under uncertainty conditions.

Overall, the simulation experiment confirms the feasibility and effectiveness of the proposed multi-agent adaptive coordination model. The developed framework successfully combines agent autonomy with platform-enabled optimization, thereby achieving a dynamic balance among operational efficiency, enterprise resilience, risk minimization, and continuity of business processes within enterprise economic security systems.

## 7. Discussion of results

The obtained results make it possible to move beyond the mere identification of quantitative improvements toward interpreting systemic transformations in the functioning of enterprise management systems under conditions of uncertainty and digital transformation. The conducted simulation demonstrates that the primary effect of the digital platform is manifested not simply through local optimization of individual operational processes, but through the transformation of coordination mechanisms among autonomous enterprise agents within the corporate governance system.

The values of the Platform Efficiency Index (PEI), which reached 13.9% in the stable environment and increased to 19.7% under crisis conditions, indicate the systemic nature of the platform's impact on enterprise economic security. Importantly, the coordination effect becomes stronger precisely under elevated uncertainty conditions. This suggests that the digital platform performs not only an optimization function but also acts as an adaptive governance mechanism capable of supporting business continuity, organizational stability, and enterprise resilience under environmental turbulence. Such findings are consistent with contemporary concepts of resilient and adaptive enterprise systems, where coordination capability and dynamic responsiveness are considered critical determinants of long-term organizational sustainability.

A deeper analysis demonstrates that the main contribution to this effect is generated by the adaptive coordination mechanism implemented through the digital platform. The Coordination Effect Index (CEI), which remains close to 60% in both operational scenarios, confirms that synchronization among autonomous managerial, operational, analytical, and risk-management agents is the principal factor driving efficiency improvement. The reduction in operational disruptions by more than 60% and the simultaneous decrease in deviations from planned enterprise performance indicators by more than half indicate that the platform effectively synchronizes enterprise processes and managerial decision-making within a unified adaptive environment.

In modern enterprise ecosystems, this synchronization is critically important because even relatively minor operational disruptions may generate cascading effects influencing organizational continuity, resource allocation, managerial stability, financial performance, and strategic adaptability. Consequently, improved coordination represents not merely an operational benefit but a fundamental mechanism for strengthening enterprise economic security.

Another important finding concerns the transformation of workload distribution among enterprise agents. The reduction in the coefficient of variation from 44.7% to 15.8% demonstrates that the platform substantially mitigates the structural imbalances characteristic of traditional decentralized management systems. Under conventional coordination approaches, organizational units or agents with lower operational costs often receive disproportionately high workloads, resulting in overload concentration, reduced adaptability, and increased systemic risks.

The proposed platform-based adaptive coordination mechanism incorporates not only operational efficiency indicators but also risk exposure, resilience factors, and coordination constraints. This enables more balanced allocation of managerial and operational tasks, improves enterprise adaptability, and reduces the probability of bottleneck formation within the organizational ecosystem.

The crisis scenario particularly highlights the role of the digital platform as a resilience-enabling governance mechanism. The calculated Resilience Index (RI = 0.667) confirms that the platform-coordinated enterprise system demonstrates substantially higher resistance to operational disturbances, uncertainty, and environmental instability. The reduction in critical operational failures by approximately two-thirds indicates that the proposed adaptive coordination framework is capable of maintaining continuity of enterprise operations even under conditions of severe instability and elevated systemic risk exposure.

This finding is especially important because modern enterprise systems are highly vulnerable to cascading disruptions. Operational failures, coordination breakdowns, cyber incidents, financial instability, or resource constraints may rapidly propagate throughout the enterprise ecosystem and negatively affect organizational sustainability. Therefore, resilience-oriented adaptive governance becomes strategically more important than pure operational efficiency under crisis conditions.

The Pareto analysis and the results obtained through the Weighted Sum Model (WSM) provide additional insights into the nature of optimality within enterprise management systems. The findings confirm that optimal coordination strategies are inherently context-dependent. Under stable conditions, balanced alternatives minimizing operational costs and coordination time remain preferable, whereas crisis environments shift optimization logic toward resilience-oriented strategies, even at the expense of higher operational expenditures.

This observation is fully consistent with modern approaches to enterprise risk management and economic security, according to which managerial priorities progressively move from pure efficiency optimization toward organizational robustness, adaptability, and continuity preservation under uncertainty conditions.

The sensitivity analysis further confirms the adaptive nature of the proposed model. Changes in the weight assigned to risk-related factors produce a systematic transition between economically efficient and resilience-oriented coordination strategies. This demonstrates that the proposed framework can function as a dynamic decision-support instrument capable of adjusting enterprise governance strategies according to changing environmental conditions, threat intensity, and managerial priorities.

The obtained results also have important theoretical implications. The study confirms that the effectiveness of enterprise economic security systems depends not only on the operational characteristics of individual organizational units but primarily on the architecture of interactions among autonomous agents within the corporate governance ecosystem. The proposed framework demonstrates that a digital platform may function as an active coordination entity integrating information flows, optimizing managerial decisions, supporting adaptive governance, and ensuring synchronized behavior within a multi-agent enterprise environment.

This extends existing approaches in which digital platforms are predominantly considered passive infrastructures for information exchange or operational automation rather than active adaptive coordination and decision-support mechanisms.

The findings are also consistent with previous studies emphasizing the importance of coordination and adaptability for reducing disruption impacts within enterprise systems. At the same time, the present study contributes a new perspective by demonstrating the effectiveness of platform-based adaptive coordination under conditions of multi-agent autonomy, organizational decentralization, and uncertainty.

From a practical perspective, the results confirm the feasibility of implementing digital platforms as adaptive coordination instruments within enterprise management systems. The proposed framework improves resource utilization, reduces operational disruptions, enhances synchronization among organizational processes, and strengthens enterprise resilience under uncertainty conditions. This is particularly important for enterprises operating within unstable economic environments, conditions of digital transformation, geopolitical turbulence, or post-crisis recovery processes.

At the same time, the study has several limitations. The simulation-based nature of the proposed framework requires the use of generalized parameters, which may limit the precision of practical applications in specific enterprise environments. Furthermore, the model does not fully incorporate behavioral aspects of agent interaction, including strategic opportunism, informational asymmetry, bounded rationality, and complex organizational conflicts.

These limitations create opportunities for future research, particularly regarding the integration of empirical enterprise data, application of machine learning methods, incorporation of behavioral economics approaches, and extension of the framework toward more complex adaptive governance and self-learning coordination mechanisms.

Overall, the obtained results confirm that the proposed platform-based multi-agent adaptive coordination framework provides not only operational optimization effects but also systemic improvements in enterprise resilience, adaptive governance, and economic security under conditions of uncertainty and digital transformation.

**8. Conclusions.** This study developed a multi-agent adaptive coordination model for ensuring enterprise economic security in the context of corporate governance under conditions of digital transformation and environmental uncertainty. Unlike traditional enterprise management approaches based either on rigid hierarchical coordination or fragmented decentralized decision-making, the proposed framework integrates autonomous agent behavior with a platform-oriented adaptive coordination mechanism capable of supporting enterprise resilience, business continuity, and risk-oriented governance.

The principal scientific contribution of the study lies in the formalization of enterprise coordination processes as a multi-objective optimization problem simultaneously incorporating operational efficiency, coordination responsiveness, and systemic risk minimization. In addition, the study proposed several integrated performance indicators, including the Platform Efficiency Index (PEI), the Coordination Effect Index (CEI), and the Resilience Index (RI), enabling quantitative assessment of the impact of digital platform coordination on enterprise economic security and organizational stability.

The results of the simulation experiment confirm the effectiveness of the proposed framework. Under stable operating conditions, implementation of the digital platform reduced total operational and managerial costs by 10.37%, decreased average coordination time by 13.04%, reduced the number of operational disruptions by 66.67%, and lowered deviations from planned enterprise performance indicators by more than half. Under crisis conditions characterized by elevated uncertainty and instability, the primary effect was associated with increased enterprise resilience: the integrated risk index decreased by 29.79%, while the number of critical operational failures was reduced by 66.7%.

The obtained results demonstrate that the main value of the digital platform lies not merely in optimizing individual operational processes, but in enabling systemic adaptive coordination among enterprise agents within the corporate governance ecosystem. This is confirmed by the high values of the Coordination Effect Index (approximately 60%) and by the substantial reduction in workload imbalance among enterprise agents, reflected in the decrease of the coefficient of variation from 44.7% to 15.8%. These findings indicate that the platform effectively mitigates structural imbalances characteristic of decentralized enterprise management systems.

The study additionally demonstrates that the proposed framework generates a set of Pareto-efficient coordination strategies, enabling adaptation of managerial decisions to varying environmental conditions and strategic priorities. Under crisis environments, the system prioritizes resilience-oriented and low-risk coordination strategies, even at the expense of higher operational costs, whereas stable environments favor balanced alternatives combining operational efficiency, coordination quality, and organizational reliability.

Consequently, the research confirms that multi-agent adaptive coordination based on digital platforms enables a balance between the autonomy of enterprise agents and the global efficiency of the enterprise management system. This forms a new conceptual foundation for enterprise economic security management in which the digital platform acts as an active data integrator, adaptive coordination mechanism, risk-management instrument, and intelligent decision-support environment under uncertainty conditions.

The practical significance of the proposed approach lies in the possibility of applying the model to enterprise management tasks, including optimization of managerial coordination, reduction of operational and systemic risks, strengthening of business

continuity, improvement of organizational resilience, and enhancement of adaptive governance mechanisms. This is particularly important for enterprises operating under conditions of digital transformation, environmental instability, geopolitical turbulence, and post-crisis economic recovery.

At the same time, the study has several limitations associated with the simulation-based nature of the modeling approach and the use of generalized operational parameters. Future research should therefore focus on empirical validation of the proposed framework using real enterprise data, integration of machine learning methods for predictive risk assessment, incorporation of behavioral and institutional factors into the coordination process, and extension of the model toward more complex adaptive governance and self-learning enterprise systems.

Overall, the proposed approach demonstrates significant potential as an effective enterprise management instrument capable of strengthening economic security, improving adaptive governance, increasing organizational resilience, and ensuring continuity of enterprise operations under conditions of uncertainty and digital transformation.

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