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A COMPREHENSIVE MECHANISM FOR MANAGING THE ECONOMIC SECURITY OF UKRAINIAN METALLURGICAL ENTERPRISES BASED ON A CONTOUR-INDEX MODEL

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The article substantiates a comprehensive mechanism for managing the economic security of Ukrainian metallurgical enterprises based on a contour-index model adapted to conditions of wartime instability, energy constraints, logistical disruptions, digital threats, and increasing regulatory and carbon pressure from the European Union. The relevance of the study stems from the fact that the partial recovery of production in the industry is not accompanied by a proportional recovery of innovation, technological, and market resilience, and therefore cannot be considered a sufficient indicator of an adequate level of economic security. The aim of the article is to develop an adaptive mechanism that integrates monitoring, integral assessment, selection of a portfolio of managerial decisions, and control of their effectiveness within a unified system. Economic security of a metallurgical enterprise is proposed to be interpreted as the capacity to sustain continuity of value creation, fulfil contractual obligations, and maintain controllability of production processes under external disturbances without loss of financial stability, human resource capacity, and access to markets. An index of adaptive economic security is developed, combining financial, production, energy, innovation, digital, and regulatory parameters normalised on a unified scale. An optimisation framework for selecting a portfolio of managerial actions is proposed, aimed at minimising expected losses and costs under existing budgetary, human resource, and technological constraints. The role of a competence centre is substantiated as an organisational regulator of adaptability, providing analytical, coordination, educational, and communication support to the management cycle. The practical significance of the results lies in the possibility of applying the proposed mechanism to prioritise decisions related to energy autonomy, cyber resilience, logistics diversification, equipment modernisation, and low-carbon investments. The scientific novelty consists in combining the contour approach, index-based assessment, and portfolio decision logic within a single management system of economic security oriented towards reducing future losses and maintaining the long-term competitiveness of metallurgical enterprises.

Keywords: industry, economic security, adaptive management, contour-index mechanism, integral assessment, digital resilience, decarbonisation, regulatory-carbon risks, sustainable development.

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Introduction and formulation of the problem

Metallurgy remains a core industrial pillar: in 2024, the iron and steel sector accounted for 7.2% of Ukraine's gross domestic product (including related value chains), more than 15% of merchandise exports, invested approximately USD 650 million, and contributed nearly USD 0.9 billion in tax revenues [1].

Statistical evidence confirms the structural nature of losses. Steel production declined from 21.366 million tonnes in 2021 to 6.263 million tonnes in 2022, representing a decrease of approximately 70.7%, and recovered only to 7.575 million tonnes in 2024, which remains significantly below pre-war levels [2].

A critical bottleneck in economic security has been the decline in innovation and modernisation capacity. According to estimates by GMK Center, innovation expenditure in metallurgy amounted to USD 1.3 million in 2024 compared to USD 69.7 million in 2020, while the share of innovation-active enterprises in the sector was only 9.8% in 2024 [3].

This asymmetry generates the risk of "recovery without development", where production indicators partially improve, yet the technological and energy base does not modernise at a sufficient pace, thereby reducing competitiveness and increasing operational risks and cost intensity.

Regulatory pressure on the export contour is intensifying due to the European Union's Carbon Border Adjustment Mechanism, applied in its transitional phase since 1 October 2023 and entering its definitive phase on 1 January 2026 [4].

For iron and steel, this regime entails reporting requirements on embedded emissions during the transitional period and the gradual introduction of financial obligations thereafter. Analytical materials from the Low Carbon Ukraine programme indicate that in 2023, 79% of Ukraine's iron and steel exports fell under the CBAM framework (compared to 40% in 2021), reinforcing the dependence of enterprise economic security on the carbon intensity of products and the structure of export markets [5].

The research problem lies in the absence of an economic security mechanism that is simultaneously measurable, adaptive, and capable of managing a portfolio of decisions within the triangle of "wartime resilience–decarbonisation compliance–digital resilience".

In applied economics and management, enterprise economic security is most often conceptualised as a multidimensional system encompassing financial, human resource, informational, and technical-technological components.

The strength of this approach lies in the completeness of the "security map", while its limitation consists in the difficulty of integrating these components into a unified decision-making model, particularly under high-frequency risk conditions.

For example, Yu. Ohrenych and co-authors propose a mechanism with defined subject, object, principles, functions, and instruments, as well as response strategies depending on the states of "danger–risk–threat–security" [6]. However, this concept lacks a formalised linkage between indicators and the budgetary logic of managerial actions, which is critical for capital-intensive metallurgy under resource constraints.

In parallel, a scientific discourse is evolving on organisational resilience and risk management as complementary practices. Studies by V. Zadoia and T. Charkina confirm that a comprehensive understanding of resilience requires simultaneous consideration of operational and relational dimensions, as well as their contribution to "survival" and "sustainability" [7].

For metallurgical enterprises, this implies that security cannot be reduced to financial ratios alone, but must include the network reliability of suppliers, energy partners, logistics operators, and communities.

Systematic reviews of supply chains indicate that digital solutions enhance resilience primarily through increased transparency and response speed, although the effectiveness of different technological "packages" varies. For metallurgy, this is particularly relevant, as digital control contours in production and logistics simultaneously reduce operational risks while expanding the cyber threat surface, which must be incorporated into the economic security mechanism as a distinct dimension.

Additionally, contemporary studies in risk management demonstrate the relevance of combining traditional risk assessment (probability and impact) with the evaluation of resilience in terms of recovery capacity and resource reconfiguration [8; 9].

Such integration is productive for the development of economic security mechanisms, as it allows consideration not only of risk prevention but also of the system's ability to maintain functionality under disruption and constraints.

Specialised studies on Ukraine indicate that the future competitiveness of industrial sectors increasingly depends on spatial reconfiguration of production, access to low-carbon energy, the use of green hydrogen, and significant investments in supply chain restructuring [10]. This implies that decarbonisation can no longer be treated as external to enterprise economic security. For metallurgy, it is directly linked to market access, capital availability, and stable sales channels.

The research gap lies in the fact that existing approaches either provide detailed descriptions of economic security components without integrating them into a unified management system, or analyse resilience and risk management outside the regulatory pressure of CBAM, or treat decarbonisation solely as a techno-economic issue. As a result, enterprises obtain useful risk characteristics but lack a tool that

determines when intervention is required, where limited resources should be allocated, and which set of actions will yield the greatest effect.

Purpose of the article

The purpose of the article is to develop a comprehensive contour-index mechanism for the adaptive management of the economic security of a metallurgical enterprise, combining monitoring, integral assessment, the selection of a portfolio of managerial decisions, and control over their effectiveness under conditions of wartime, energy, logistical, digital, and regulatory-carbon risks, while also ensuring the integration of decarbonisation compliance and digital resilience into a unified managed system for sustaining long-term development and competitiveness.

Presentation of the main material

У Within the scope of the study, the economic security of a metallurgical enterprise is understood as the ability to maintain continuity of value creation, fulfil contractual obligations, and preserve the controllability of production processes under the influence of external factors without losing financial stability, workforce capacity, or access to sales markets. Such an interpretation corresponds more closely to the actual operating conditions of an industrial enterprise than a narrow reduction of security solely to financial indicators.

This approach makes it possible to move from describing individual threats to constructing an integrated mechanism for managing economic security.

In practical terms, this mechanism operates as a closed cycle. First, the enterprise identifies risk signals, then carries out monitoring and early warning, after which it assesses its condition, selects a package of actions, implements it, and verifies the result. This makes it possible not to wait until a problem turns into an actual loss, but to respond at a stage when the situation can still be corrected.

For metallurgy, this cycle encompasses at least three major contours. The first relates to wartime, energy, and logistical resilience. The second is associated with decarbonisation compliance and the preservation of positions in export markets. The third covers digital resilience, including cyber protection, data protection, and the reliability of information systems. A problem arising in any one of these contours quickly spills over into the others; therefore, considering them separately is no longer sufficient.

The quantitative core of the model is the enterprise's adaptive economic security index:

$$I_t = \sum_{i=1}^{m} w_i x_{i,t}, \qquad \sum_{i=1}^{m} w_i = 1, \qquad w_i \geq 0, \tag{1}$$

where I_t denotes the integral level of economic security at time t;

$x_{i,t}$ – the normalised value of the i-th indicator;

w_i – the weight of the indicator;

m – the number of parameters.

The set of parameters should reasonably include financial, production, energy, innovation, digital, and regulatory dimensions.

For example, the following indicators may be considered: profitability, downtime duration, the share of backup energy supply, the level of digitalisation of critical processes, carbon intensity of products, supply reliability, the share of exports to markets with stringent emissions requirements, as well as indicators of innovation activity.

Two rules are applied for normalising the indicators. If an increase in the indicator improves the level of security, the following formula is used:

$$x_{i,t} = \frac{z_{i,t} - \min(z_i)}{\max(z_i) - \min(z_i)}. \tag{2}$$

If an increase in the indicator deteriorates the level of security, an alternative formula is applied:

$$x_{i,t} = 1 - \frac{z_{i,t} - \min(z_i)}{\max(z_i) - \min(z_i)}, \tag{3}$$

where $z_{i,t}$ is the actual value of the indicator;

$\max(z_i)$ are $\min(z_i)$ the boundary benchmarks established based on historical data series, regulatory standards, or industry benchmarks.

This approach makes it possible to transform heterogeneous indicators into a unified scale from 0 to 1 and render them suitable for joint analysis.

The weights should be determined using a combined approach. One part of the weights should be based on expert assessment, taking into account the specific features of the enterprise. The other part should reflect the intensity of external pressures-wartime risks, energy instability, carbon regulation, scarcity of investment resources, and digital threats.

As a result, the model does not remain abstract but can be calibrated to the actual operating conditions of the enterprise.

The index itself is not an end in its own right. It serves as a tool for selecting a portfolio of actions that minimises expected losses under existing resource constraints. In formalised terms, this can be expressed as follows:

$$\min_{A \in \Omega} [\mathbb{E}(L(Z_t, A)) + C(A)], \tag{4}$$

where A denotes the portfolio of managerial actions;

Z_t is the vector of external threats;

$L(Z_t, A)$ represents the expected losses resulting from

disruptions to production, financial, or market stability; $C(A)$ is the cost of implementing the selected portfolio; Ω is the set of feasible decisions subject to budgetary, human resource, and technological constraints.

In applied terms, this means that backup energy supply, cyber protection, logistics diversification, equipment modernisation, and low-carbon investments can be considered within a single comparative framework. Management is therefore presented not with a simple list of desirable actions, but with a set of alternatives characterised by different costs and varying effects in reducing future losses.

Industry data for 2021-2024 reveal a contradictory picture. On the one hand, in 2024 steel production in Ukraine increased to 8.1 million tonnes compared to previous years; on the other hand, this result remains significantly below the 21.9 million tonnes recorded in 2021 [2] (Fig. 1).

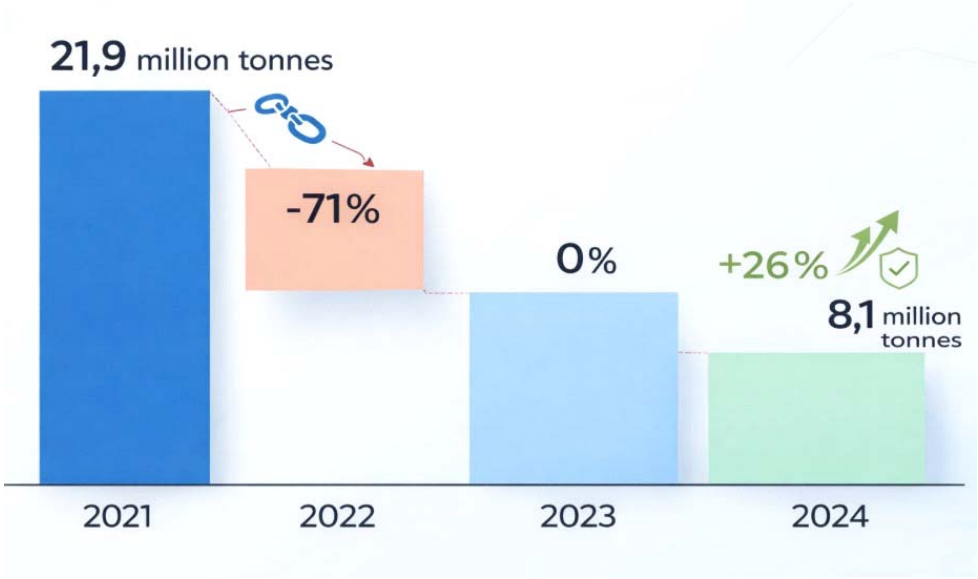

Fig. 1. Waterfall chart of steel production in Ukraine (2021-2024)
Source: compiled by the author based on [2]

Based on these data, it may be concluded that the recovery of physical output cannot automatically be equated with the recovery of economic security. An enterprise may increase production while remaining vulnerable because of high energy intensity, weak modernisation, fragile logistics, or the risk of losing export markets.

No less illustrative are the parameters of innovation activity. Expenditure on innovation in metallurgy declined from USD 69.7 million in 2020 to USD 1.3 million in 2024, that is, by approximately 98.1%. This indicates not merely a reduction in investment, but the effective emergence of a technological gap that constrains the long-term modernisation of the industry. This is further corroborated by the fact that the share of innovation-active enterprises in metallurgy amounted to only 9.8% in 2024 [3].

At such a level, it is difficult to speak of the widespread diffusion of new technologies, digital solutions, or modern organisational practices. Put differently, the revival of production has occurred more rapidly than the restoration of development capacity.

Alongside production, innovation, and market imbalances, another critical contour of vulnerability is taking shape, namely the regulatory-carbon dimension. Its significance for Ukrainian metallurgy has intensified sharply owing to the extension of the CBAM mechanism to iron and steel and the transition to its definitive operational regime from January 1, 2026 [4].

As a result, the competitiveness of enterprises is increasingly determined not only by output volumes, production costs, or export logistics, but also by their ability to document embedded emissions, the structure of energy consumption, and compliance with the environmental requirements of the European market.

The situation is further exacerbated by the sector's high export exposure. According to Low Carbon Ukraine, in 2023, 79% of Ukrainian iron and steel exports were subject to carbon border adjustment measures [5]. It is therefore appropriate to summarise the principal changes that shaped the condition of Ukraine's metallurgy in 2021–2024 and to distinguish those factors that directly transform the requirements imposed on enterprise economic security management systems (Table).

Table

Summary of the principal changes in Ukraine's metallurgy in 2021–2024

Indicator	2021	2022	2023	2024	Analytical conclusion
Steel production, million tonnes	21.9	6.3	6.2	8.1	In 2022, a sharp production shock occurred; in 2023, the industry remained in a phase of depressed reproduction; in 2024, only a partial recovery was recorded
Steel production index relative to 2021, %	100.0	29.4	29.0	35.5	Even in 2024, steel output amounted to only slightly more than one-third of the pre-war level
Annual rate of change in steel production, %	–	–70.6	–1.6	+22.6	Following the collapse of 2022, no tangible recovery occurred in 2023; the positive dynamics of 2024 do not compensate for previous losses
Innovation expenditure of enterprises in the sector	Baseline pre-war level	Sharp decline	Minimisation	Localised recovery in selected areas	Innovation activity lost its systemic character and was displaced by short-term survival priorities
Dependence on external sales markets	High	Critically high	Critically high	High	The resilience of the industry is substantially determined by external market conditions, logistics, trade restrictions, and access to export channels
Dominant type of managerial response	Development and modernisation	Anti-crisis survival	Maintenance of operational capacity	Partial recovery and adaptation	Traditional financial control does not capture the full range of production, logistics, market, and innovation risks

Source: generalised by the author based on [11–12]

Table 1 summarises the key parameters of the transformation of Ukraine's metallurgy in 2021–2024 and allows several fundamental trends to be identified: a sharp production shock in 2022, the absence of a full-scale recovery in 2023, partial revival in 2024, the contraction of systemic innovation activity, and the persistence of a high dependence of the sector on external sales markets.

Under such conditions, traditional financial controlling no longer provides sufficient managerial sensitivity, as it primarily captures the consequences of the crisis but does not enable the timely integration of production, logistical, export, technological, and investment risks into the decision-making process.

As a result, there arises a need for a model that integrates the assessment of economic security with specific managerial responses and risk-oriented intervention tools.

The proposed approach envisages the incorporation of decarbonisation compliance into the internal parameters of the economic security mechanism, since under CBAM conditions it directly affects costs, access to the EU market, and the long-term competitiveness of a metallurgical enterprise.

In this context, the economic security mechanism of a metallurgical enterprise is understood as a holistic system of interrelated processes of monitoring, assessment, decision selection, and control, aimed at neutralising threats and ensuring sustainable development under conditions of multiple risks.

Risks of different types, resilience indicators, and response costs are integrated into a single optimisation framework for the formation of a portfolio of managerial actions, thereby implementing the principles of multi-criteria decision-making and the integration of managerial decisions.

The analysis of industry data confirms that an increase in production volumes alone is not a sufficient indicator of an adequate level of economic security if the innovation, digital, and regulatory dimensions remain weak.

This conclusion follows from the systemic nature of economic security: the economic security of an enterprise is not formed as a simple sum of isolated indicators, but as an emergent result of the interaction of all functional domains.

The effective functioning of the "monitoring–assessment–decision selection–control" loop depends on the development of the enterprise's internal capacity to collect, interpret data, and promptly transform them into managerial actions.

The proposed mechanism is presented as a contour-index adaptive system in which external disturbances are transformed into data flows for monitoring, then into an integral assessment of the state of economic security, after which they transition into the domain of managerial decision-making and subsequent control verification (Fig. 2).

Importantly, all stages of the cycle operate not in isolation but within a multi-contour managerial environment encompassing innovation, digital, regulatory, production, financial, energy, and market contours.

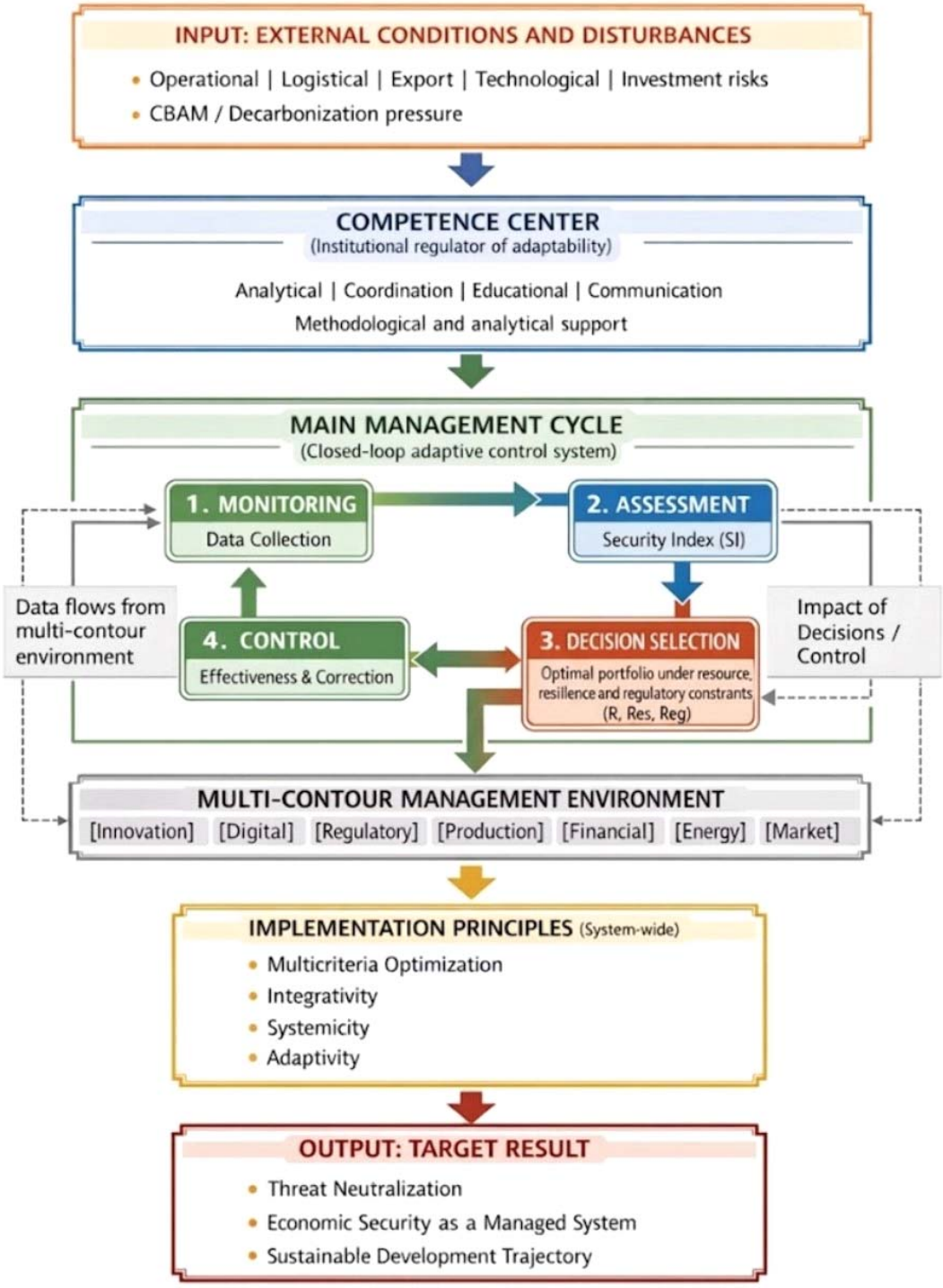

Fig. 2. Comprehensive contour-index mechanism for the adaptive management of the economic security of a metallurgical enterprise

Source: developed by the author

In this context, the establishment of a competence centre integrating analytical, coordination, educational, and communication functions contributes to aligning production, financial, energy, digital, and market decisions within a metallurgical enterprise. Such a centre serves as the organisational embodiment of the principle of adaptability, ensuring a rapid response to changes in the external environment and internal coherence between strategic and operational decisions.

The developed model transforms economic security into a manageable system with clearly defined measurable indicators and a structured sequence of actions.

The central element of the assessment contour is the security index (SI), which aggregates the influence of key enterprise performance parameters and enables the translation of heterogeneous environmental signals into a comparable managerial format. Its purpose lies not only in capturing the current state but also in identifying critical deviations between system contours that form the basis for selecting priority managerial actions.

Wartime, energy, logistical, digital, and regulatory-carbon risks are integrated into a unified assessment framework directly linked to the formation of a portfolio of managerial decisions. This approach implements the principle of proactivity, as it focuses not only on the current state but also on preventing potential losses through comprehensive risk management.

Data for 2020-2024 indicate that the partial recovery of steel production volumes in 2024 has not eliminated the fundamental vulnerabilities of the sector. The significant reduction in innovation expenditure, the low share of innovation-active enterprises, and the intensification of regulatory pressure on export activities point to deeper structural constraints on development.

Such a toolkit enables enterprises to allocate limited resources rationally among measures for protecting physical infrastructure, ensuring energy autonomy, strengthening cyber resilience, and implementing low-carbon modernisation. This, in turn, creates a basis for shifting from fragmented responses to isolated threats towards the systematic management of potential losses in the long term, in accordance with the principles of building dynamic capabilities under conditions of high uncertainty.

At the same time, the principles of multi-criteria decision-making, integration, systemicity, and adaptability apply to the mechanism as a whole, from the selection of input data and the construction of indicators to the evaluation of alternatives, the implementation of managerial decisions, and the adjustment of subsequent actions.

Promising directions for further research include the detailed specification of the model at the level of individual enterprises, with an expanded indicator base incorporating quarterly financial, energy, logistical, and digital metrics.

Particular interest lies in developing an index of regulatory compliance cost for exports to the European Union, based on actual embedded emissions, the structure of energy consumption, and the costs associated with CBAM compliance. Such development would further implement the principle of comprehensiveness by integrating macro- and microeconomic dimensions of economic security.

Conclusion

The proposed approach provides grounds to assert that, under current conditions, the economic security of a metallurgical enterprise should be understood not as a set of isolated protective measures, but as a regime of managed adaptation to an environment characterised simultaneously by wartime, energy, market, digital, and regulatory-carbon constraints.

The scientific contribution of the study lies in substantiating a management structure that transforms heterogeneous risk signals into an ordered system of managerial choice and ensures the alignment of short-term resilience with the long-term capacity of the enterprise for renewal.

In contrast to approaches where security is defined primarily through isolated indicators or ex post loss assessments, the developed mechanism is oriented towards maintaining enterprise controllability under conditions of instability, resource scarcity, and increasing requirements for export compliance.

The practical significance of the results lies in the fact that the proposed mechanism establishes a methodological basis for prioritising managerial actions according to their contribution to reducing future losses, preserving market presence, and maintaining the functional integrity of the enterprise.

Such an approach is particularly relevant for Ukrainian metallurgy, where the partial recovery of production does not eliminate accumulated technological, institutional, and regulatory gaps.

Therefore, enhancing economic security in the sector should be associated not with the expansion of individual protective instruments, but with the formation of a comprehensive system of decisions capable of synchronising the investment, energy, digital, and decarbonisation trajectories of enterprise development.

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КОМПЛЕКСНИЙ МЕХАНІЗМ УПРАВЛІННЯ ЕКОНОМІЧНОЮ БЕЗПЕКОЮ МЕТАЛУРГІЙНИХ ПІДПРИЄМСТВ УКРАЇНИ НА ОСНОВІ КОНТУРНО-ІНДЕКСНОЇ МОДЕЛІ

Абражан І. А.

У статті обґрунтовано комплексний механізм управління економічною безпекою металургійних підприємств України на основі контурно-індексної моделі, адаптованої до умов воєнної нестабільності, енергетичних обмежень, логістичних розривів, цифрових загроз і посилення регуляторно-вуглецевого тиску з боку Європейського Союзу. Актуальність дослідження зумовлена тим, що часткове відновлення виробництва в галузі не супроводжується пропорційним відновленням інноваційної, технологічної та ринкової стійкості, а отже не може розглядатися як достатня ознака належного рівня економічної безпеки. Метою статті є розроблення адаптивного механізму, який поєднує моніторинг, інтегральне оцінювання, вибір портфеля управлінських рішень і контроль їх результативності в єдиній системі. Економічну безпеку металургійного підприємства запропоновано трактувати як здатність підтримувати безперервність створення вартості, виконання контрактних зобов'язань і керованість виробничих процесів під дією зовнішніх збурень без втрати фінансової стійкості, кадрової спроможності та доступу до ринків збуту. Розроблено індекс адаптивної економічної безпеки, що поєднує фінансові, виробничі, енергетичні, інноваційні, цифрові та регуляторні параметри, нормовані на єдиній шкалі. Запропоновано оптимізаційну постановку вибору портфеля управлінських дій, орієнтовану на мінімізацію очікуваних втрат і витрат за наявних бюджетних, кадрових і технологічних обмежень. Обґрунтовано роль компетентнісного центру, як організаційного регулятора адаптивності, що забезпечує аналітичну, координаційну, освітню та комунікаційну підтримку управлінського циклу. Практичне значення результатів полягає у можливості використання запропонованого механізму для пріоритезації рішень щодо енергетичної автономії, кіберстійкості, диверсифікації логістики, модернізації обладнання та низьковуглецевих інвестицій. Наукова новизна полягає в поєднанні контурного підходу, індексного оцінювання та портфельної логіки вибору рішень у межах єдиної керованої системи економічної безпеки, орієнтованої на зниження майбутніх втрат і підтримання довгострокової конкурентоспроможності металургійних підприємств.

Ключові слова: промисловість, економічна безпека, адаптивне управління, контурно-індексний механізм, інтегральне оцінювання, цифрова стійкість, декарбонізація, регуляторно-вуглецеві ризики, стійкий розвиток.

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The article substantiates a comprehensive mechanism for managing the economic security of Ukrainian metallurgical enterprises based on a contour-index model adapted to conditions of wartime instability, energy constraints, logistical disruptions, digital threats, and increasing regulatory and carbon pressure from the European Union. The relevance of the study stems from the fact that the partial recovery of production in the industry is not accompanied by a proportional recovery of innovation, technological, and market resilience, and therefore cannot be considered a sufficient indicator of an adequate level of economic security. The aim of the article is to develop an adaptive mechanism that integrates monitoring, integral assessment, selection of a portfolio of managerial decisions, and control of their effectiveness within a unified system. Economic security of a metallurgical enterprise is proposed to be interpreted as the capacity to sustain continuity of value creation, fulfil contractual obligations, and maintain controllability of production processes under external disturbances without loss of financial stability, human resource capacity, and access to markets. An index of adaptive economic security is developed, combining financial, production, energy, innovation, digital, and regulatory parameters normalised on a unified scale. An optimisation framework for selecting a portfolio of managerial actions is proposed, aimed at minimising expected losses and costs under existing budgetary, human resource, and technological constraints. The role of a competence centre is substantiated as an organisational regulator of adaptability, providing. The practical significance of the results lies in the possibility of applying the proposed mechanism to prioritise decisions related to energy autonomy, cyber resilience, logistics diversification, equipment modernisation, and low-carbon investments. The scientific novelty consists in combining the contour approach, index-based assessment, and portfolio decision logic within a single management system of economic security oriented towards reducing future losses and maintaining the long-term competitiveness of metallurgical enterprises.

Keywords: industry, economic security, adaptive management, contour-index mechanism, integral assessment, digital resilience, decarbonisation, regulatory-carbon risks, sustainable development.

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