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APPLYING INTERNATIONAL TECHNOLOGY TRANSFER TO DEVISE MANAGEMENT STRATEGIES FOR MINING AND METALLURGICAL ENTERPRISES IN A CIRCULAR ECONOMY

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This study investigates processes of managing enterprises in the mining and metals production sector in the framework of a circular economy based on international technology transfer. The task addressed relates to the issue of adapting strategic mechanisms of industry management to the conditions of a circular economy. The result is the construction of trend models based on actual data for 2010–2023 and extrapolated to 2024–2025. They are used as the basis for assessing business activity and determining the competitiveness of the industry and its subsectors. Special features of the study are the application of a strategic approach to managing enterprises in the mining and metals production sector based on modernization and the use of international technology transfer. The effect obtained is to enable the transition to higher technological structures, to strengthen the internal and external competitiveness of enterprises. It is shown that 2021 became a bifurcation point when the positive trend in sales growth over 2020–2021 increased from UAH 543.8 billion to UAH 959.9 billion but, during 2021–2022, it changed sharply to negative with the analyzed indicator decreasing to UAH 392.8 billion.

This study's results are distinguished by the substantiation of a strategic approach to the development of the mining and metals industry in the risk-oriented environment of the circular economy. Unlike existing approaches, the proposed one is based on the synthesis of adaptive mechanisms and principles of sustainable development. The scope of the findings covers ways devised to solve the tasks of this sector's development on an innovative basis. Conditions for the practical application of the results are the design and implementation of strategic target programs for engaging enterprises from the mining and metals production sector in international technology transfer

Keywords: international transfer, sustainable development, technologies, innovations, strategies, adaptive management, mining and metallurgical, circular economy

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1. Introduction

The Ukrainian mining and metals industry (MMI) is an important sector of the national economy, which acts as its basis and enables functioning of other related types of economic activity in the field of mechanical engineering, energy, and construction. Its internal potential is provided by a powerful contribution to the formation of gross domestic product (GDP) and job creation. Significant foreign economic potential allows for the receipt of foreign exchange earnings to the accounts of mining and metallurgical enterprises, balancing the state's balance of payments. However, MMI currently is under significant pressure from military-political and economic uncertainty. Enterprises face systemic risks of loss of production capacities and logistics infrastructure because of military activities and temporary occupation of the territories where they are located.

Changes in the domestic and foreign markets that provide resources and demand for finished products from MMI re-

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quire devising and implementing measures to strengthen the competitiveness of the industry. There is an urgent need to change logistics routes to ensure supply and sales, as well as to take into account the economic risks of price fluctuations on world markets.

The solution to the outlined tasks should be based on the search for new transport corridors, the implementation of international standards in the field of production quality and ecology, the production of "green" and high-tech articles by enterprises in the industry. The prerequisites for strengthening the competitiveness of MMI are the introduction of mechanisms for strategic management of operational and innovation and investment activities of enterprises based on integration into international value chains and the use of the advantages of international technology transfer. Solving the problems of resource conservation, material and energy conservation of enterprises in the industry can be achieved by implementing the principles of the circular economy. It can balance their economic, social, and environmental priorities in the context of strengthening the financial stability and restoration of MMI, as well as the sustainable development of the national economy.

The requirements for reducing the cost of production, optimizing production processes, increasing the environmental safety of production, reducing harmful emissions and waste volumes to mitigate the negative impact on the environment require the implementation of non-standard innovative solutions. They should be based on the technological renewal of MMI enterprises, the integration of advanced technologies and international transfer into the practice of their activities, which would allow for the flexibility and sustainability of the management system, economic and environmental safety.

Thus, the scientific issue of implementing international technology transfer for devising enterprise management strategies is important. It is significant for the mining and metals industry in the circular economy in view of its institutional features related to extraction, use of natural raw materials, and the harmful impact of technological processes on the external environment. Therefore, research on the application of a strategic approach to solving the problems of the industry, its modernization, the introduction of innovations, as well as the transition to higher technological structures to strengthen the competitiveness of enterprises, is a relevant and timely task.

2. Literature review and problem statement

Historical foundations for the evolution of the Donetsk mining and metallurgical center are outlined in work [1], but there is no assessment of their impact on the formation of the modern image of the region as an old-industrial one. Certain limitations of that study were overcome in [2], which generalized modern trends and results related to the functioning of the Ukrainian mining and metallurgical industry. However, it would be useful to determine the possible losses of the industry and the consequences for the Ukrainian economy of the effect of identifying negative factors. The fundamental imperatives of eliminating the uncertainty in the functioning of an iron ore enterprise based on monitoring its activities are the subject of research reported in [3]. It is important to strengthen the predictive aspect of the obtained results in order to reduce the negative impact on the efficiency of the enterprises. The issue of uncertainty in the operating environment of MMI enterprises is considered in work [4] in the context of knowledge representation in intelligent automation systems for power system management. However, issues related to ensuring energy efficiency in accordance with the principles of the circular economy remain unresolved. In [5], hierarchical and structural-system approaches to measuring the efficiency of functioning and the level of internationalization of mining and metallurgical industrial groups of Ukraine based on econometric modeling in order to determine the current vectors of MMI development are substantiated. Given the high energy consumption of the industry, a limitation of the work is considered to be insufficient attention to energy saving as the most important component of the efficiency of mining and metallurgical enterprises and their groups. The results of work [6] are ensuring the operational efficiency of MMI enterprises on the basis of sustainable development, the combination of the principles of which with the basic principles of the circular economy would make it possible to strengthen the theoretical and methodological level of solving the problems in the industry.

In [7], ways of supporting the energy transition and actions on climate change in China based on the implementation of the goals of the "dual carbon" and the introduction of a number of relevant political provisions are substantiated. However, strategic recommendations for transferring the Chinese experience to other countries that seek to achieve the goals of the climate and energy strategy are limited and not sufficiently complete. These shortcomings are also inherent in [8], which notes that China dominates research on technologies for recycling precious metals from electronic waste in the context of sustainable development. However, the possibilities for international cooperation in this area are not clearly outlined.

Paper [9] assesses the role of local investments supporting the energy transition, depending on the level, structure, and dynamics of changes in carbon emissions in the regions of Poland. It has been convincingly proven that the greatest challenge for local governments is emissions from the following sources: diffuse (agriculture) and linear (transport). The study focuses on the national level, detailing the reasons for the stagnation of carbon emissions at the regional level. The significance of its results would increase if the long-term consequences of investments in the low-carbon economy were predicted at the supranational level.

In paper [10], conceptual principles for the development of innovations in the European raw materials sector through the evolution of the knowledge triangle (business, higher education, and research) are proposed. The formalized model structure includes a specially designed platform divided into three main areas: inventory of raw materials sector participants; information on the promotion and dissemination of business ties; reporting on economic integration. However, there is a lack of practical recommendations for the implementation of the specified platform and the involvement of business entities from European countries in it.

Work [11] examines the tasks of restoring metal-contaminated areas as a result of the impact of mining or processing of critical raw materials, which poses significant environmental and medical problems. An option for overcoming the difficulties is to combine technologies for the recovery and reuse of metals along processing chains with practices of "green" rehabilitation, which involve the transition from waste to resources.

Study [12] reviews and substantiates the prospects for the management of non-ferrous metallurgy and mineral processing based on methods of economic and mathematical modeling and optimization, as well as the use of artificial intelligence. Despite the use of digital twin systems and intelligent management, process modeling and their interpretation are limited by the problems of lack of information, the complexity of forming large databases and integration into the traditional enterprise management system.

The subject of the study reported in [13] is environmental management, which is of crucial importance for achieving sustainable development, especially in the context of rapid urbanization, industrial expansion, and climate change. The proposed stages of environmental management "Driver-Pressure-State-Impact-Response" should be supplemented with components of monitoring, adaptation, restoration, implementation of environmental initiatives.

An important result of work [14], aimed at ways to reduce carbon emissions in the steel industry, is proposals for the use of new technologies to achieve carbon neutrality. They are categorized into "hot", "growing", "mature", and "weak" signals to identify key technological paths that shape the future of decarbonization of ferrous metallurgy. However, the proposed transformational roadmap for overcoming technological uncertainty in terms of balancing economic competitiveness and environmental imperatives requires detailing and additional argumentation.

In [15], Industry 4.0 technologies are adapted to environmentally friendly waste management in mining in terms of effective use of slag. However, there are no proposals regarding the prospects for introducing new technological approaches into the operational activities of enterprises in the industry and assessing their impact on the economy, ecology, energy conservation, sustainable and circular development.

The aforementioned gaps are partially eliminated in work [16], which formalizes the capabilities of Industry 5.0 to ensure the sustainability of innovative development of industrial systems based on a combination of advanced technologies with the principles of the circular economy. The principles of the proposed intellectual circularity system for Industry 5.0 are convincing but the possibilities of inter-sectoral cooperation within its framework are broader than those identified.

Related to the above-mentioned issues is the content of paper [17] that considers the political and regulatory perspectives of management and recycling of spent batteries from the standpoint of a critical assessment of facts and prospects. Despite its important practical significance, the possibilities of formulating conclusions regarding fundamental principles in the field of waste management, environmental policy, and public administration have not been fully realized.

In [18], the dual transition to the integration of digital and green transformations in industrial organizations was investigated in terms of conceptualization, implementation structure, and research program. The intersection of ideas on digitalization and sustainable development would be appropriate to be supplemented with proposals for resource conservation based on the principles of the circular economy. A broad overview of the state of hydrogen use for decarbonization of heavy industry over the past decade with detail at the subsector level was performed in [19]. However, there is a lack of determination of the realistic potential for replacing gray hydrogen with green hydrogen, determining the level of its readiness associated with direct and indirect technologies. The results of the development of strategic management of the corporation through the implementation of scenario analysis are reported in [20].

Despite the availability of scientific and applied research on strategic management mechanisms of MMI enterprises, there remain a number of unresolved issues that are caused by modern transformational and crisis processes in the economy of Ukraine and the world. In particular, the lack of a comprehensive methodology for adapting strategic mechanisms for the development of MMI enterprises to the conditions of martial law, post-war recovery, and integration into the European economic space requires the adoption of non-standard solutions. They should be based on increasing attention to the circular economy as an environment for the functioning of MMI enterprises, the integration of innovative and risk-oriented approaches to development based on the use of flexible strategies under conditions of high uncertainty. All this gives grounds to argue that it is advisable to conduct a study aimed at managing MMI enterprises in the framework of a circular economy based on technology transfer.

3. The aim and objectives of the study

The purpose of our study is to improve the ways of using international technology transfer for strategic management of enterprises in the mining and metals industry in the framework of circular economy based on adaptation to the risks of the internal and external environment. This will provide an opportunity to increase the efficiency of resource use by implementing technologies of closed production cycles, reducing raw material losses, and reusing materials.

To achieve the goal, the following tasks were set:

– to define the theoretical essence of adaptive strategic management mechanisms of enterprises in the mining and metals industry in the circular economy based on a risk-oriented approach;

– to conduct an empirical assessment of the business activity of enterprises in the mining and metals industry in the framework of a circular economy;

– to formalize the stages in the formation of the circular economy and international technology transfer in the mining and metals industry;

– to substantiate the priority areas of international technology transfer by enterprises in the mining and metals industry in the framework of a circular economy.

4. The study materials and methods

The object of our study is the management processes of mining and metallurgical enterprises in the framework of a circular economy based on technology transfer.

The study on the feasibility of implementing adaptive strategic management mechanisms based on the principles of a circular economy and intensive use of technology transfer is based on two hypotheses – a principal one and a working one. They do not contradict each other since they are complementary: the principal hypothesis is of a theoretical and methodological nature, and the working one is theoretical and methodological and applied.

The principal hypothesis assumes the feasibility of implementing adaptive strategic management mechanisms based on the principles of a circular economy and intensive use of technology transfer. It is expected that its implementation could allow MMI enterprises to optimize production processes, ensure continuous technological renewal, strengthen environmental and economic sustainability, as well as create prerequisites for long-term innovative development.

The study assumes that the main factors for increasing the efficiency of the mining and metals industry are the synergy of the circular economy, strategic adaptive management, and technology transfer. It will provide an innovative business model for the development of enterprises in the industry in the long term, increasing their resilience to risks under crisis conditions (energy, resource, logistics, environmental, financial, etc.).

The working hypothesis of our study assumes the synthesis of the principles of the circular economy, adaptive strategic management, innovative development for the rational use of resources, waste processing, closed production cycles. Confirmation of the above hypothesis will make it possible to increase economic and environmental efficiency, accelerate the implementation of innovations, reduce operational risks, contribute to the modernization of production processes in MMI and strengthen the competitiveness of enterprises. Additional arguments in favor of the hypothesis put forward are the advantages of flexible planning, rapid response to internal and external changes, digitalization of business processes, technology transfer, scientific and production interaction, public-private partnership.

To confirm the reliability of the research results, five alternative hypotheses about the basic principles of strategic adaptive development of MMI enterprises in the framework of a circular economy were adopted. The first two hypotheses (resource efficiency and innovative competitiveness) are closely related as they prioritize reducing material and energy costs by gaining competitive advantages in the international technology transfer market. The third and fourth hypotheses concern sustainability (environmental and economic) and are based on the need to eliminate negative environmental impacts on the environment, as well as ensure stable financial growth, even in conditions of market instability. The fifth hypothesis (technology integration) is based on the need to use systematic technology transfer to accelerate the integration of new production technologies into the business processes of enterprises.

The information basis of the study is the statistical data from the State Statistics Service of Ukraine for 2010–2023, which are compiled according to the classification of economic activities in KVED-2010 by sections [21]: 07 "Mining of metal ores", 24 "Manufacture of basic metals". Section 07 includes the following groups: 07.1 – mining of iron ores, 07.2 – mining of non-ferrous metal ores. Section 24 includes the following groups: 24.1 – manufacture of basic iron and steel and of ferro-alloys; 24.2 – manufacture of tubes, pipes, hollow profiles and related fittings, of steel, 24.3 – manufacture of other products of first processing of steel, 24.4 – manufacture of basic precious and other non-ferrous metals, 24.5 – casting metals.

Our research methodology involves analyzing the dynamics and structure of sales volumes by MMI enterprises during 2010–2023, formalizing trends for extrapolating indicators for 2024 and forecasting for 2025. The solution to the research tasks is facilitated by economic diagnostics of MMI subsectors, the use of adaptive mechanisms under martial law conditions, and predicative methods to substantiate their post-war restoration. In the process of conducting scientific and applied research, forming conclusions and recommendations in the paper, a wide range of general scientific and special methods were used. Theoretical methods of analysis and synthesis were applied to systematize scientific approaches to the interpretation of the circular economy, technology transfer, adaptive strategic management, and to identify relationships between them. The abstract-logical method was used to form a conceptual model of adaptive management of MMI in a circular economy, and induction and deduction were used to form hypotheses, put forward patterns, and generalize trends in the development of MMI. The system approach is the basis for interpreting an MMI enterprise as a complex production and economic system that interacts with the environmental and technological environment. Empirical methods were applied to analyze the dynamics and structure of sales volumes by MMI enterprises over 2010–2025. The trend analysis method was implemented in the EXCEL environment and used to formalize the dynamics of sales volumes in MMI as a whole and its sub-industries. The method of building adaptive strategic mechanisms was used to determine key points of adaptation of MMI enterprises' development strategies to changes in the economic environment of the market, environmental requirements and technological trends. The morphological analysis method allowed us to substantiate the definition of adaptive strategic mechanisms for the development of a circular economy based on technology transfer.

5. Results of research on the use of international technology transfer for strategic management of enterprises in the mining and metals industry

5. 1. Theoretical essence of adaptive strategic mechanisms for managing enterprises in the mining and metals industry in a circular economy based on a risk-oriented approach

In the economy, adaptation mechanisms are a system of forms, methods, tools, strategies, and procedures that ensure its stability as a system, as well as industries, regions, and business entities to changes in the operating environment [22]. Their purpose is to counteract the negative impact of crisis phenomena and use new opportunities for growth. Adaptation mechanisms operate at different economic levels (macro-, meso-, micro-):

– at the macroeconomic level, the purpose of the mechanisms is flexible regulation of the competitive environment, budget financing, tax burden, and credit provision within the framework of anti-crisis fiscal and monetary policy. The tools for their implementation are the introduction of tax holidays and stimulation of public spending for strategic sectors of the national economy, monetary stabilization, development of competitive sectors to reduce dependence on one industry or market [23];

– at the industry level, the purpose of the mechanisms is to ensure the industry's ability to adapt to changes in the internal and external environment, minimize risks and maintain competitiveness. Such mechanisms are formed under the influence of market conditions, government policy, technological changes, social and environmental requirements, globalization factors;

– at the microeconomic level (enterprises) – these are mechanisms for diversifying sources of income by expanding the range, entering new markets, creating additional services; cost optimization mechanisms that ensure energy efficiency [24]. These mechanisms include outsourcing non-core functions, implementing automation technologies; mechanisms for forming stabilization funds (financial reserves), risk insurance, hedging currency and price fluctuations. Mechanisms for attracting investments are based on the use of IPO – Initial Public Offering (initial placement of shares and other securities), bond loans, crowdfunding, venture capital; green bonds, etc. [25]. Mechanisms for the development of public-private partnerships (PPPs) are focused on attracting private investment to infrastructure and strategic projects.

Thus, the combination of the principles of strategic thinking, organizational flexibility, technological modernization, and systemic response to change constitutes the theoretical basis of adaptive strategic management mechanisms for MMI enterprises [26]. The purpose of the latter is to strengthen the sustainability and increase the efficiency of the industry, support the competitiveness of products, and ensure compliance with global trends (digitalization, decarbonization, circularity).

The circular economy model, or closed economy, involves the maximum conservation of resources, minimization of their waste and reuse throughout the entire life cycle of products [27]. The areas of application of the circular economy and the basic principles of its functioning have evolved significantly over time. At the initial stages, its main goal was any waste management. Over time, the principles of resource reuse and re-engineering of business processes from the standpoint of their modernization were added to the original concept [28]. As a result, more effective and sustainable business models were built, reoriented from simple waste management to more circular ones, which ensure resource savings, waste minimization and reduced dependence on natural resources. The principles of the circular economy are based on the importance of material reuse and integrated management of all stages of the product life cycle – from its fabrication to its final decommissioning.

The basic principles of the circular economy, which are becoming the foundation for sustainable development at the global level, are the rational use of resources, minimization of waste generation, and the implementation of closed cycles [29]. Restructuring business processes based on the principles of the circular economy involves adapting traditional linear models of production and consumption to the requirements of ensuring maximum efficiency in the use of resources, their reuse, and future recycling.

Given the high resource intensity and environmental sensitivity of MMI, the circular economy business model becomes a new environment for its operation, which determines competitiveness and environmental safety, as well as approaches to the development and implementation of modernization strategies. The business model closes resource flows based on the multiple use of metals (steel, aluminum, copper) by processing them without loss of properties, as well as the reuse of by-products (slag, dust, tailings, sludge). Its advantages are a reduction in primary ore extraction due to the transition from the exploitation of ore reserves to a reorientation to secondary metallurgy to reduce energy consumption and environmental pressure. Digitalization and optimization of production cycles based on Industry 4.0 technologies will make it possible to reduce the use of raw materials, improve ore quality control mechanisms, and optimize smelting and rolling processes.

The main areas of implementation of the circular economy in MMI are given in Table 1.

Circular economy has economic, environmental, and social benefits for MMI [30]. Economic benefits include reduced energy and primary raw material costs; stability in the face of fluctuating ore prices; the ability to attract "green" investments. Environmental benefits are based on reduced CO_2 emissions, reduced landfill and tailings areas, and their negative impact on soils and ecosystems. Social benefits include job creation in processing, recycling, and engineering; increased production safety; and improved environmental living conditions for the population.

Table 1

Main directions of implementing the circular economy in MMI

No. of entry	Direction	Ways of implementation
1	Use of secondary raw materials	– use of innovative technologies to increase the percentage of recycled steel output from primary pig iron
		– reduction of cost and energy costs for aluminum production based on shifting emphasis from bauxite to scrap
2	Recycling of industrial waste	Expansion of the use of MMI waste as technological resources based on the use of metallurgical slags in the cement industry, road construction; return of sludge to production; use of waste rocks as non-metallic raw materials
3	Energy-efficient and low-carbon technologies	Replacement of blast furnaces with electric arc furnaces, expansion of hydrogen-based steelmaking; utilization of blast furnace and coke oven gases
4	Land and resource restoration	Reclamation of territories after quarries; restoration of soil, water resources; environmental monitoring in real time
5	Product circularity	Taking into account the life cycle of products of metallurgical enterprises when designing products for easy dismantling of equipment, simplifying the disposal and recycling of production waste

The circular model is becoming a key competitive advantage in the global market with high environmental standards and carbon import adjustment mechanisms (EU ETS – European Union Emissions Trading System, CBAM – Carbon Border Adjustment Mechanism). This is due to the rapid growth in demand for "green" steel, as investors prefer low-carbon producers. For countries with a powerful MMI, including Ukraine, the transition to a circular model is the basis for modernizing metallurgy, reducing resource risks, and increasing the sustainability of the industry.

5. 2. Empirical assessment of business activity of mining and metallurgical enterprises in the framework of a circular economy

Empirical analysis was conducted on the basis of official statistical data described in chapter 4. The sample was divided into two time intervals:

1) 2010–2021;

2) 2021–2023 based on the stability of trend dynamics.

The type of trend functions was selected in the EXCEL environment using the criterion of maximizing the multiple coefficient of determination. In the obtained equations, the resulting indicator y is the cost of sales by MMI enterprises, measured in billions of UAH, the factor x is the year, represented by the period number. Extrapolation and forecasting were conducted on the basis of trend equations obtained from the results of modeling in the second interval, by substituting the values of the factor x in them (4 for 2024, 5 for 2025).

During 2010–2021, the value of sales of products by MMI enterprises increased from UAH 273.3 billion to UAH 959.9 billion, or 3.51 times (Table 2).

Table 2

Analyzing the dynamics of sales volumes by MMI enterprises during 2010–2025 (UAH billion) and the dynamics in average exchange rate of the hryvnia to the US dollar per year (UAH/USD)

Year	Rate	Sales volume of products by codes of types of economic activity									
		07	07.1	07.2	24	24.1	24.2	24.3	24.4	24.5	Total
2010	7.9	56.0	50.7	5.3	217.3	181.2	16.5	5.5	12.6	1.7	273.3
2011	8.0	75.5	68.8	6.7	273.1	231.1	19.1	6.2	14.0	2.7	348.6
2012	8.0	61.3	58.2	3.1	228.0	179.5	23.5	5.4	13.5	6.2	289.3
2013	8.0	68.4	65.1	3.3	201.0	160.8	18.9	5.9	12.8	2.5	269.4
2014	11.9	77.4	72.5	4.8	242.1	201.2	21.5	6.2	12.2	1.0	319.5
2015	21.8	82.7	73.6	9.1	279.9	231.7	21.2	6.5	19.2	1.2	362.5
2016	25.6	101.3	82.8	18.5	300.3	251.8	20.7	8.9	17.6	1.4	401.6
2017	26.6	132.3	117.4	14.9	388.8	318.5	30.5	11.3	25.9	2.6	521.0
2018	27.2	143.0	128.7	14.3	487.8	398.7	39.7	13.3	31.6	4.4	630.7
2019	25.8	155.2	143.1	12.1	398.1	333.0	22.8	12.9	26.0	3.5	553.3
2020	27.0	167.5	154.4	13.1	376.3	314.1	21.8	12.2	25.3	3.0	543.8
2021	27.3	306.3	289.2	17.1	653.6	554.4	35.3	20.2	38.8	4.9	959.9
2022	32.3	112.7	104.4	8.3	280.0	208.5	30.3	15.7	21.3	4.2	392.8
2023	36.6	91.4	85.1	6.3	255.2	177.6	37.4	19.0	16.8	4.5	346.6
2024*	40.2	59.6	55.3	4.3	212.4	117.2	56.6	21.6	13.0	4.0	272
2025**	41.7	46.3	42.5	3.8	218.4	92.2	87.9	23.8	10.9	3.6	264.7

*Note: * – extrapolation; ** – forecast.*

To ensure cross-country comparisons, the table shows the average exchange rate of the hryvnia to the US dollar. They are obtained from the official portal of the NBU in the tab "Official exchange rate of the hryvnia to foreign currencies (average for the period)" at: https://bank.gov.ua/files/Exchange_r.xls. The format of the average exchange rate (UAH/100 USD) has been converted to the format of UAH/USD for the convenience of visual representation of calculations.

In dollar equivalent, during 2010–2021, the cost of sales by MMI enterprises increased from USD 34.6 billion to USD 35.2 billion, or only 1.02 times (versus 3.51 times in estimates in UAH). This indicates a significant inflationary impact on the cost indicators of MMI activities, taking into account which allows us to conclude that there is no real growth in the industry.

Below we present the coefficients of dynamics in the performance indicators of MMI, calculated in hryvnia terms but for cross-country comparisons they need to be adjusted for the rate of change of the official hryvnia exchange rate according to Table 2.

The highest growth rates of sales volumes in MMI during 2010–2023 were demonstrated by enterprises with the following KVED codes: 24.3 – production of other primary steel processing products (by 3.5 times), 24.5 – metal casting (by 2.7 times), 24.2 – production of pipes, hollow profiles and fittings made of steel (by 2.3 times). This indicates the preservation of competitive advantages in sub-sectors focused on products with a higher share of added value and greater flexibility in the demand structure. These sub-sectors are characterized by relatively higher flexibility in responding to changes in demand, orientation towards the domestic market of mechanical engineering, energy and construction, as well as a higher degree of metal processing, which provides greater added value. Maintaining demand for products in these segments is ensured by modernization of production, production of special-purpose products (castings, profiles, pipes), and lower dependence on export logistics compared to the classic production of semi-finished articles.

The highest growth rates were demonstrated by the metal ore mining industry (5.47 times), primarily due to the extraction of iron ores (5.7 times). Growth rates at the level of the average industry level on the market were demonstrated by enterprises extracting non-ferrous metal ores (3.23 times), production of other primary steel processing products (3.67 times).

The following MMI sub-industries had lower growth rates: metallurgical production (3.01 times), including due to the production of pig iron, steel, and ferroalloys (3.06 times), production of precious and other non-ferrous metals (3.08 times), metal casting (2.88 times), production of pipes, hollow profiles, and fittings from steel (2.14 times).

In 2022, the trend towards an increase in the volume of products sold by MMI enterprises changed to the opposite. The reduction index by industry during 2022–2025 was 3.63 times, the highest reduction rates were observed at enterprises in the metal ore mining sector (6.62 times), including due to the extraction of iron ores (6.8 times) and non-ferrous metal ores (4.5 times), as well as at enterprises producing pig iron, steel, and ferroalloys (6.01 times). The reduction index in the production of precious and other non-ferrous metals (3.56 times) corresponds to the industry average. Metallurgical production demonstrated a lower reduction rate compared to the industry average (2.99 times), including due to metal casting (1.36 times). Only two industries demonstrated a 2.5-fold increase in sales during 2022–2025: production of pipes, hollow profiles, and steel fittings (2.5 times (reduction index 0.4)), as well as production of other primary steel processing products, metal casting (1.18 times (reduction index 0.85)).

Evaluating the dynamics of sales volumes of MMI products during 2010–2025, one should note its reduction by 3%, including due to the extraction of metal ores – by 17% (iron – by 16%, non-ferrous metal ores – by 28%), the production of precious and other non-ferrous metals – by 13%. The production of pig iron, steel, and ferroalloys almost halved. The sales volume of metallurgical production articles increased by 1%. The following sub-sectors demonstrated the highest growth rates: production of pipes, hollow profiles and fittings from steel (by 5.33 times), production of other primary steel processing products (4.33 times), production of precious and other non-ferrous metals (2.12 times). Significant growth and exceeding their rates above the industry averages led to an increase in the share of the specified sub-sectors in sales volumes.

Analysis of dynamics in the structure of sales volumes of products by MMI enterprises during 2010–2025 (Table 3) is represented without taking into account the change in the official exchange rate of the hryvnia to the US dollar.

This is determined by a horizontal approach to the structural analysis of sales volumes by MMI enterprises by their sub-industries within the framework of the annual period, when estimates in hryvnias and USD will provide the same results.

The share of production of pipes, hollow profiles, and fittings made of steel increased from 6.04% to 33.21% with an average value of 8.80%. The contribution of production of other primary steel processing products to sales volumes by MMI increased from 2.01% to 8.99% (average value – 3.20%), and metal casting – from 0.62% to 1.32% (average value – 0.85%). The share of production of precious and other non-ferrous metals remained relatively stable throughout the analyzed period and fluctuated at the level of 4.63%.

Table 3

Analysis of dynamics in the structure of sales volumes of products by MMI enterprises during 2010—2025, %

Year	Codes of types of economic activity									
	07	07.1	07.2	24	24.1	24.2	24.3	24.4	24.5	Разом
2010	20.49	18.55	1.94	79.51	66.30	6.04	2.01	4.61	0.62	100.00
2011	21.66	19.74	1.92	78.34	66.29	5.48	1.78	4.02	0.77	100.00
2012	21.19	20.12	1.07	78.81	62.05	8.12	1.87	4.67	2.14	100.00
2013	25.39	24.16	1.22	74.61	59.69	7.02	2.19	4.75	0.93	100.00
2014	24.23	22.69	1.50	75.77	62.97	6.73	1.94	3.82	0.31	100.00
2015	22.81	20.30	2.51	77.21	63.92	5.85	1.79	5.30	0.33	100.00
2016	25.22	20.62	4.61	74.78	62.70	5.15	2.22	4.38	0.35	100.00
2017	25.39	22.53	2.86	74.63	61.13	5.85	2.17	4.97	0.50	100.00
2018	22.67	20.41	2.27	77.34	63.22	6.29	2.11	5.01	0.70	100.00
2019	28.05	25.86	2.19	71.95	60.18	4.12	2.33	4.70	0.63	100.00
2020	30.80	28.39	2.41	69.20	57.76	4.01	2.24	4.65	0.55	100.00
2021	31.91	30.13	1.78	68.09	57.76	3.68	2.10	4.04	0.51	100.00
2022	28.69	26.58	2.11	71.28	53.08	7.71	4.00	5.42	1.07	100.00
2023	26.37	24.55	1.82	73.63	51.24	10.79	5.48	4.85	1.30	100.00
2024*	21.91	20.33	1.58	78.09	43.09	20.81	7.94	4.78	1.47	100.00
2025**	17.49	16.06	1.44	82.51	34.83	33.21	8.99	4.12	1.36	100.00
Average	24.64	22.56	2.08	75.36	57.89	8.80	3.20	4.63	0.85	100.00

*Note: * – extrapolation; ** – forecast.*

During 2010–2025, the bulk of MMI sales is provided by metallurgical production (with an average value of 75.36%, its share increased from 79.51% to 82.51%). The second largest, by average value, is the production of iron, steel, and ferroalloys (57.89%); however, a significant reduction in the volume of sales by the subsector caused a decrease in its share from 66.3% to 34.83%. The following reasons for the high share of enterprises in section 24, which constitute the basic, primary nature of production, have been identified. Subsection 24.1 (production of iron, steel, ferroalloys) is the basis of the entire vertically integrated metallurgical industry. It is these enterprises that provide raw materials and semi-finished products for all subsequent stages of production in MMI; therefore, their volumes are the largest. Even with fluctuations in demand for finished products, basic semi-finished products are in great demand and scale of production. Metallurgical blast furnaces and processing plants must operate in a continuous cycle, as their shutdown leads to large losses, so production volumes must be maintained, even with reduced margins.

The extrapolation and forecast of sales volumes of MMI products for 2024–2025 were performed based on the data in Table 2, based on the possibilities of statistical formalization, in two stages: 2010–2021 (growth), 2021–2023 (reduction). The results of formalization of trends, represented by regression equations and multiple determination coefficients, are given in Table 4.

At the first stage, all the functions given in Table 2 are represented by the ascending branches of the parabola. For sub-sector 24.3, the equation of the polynomial function (1) was derived according to the data for 2010–2025 with a high value of the multiple coefficient of determination (R^2), which demonstrates stable growth, unlike other sub-sectors

$$y = 0.0626x^2 + 0.1903x + 4.694,\ R^2 = 0.8917. \quad (1)$$

For sub-industry 24.5 – metal casting, the time intervals of the first stage are determined as 2010–2014, and the dynamics in the volume of products sold are described by the ascending branch of the parabola (2) with a multiple coefficient of determination of 0.6759

$$y = -0.8714x^2 + 5.0686x - 2.8,\ R^2 = 0.6759. \quad (2)$$

At the second stage, all functions given in Table 2 are represented by a decreasing power function, as evidenced by negative values of the power index and indicate a reduction in the volume of sales of agricultural and industrial enterprises. For sub-sector 24.5 – metal casting, the time intervals of the second stage are determined as 2014–2023, and the dynamics in the volume of sales are described by a descending branch of a parabola (Table 3) with a multiple coefficient of determination of 0.7792

$$y = -0.0617x^2 + 1.0302x + 0.1024,\ R^2 = 0.7792. \quad (3)$$

Thus, the general trend of the circular economy at the first stage (2010–2021) is an increase in the business activity of MMI enterprises, at the second stage (2022–2025) it is a decrease. Since Ukraine has relatively poorly developed products with high added value (mechanical engineering, special casting, metal structures), the bulk of sales by MMI enterprises falls on primary metallurgy. The identified trends are explained by the stable demand for raw materials from the primary metallurgy of Ukraine, the export orientation of the iron ore segment, and relatively less sensitivity to fluctuations in domestic demand. The main factors in the decrease in sales volumes by MMI enterprises, starting from 2022, are military operations, blockade of seaports, disruption of logistics chains, a decrease in global demand for Ukrainian ore, and partial loss of production capacities.

Table 4

Formalization of the dynamics of trends in sales volumes of products by MMI enterprises according to data from 2010—2025

KVED code	First stage		Second stage	
	Regression equation (2010–2021), y – billion UAH, x – period number	Coefficient of multiple determination R^2	Regression equation (2021–2023), y – billion UAH, x – period number	Coefficient of multiple determination R^2
07	$y = 2.5232x^2 - 16.036x + 86.47$	0.8916	$y = 289.34x^{-1.138}$	0.9813
07.1	$y = 2.5475x^2 - 17.557x + 84.843$	0.8843	$y = 272.51x^{-1.152}$	0.9806
07.2	$y = -0.0236x^2 + 1.5128x + 1.6341$	0.6292	$y = 16.722x^{-0.923}$	0.9942
24	$y = 3.6084x^2 - 16.093x + 246.34$	0.7922	$y = 614.81x^{-0.896}$	0.9608
24.1	$y = 3.2705x^2 - 16.334x + 208.69$	0.7986	$y = 520.82x^{-1.077}$	0.9746
24.2	$y = 1.2472x + 16.185$	0.4021	$y = 6.05x^2 - 23.15x + 52.40$	0.999
24.4	$y = 0.1751x^2 - 0.1409x + 12.22$	0.8339	$y = 38.137x^{-0.773}$	0.9944
Total	$y = 6.1336x^2 - 32.158x + 332.87$	0.8428	$y = 903.7x^{-0.966}.\ R^2 = 0.9684$	0.9684

5. 3. Formalization of stages in the formation of the circular economy and international technology transfer in the mining and metals industry

The formation of the circular economy and international technology transfer in the mining and metals industry has gone through a number of stages, which are determined by the laws of evolutionary development.

At the first stage of the development of the circular economy (2010–2021), the business activity of MMI enterprises was formed under the influence of global business cycles, geopolitical processes, structural transformations of the steel market, and internal problems of the industry. We assesssed it in four substages.

During 2010–2013, there was a post-crisis recovery and slow growth of the national economy. The main factors stimulating changes in the business activity of MMI were the recovery after the global financial crisis (2008–2009). During the specified period, there was an increase in demand for steel from China, the EU, and Turkey, a gradual recovery of prices for ore and metal products, and an increase in the volume of exports by Ukrainian mining and metallurgical enterprises. The main disincentive factors were high physical wear and tear of equipment and low energy efficiency of agricultural enterprises, their dependence on imported coking coal raw materials, and high currency and logistics risks. Despite the growth in export volumes, its structure was excessively concentrated (mainly semi-finished products), which reduced added value and inhibited investment activity of mining and metallurgical enterprises.

During 2014–2016, there was a decline in business activity, a reduction in production, and the suspension of many MMI enterprises due to the geopolitical crisis and structural shock. The main industry factors for the decline in business activity in MMI are the military conflict and the loss of control over key enterprises in the Donetsk and Luhansk oblasts, disruption of logistics, and an increase in cost prices due to transport restrictions [31]. Their negative impact is amplified by the macroeconomic factor of the devaluation of the national currency, which temporarily increased export attractiveness, but increased costs for imported technologies, spare parts, and energy resources. A de-stimulating factor at the supranational level is the fall in prices for steel and ore on world markets due to the expansion of Chinese producers, which led to the closure of unprofitable domain and open-hearth furnaces in Ukraine.

During 2017–2019, MMI restoration processes and modernization trends in the industry were observed. The main factors stimulating business activity are related to the global increase in prices for steel and iron ore raw materials, as a result of which the market entered a recovery phase and export margins increased. Innovative modernization of enterprises is ensured by the transition to energy-efficient technologies based on the reconstruction of domains, the launch of new sinter plants with cleaning systems, and automation of quarrying. It is important to adapt logistics and diversify export routes by developing port infrastructure and reducing dependence on eastern transport routes. As a result of increasing environmental pressure from the EU, enterprises are forced to invest in environmental modernization (treatment plants, dust and gas cleaning equipment), digitalization, and the implementation of interconnected management systems based on Industry 4.0.

During 2020–2021, the dynamics of business activity of MMI enterprises were influenced by pandemic restrictions and a significant increase in raw material prices. In 2020, COVID-19 caused a drop in demand and domestic steel consumption, temporary shutdowns of plants in the EU and Asia, and a decrease in trade volumes. 2021 is characterized by a price boom, when world prices for steel and iron ore reached historic highs due to the implementation of infrastructure programs in the USA and China, as well as a supply shortage after lockdowns. This led to a record increase in sales volumes by MMI enterprises. The main disincentive factors for MMI enterprises during the specified period were problems with logistics, disruptions in global supply chains, and an increase in freight costs due to a shortage of containers. As a result of increased environmental regulation, enterprises faced the requirement of decarbonization and the need to invest in "green" technologies. They actively addressed internal structural problems caused by the high energy intensity of blast furnace and open-hearth production, insufficient modernization rates, and dependence on imported coke and equipment. As a result, there was a significant increase in business activity of MMI enterprises in 2021 against the backdrop of significant long-term risks.

The main reasons for the decrease in sales volumes by MMI enterprises in Ukraine (2022–2025) are russian military aggression and the destruction of infrastructure. The greatest negative impact is the physical destruction of metallurgical enterprises in Mariupol (Azovstal, Ilyich MMK), Alchevsk, Avdiivka, etc., the occupation of territories where plants and mines were located. Damage to energy infrastructure and logistics facilities (ports, railway sections, bridges), blocking of Black Sea seaports and traditional export routes (Mariupol, Berdyansk, Mykolaiv, Kherson) limited the possibilities of supporting and growing business activity of MMI enterprises. The use of alternative routes entailed an increase in delivery costs due to the redirection of flows by land routes (railway, Danube ports), which caused an increase in the price of MMI enterprises' products and reduced their competitiveness.

Factors that discourage the development of MMI enterprises are slowing demand on world markets, industrial production in the EU, falling prices for steel and ore in 2022, reduced investment in the construction sector due to the increase in central bank rates. Negative factors for the development of MMI are logistical constraints and rising costs; long supply chains, shortage of wagons, delays at the western border of Ukraine; significant increase in the price of energy and transportation costs. This reduced sales margins, limited access to working capital, reduced creditworthiness due to the deterioration of the financial condition of MMI enterprises, led to high interest rates on loans, worsening conditions for financing investments and working needs. There has also been an increase in environmental pressure in the conditions of the "green transition" in the EU, the introduction of the CBAM mechanism – a carbon tax, which makes Ukrainian metallurgical products less competitive without decarbonization, and also requires investments in "green" technologies blocked due to the war.

During 2022–2025, the share of the mining and metals industry (MMI) in the structure of Ukraine's industrial GDP decreased due to the above-mentioned changes. In this context, the Ukrainian metallurgical industry is faced with the need to transition to steel production with zero or minimal carbon emissions. Such a step is not only of environmental importance, but also strategically important for the country's future integration into the European market, harmonization with EU regulations, and ensuring access to common financial resources.

However, decarbonization of the national industry is an extremely complex task that Ukraine cannot solve solely with its own resources, especially given the challenges associated with the war. In this regard, access to European financial funds, loans, and technological cooperation are becoming the main success factors. A limited number of Ukrainian enterprises use EAF (electric arc furnace) electric steelmaking technology, the most known of which are Interpipe Steel in Dnipro and Dniprospetsstal in Zaporizhia.

The current conditions for the functioning of MMI require the use of modern and adaptive management methods to overcome internal and external challenges. The most important of them are the consequences of military operations, changes in logistics chains, fluctuations in world prices for metal products, increased environmental regulation and global trends towards the implementation of "green" metallurgy.

5. 4. Substantiating priority areas of international technology transfer by enterprises in the mining and metals industry in the framework of a circular economy

A general indicator of business activity and the importance of the role of MMI is the share of the volume of products sold in the total national economy (Fig. 1).

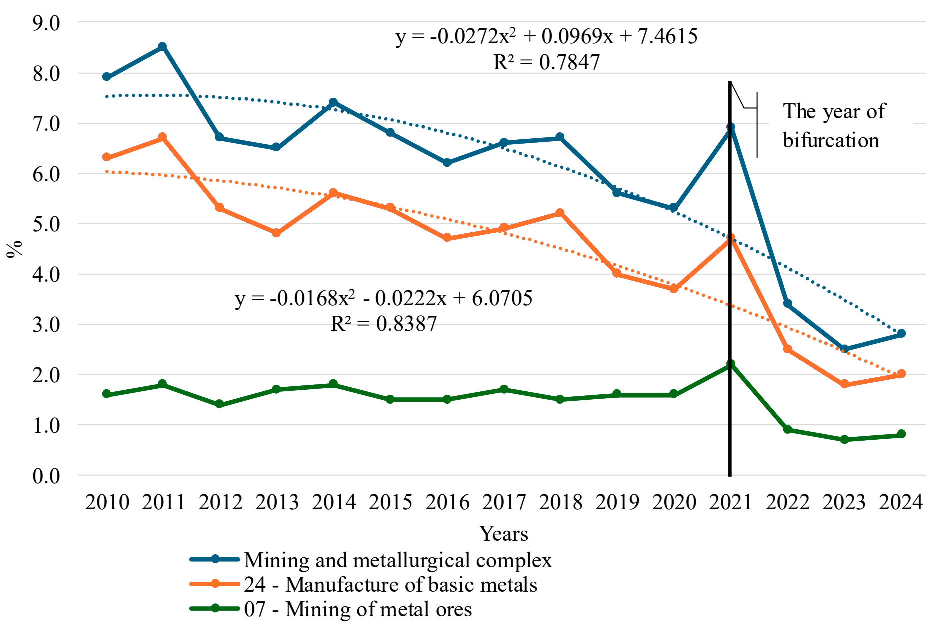

Fig. 1. Formalization of dynamics in the specific weight of the volume of sales of finished products in the mining and metals industry and its sub-sectors in the total volume of the national economy, %

During 2010–2024, the share of MMI decreased from 7.9% to 2.8%, metallurgical production – from 6.3% to 2.0%, and metal ore extraction – from 1.6% to 0.8%, which indicates a decrease in the role of MMI in the reproductive processes in the national economy. However, the dynamics of the analyzed indicator were not linear. During 2010–2020, the share of MMI decreased from 7.9% to 5.3%, metallurgical production – from 6.3% to 3.7%. The share of metal ore extraction was relatively stable and fluctuated at the level of 1.6% to 0.8%. However, in 2021, there was a sharp increase in the share of the volume of sales of finished products in the total volume of the national economy. In general, the share in the industry increased from 5.3% to 6.9%, in metallurgical production – from 3.7% to 4.7%, in metal ore mining – from 1.6% to 2.2%. In 2022, there was a sharp decrease in the analyzed indicator in the industry as a whole – from 6.9% to 3.4% (by 2.0 times). The share of metallurgical production decreased from 4.7% to 2.5% (by 1.9 times), and in metal ore mining – from 2.2% to 0.9% (by 2.4 times). All of the above indicators in 2022 dropped to a level lower than in 2020.

Thus, 2021 can be considered a bifurcation point, which is indicated in Fig. 1 by a vertical line and the corresponding mark. At that moment, the rapid upward trend was replaced by an even faster downward trend. Instead of moving to a new, well-organized level, the system rapidly entered a crisis phase in 2022 under the influence of a full-scale invasion by the Russian Federation. The presence of a bifurcation point is due to a significant number of factors. Some of them are directly related to the conditions of the war and the state of the macroeconomics, some of them are related to changes in the domestic and international commodity markets, technological transformation, environmental / regulatory challenges, etc.

As a result, we have summarized the main factors of change in the business activity by MMI:

1. Loss of assets due to destruction and their location in temporarily occupied territories, emergence of logistical problems, decrease in demand in key markets, export instability due to full-scale invasion of the Russian Federation and introduction of martial law. This intensifies competition between enterprises within the industry, accelerates structural changes, which, due to already deepened crisis challenges, can lead to a decrease in business activity. Thus, war, loss of capacity, market instability, imbalances in the structure of the industry create a strong negative background for the business activity of MMI.

2. Structural restructuring of production and technological challenges. The state of the industry's production potential requires modernization, increased energy efficiency, and the introduction of "green" technologies in the context of the European "green course". Because of the war, economic instability, blocking of markets, high energy costs, the investment potential of many enterprises has decreased, their modernization is postponed or proceeds slowly. As a result, the ability of MMI to quickly adapt to new conditions, implement circular practices, invest in energy efficiency and "green" technologies is reduced. Reorientation to circular models (sales of secondary raw materials, waste processing, reuse, scrap metal, etc.) requires significant investments, modernization, changes in management. Unfortunately, a significant proportion of MMI enterprises are not ready and/or have the resources for such a transition. At the same time, at the international level, in particular in the EU, scrap metal is becoming a strategic raw material for steel production in electric arc furnaces, taking into account the principles of the circular economy.

3. Weak regulatory and institutional environment, lack of clear legislative and regulatory incentives. It causes insufficient implementation of the circular business model by MMI enterprises, since the processing of metallurgical waste/scrap is absent or occurs in small volumes. As a result, support for circular initiatives in the industry is low, and companies lose the opportunity to support their own stable or growing business activity, remaining in a "linear" model (mining, production, waste/dumps).

4. Energy and resource costs. The high energy capacity of MMI and a sharp increase in electricity prices in 2025 reduce the competitiveness of Ukrainian enterprises in the foreign market. Alternative options are either a reduction in production volumes or the search for alternative schemes for using less energy-intensive technologies.

The main military-political factors that negatively affect the activities of MMI enterprises include the risks of martial law, loss of control over assets in temporarily occupied territories, and the destruction of industrial centers of the industry (Mariupol, Avdiivka). Regulatory restrictions include dependence on state policy regarding the energy market, tariffs, and scrap metal exports; revision of environmental legislation in accordance with EU requirements; the need for state incentives for a circular economy. The key economic and environmental destructive factors are the decline in steel production due to the war; high electricity prices and increased logistics costs; and limited opportunities to attract international investment due to failure to meet the requirements for decarbonization of the economy. The most important social factors are population migration, shortage of qualified personnel at individual enterprises; increasing public demand for environmentally friendly production and safe working conditions; reformatting of labor resources through digitalization and automation [32].

The instability of market conditions and global supply chains, risks of sanctions, transport restrictions and logistical problems complicate the implementation of changes. In addition, the insufficient development of the national innovation ecosystem, which ensures the interaction of science, business and the state, can significantly slow down the modernization processes. In general, although adaptive strategic mechanisms in the MMI face significant challenges, their implementation can contribute to the harmonious development of the industry [33].

Currently, the activities of MMI enterprises are under the influence of external shocks that restrain their development based on the traditional business model. They are represented by war, temporary loss of control over production capacities and logistics infrastructure, energy crisis, and decrease in export volumes. As a result, there is a decline in production volumes, staff reductions and a decrease in business activity of mining and metallurgical enterprises. The implementation of a circular business model provides theoretical chances for the restoration, stabilization and greening of MMI. However, its implementation faces a number of serious challenges of an institutional, financial and technological nature. The successful implementation of a circular business model will provide an opportunity to obtain competitive advantages for enterprises that modernize production and sales processes, switch to waste and scrap metal processing based on the latest technologies.

However, the number of MMI enterprises that use international technology transfer remains insignificant at present. To ensure the sustainable development of the MMI in 2021–2025, a comprehensive approach is needed. This includes the modernization of production facilities, attracting investments, support from the state and international donors, the introduction of regulatory standards and incentives, as well as adaptation to the principles of the circular economy.

The use of international technology transfer will contribute to the growth of Ukraine's scientific potential through the development of science and technology parks, industrial testing of innovations at university centers, and setting up of joint research laboratories (industry-science cooperation).

Promising areas of international technology transfer in MMI are the introduction of circular-type equipment, reduction of energy intensity, use of low-carbon technologies, development of infrastructure for processing and circulation of secondary raw materials, introduction of organizational and managerial innovations [34]. The results of the implementation of international technology transfer in MMI are focused on increasing the share of added value in the industry's products, reducing dependence on imports of equipment, raw materials and materials, as well as the development of personnel and educational approaches.

Energy adaptation and use of low-carbon technologies should be based on the integration of energy efficiency technologies through the recovery of blast furnace gas heat, the use of closed water supply systems and secondary energy resources. The use of renewable and cheap energy by MMI enterprises can be achieved by building solar and wind power plants for their own needs, as well as by integrating energy storage systems to cover peak loads. In the medium term, promising technologies include partial or complete replacement of coke with hydrogen, production of "green steel", direct iron recovery on hydrogen modules [35].

Increasing human resources and educational adaptation capabilities involves training personnel for the circular economy and innovations, as well as the formation of technological transformation teams. This requires the implementation of retraining programs for MMI employees, training in environmental, social, and governance (ESG – Environmental, Social, Governance) and product life cycle assessment (LCA – Life Cycle Assessment). Technology transfer requires specialists in automation, energy management, environmental engineering, innovation management, resource efficiency, robotics, and digital systems management.

The adaptation of Ukrainian MMI to the conditions of a circular economy requires comprehensive modernization and active implementation of modern technologies based on the renewal of production capacities, digitalization of processes and automation, and the implementation of energy-efficient and low-carbon solutions.

Thus, international technology transfer brings MMI a number of important advantages, the main of which are an increase in the volume of finished product production, a decrease in its cost due to automation and energy-saving technologies, increased labor productivity, and environmental modernization.

To stimulate the practical application of the proposed priority areas of international technology transfer by MMI enterprises in the framework of a circular economy, we recommend implementing pilot projects at the initial stages of implementation. The basic provisions of the developed Case "Decarbonization of steel production through the introduction of electric arc furnaces (EAF)" are set out below using the example of ArcelorMittal Kryvyi Rih:

1. Context / Prerequisites. The traditional blast furnace-converter technology BF-BOF (Blast Furnace – Basic

Oxygen Furnace) for the Ukrainian metallurgical industry is environmentally hazardous due to high carbon emissions. ArcelorMittal is the world's largest metallurgical company. It is represented in Ukraine under the ArcelorMittal Kryvyi Rih brand [36]. ArcelorMittal's environmental strategy envisages achieving carbon neutrality by 2050 and a significant reduction in carbon emissions by 2030. In the context of EU integration, Ukraine has undertaken to decarbonize industrial production. On January 1, 2026, CBAM norms came into force, without compliance with which Ukrainian steel producers will lose EU export markets.

2. Problem. Environmental pollution in the process of ArcelorMittal Kryvyi Rih's operational activities based on technologies. Excessive emissions of harmful substances into the atmosphere, including carbon dioxide, in blast furnace production; forced reduction of blast furnace production to the technological minimum in accordance with environmental requirements, their complete shutdown is in prospect.

3. Case goal. Development and implementation of environmental strategies to reduce the carbon footprint of ArcelorMittal Kryvyi Rih's activities based on electric arc production. Its implementation meets the requirements of the EU climate policy, allows adaptation to CBAM mechanisms. EAF allows minimizing carbon payments, reducing regulatory risks, ensuring long-term compliance with the European Green Deal.

4. Solution (management / technological). The implementation of electric arc production provides quick start-up and shutdown of operational processes, flexible regulation of production volumes, and integration with digital management systems. Integration with renewable energy sources, direct iron reduction technologies and "green" hydrogen makes EAF a key element of the technological transformation of metallurgy.

5. Implementation. Construction of EAF at the ArcelorMittal Kryvyi Rih plant to optimize production processes. The main raw material for production is scrap metal; the energy source is electricity. Electric arc production reduces the need for iron ore mining, fossil fuels, coke production and reduces costs per unit of production. Construction of EAF requires significant capital investments, but in the long term it will provide reduced costs for coke and fossil fuels, reduced cost of carbon quotas, increased production flexibility, reduced operating costs, increased energy efficiency.

6. Results. Compared to blast furnace technology, where emissions are 1.8–2.2 t CO_2 per 1 t of steel, EAF provides a reduction of up to 0.3–0.6 t CO_2 per 1 t of steel, i.e., up to 80%. Compliance with EU climate requirements and international environmental standards will increase the export potential of MMI, increase its investment attractiveness, and provide access to "green" financing. A high ESG rating of the enterprise, the reputation of the manufacturer as a climate-responsible one, will allow expanding sales markets. Given that low-carbon steel has a higher market price compared to conventional steel, and stable demand from the automotive and construction industries, an increase in sales volume of MMI enterprises should be expected.

7. Success factors and limitations. The construction of EAF at ArcelorMittal Kryvyi Rih is a scaling-up of projects previously implemented by ArcelorMittal at the Belval (Luxembourg), Sestao (Spain), Aviles (Spain), Gijon (Spain) sites. Instead of traditional steel, the product produced at EAF will be sold as XCarb® recycled and renewably produced with a very low carbon footprint. The key success factors of electric arc production are provided by access to a stable source of "clean" electricity, a developed scrap metal market, state incentives for low-carbon metallurgy, and investments in energy-efficient technologies. However, there are also limitations to the implementation of EAF technologies, associated with martial law conditions, constant security risks, destruction of infrastructure, disruption of logistics, lack of investment funds for decarbonization, and dependence on the scrap market.

8. Conclusions and lessons. The experience gained in the construction and use of EAF can be scaled up by using it by other domestic metallurgical enterprises. Ensuring compliance with EU climate policy will increase their investment attractiveness for foreign investments, including European ones. The environmental, economic and strategic advantages of building and using EAF will contribute to increasing the competitiveness and sustainable development of MMI enterprises.

9. Practical significance. The applied experience will be useful for metallurgical enterprises in the decarbonization process due to the reduction of CO_2 emissions compared to the traditional BF-BOF process. Steel production with a low carbon footprint meets modern climate requirements and market demand for "green" products and contributes to the development of a circular economy through the maximum use of scrap. However, the real climate effect will directly depend on the carbon intensity of electricity.

It can be assumed that the scaling of the developed case will have a synergistic effect for the strategic innovative and environmental management of MMI enterprises based on the use of international technology transfer.

6. Discussion of results related to the use of international technology transfer for strategic management of enterprises in the mining and metals industry

Our results are based on the generalization of theoretical concepts of the development of the mining and metals industry (MMI), statistical research, and systematization of best practices in attracting international technology transfer for the development of the industry.

Enterprises in the industry implement international quality standards, conduct certification of finished products according to them, improve labor safety thanks to the possibilities of remote production management. This simplifies the access of mining and metallurgical enterprises to world markets, as well as attracting investments and increasing the competitiveness of the industry. Despite the identified advantages, attention should be paid to the obstacles and challenges presented by the high cost of modern equipment, export restrictions due to sanctions and control over dual-use technologies. A serious challenge is the shortage in Ukraine of qualified specialists for the implementation of the latest technologies, the need to adapt the specialists involved from the EU countries to local conditions, which increases the risk of dependence on foreign suppliers.

Recommendations for adapting strategic management mechanisms for mining and metallurgical enterprises in the context of a circular economy based on international technology transfer are supported by a number of tools represented in the form of tables, formulas, and figures. The results of our study reported in Section 5 demonstrate the achievement of the goals and objectives set in Section 3. Table 1 gives main areas of implementation of the circular economy in the mining and metallurgical industry. Table 2 gives the results of analyzing the dynamics of sales volumes by the industry's enterprises in the hryvnia equivalent and the average exchange rate of the hryvnia to the US dollar for the year, which could allow for cross-country comparisons. Table 3 enhances the possibilities of analyzing the dynamics of the horizontal structure of sales volumes by MMI enterprises by its subsectors. Formalization of the dynamics of trends in sales volumes of MMI enterprises (Table 4) and the specific weight of the contribution of its subsectors to the total volume of the national economy (Fig. 1) provided an opportunity to substantiate the prospects for the development of the industry. To study the patterns of changes in the sales volumes of MMI products and their sub-industries over time (Table 4), the method of phasing and correlation-regression modeling was used. It was shown that at the first stage (2010–2021), the trends are mainly represented by the ascending branches of the parabola, and at the second (2021–2023) by the descending ones. The exception is sub-industry 24.3 – production of other primary processing products, the dynamics of which is described by an increasing polynomial function. Fig. 1 formalizes the dynamics of the share of the sales volume of finished MMI products and its main sub-industries in the total volume of the national economy. Formulas (1)–(3) describe the dynamics of trends in the sales volumes by MMI sub-industries that did not require extrapolation and forecasting procedures.

To stimulate the practical application of the proposed recommendations for international technology transfer by MMI enterprises, the basic provisions of the developed Case "Decarbonization of steel production through the introduction of electric arc furnaces (EAF)" are set out. Its content consists of the following components: context / prerequisites, problems, goal, solutions (management / technological), implementation, results, success factors and limitations, conclusions and lessons, practical significance. The case, developed for ArcelorMittal Kryvyi Rih, has great prospects for scaling up in order to obtain a synergistic effect for strategic innovation and environmental management of MMI enterprises based on the use of international technology transfer.

The features of our methods and approaches to the study of strategic mechanisms for managing MMI enterprises in a circular economy are significantly different from those common in world practice. This conclusion is drawn based on the results of the processing and critical assessment of the results of research by American, European, and Chinese scientists on the problems of international technology transfer, reported in the literature [7–19, 26, 32, 35]. Their papers mainly consider knowledge flow technologies, recommendations for increasing the role of human capital, the formation of clusters and innovations at the firm level. They are oriented towards economies with high technological structures, where the use of circularity and technology transfer tools is common practice. In contrast, the MMI of Ukraine was formed as a basic industrial sector focused on mass production of metal products, which led to the dominance of an industrial technological structure with high resource and energy intensity. At the current stage of development of the Ukrainian MMI, technologies belonging to III–IV technological systems prevail (blast furnace production of pig iron, open-hearth (partial) and converter steel production. They are characterized by a low level of deep processing of raw materials, high energy consumption, significant environmental impact, and orientation towards the export of semi-finished products). The institutional sources of the technological gap in the MMI, which is manifested in the low share of high-tech metal products, limited use of "green" technologies, insufficient implementation of the principles of the circular economy, and weak integration into global value chains, have been identified. These factors reduce the competitiveness of Ukrainian metallurgy in world markets and complicate the implementation of international environmental obligations. Despite the fact that studies by Ukrainian scientists [1–6, 23, 24, 28–30, 33, 34] more accurately reflect the realities of the functioning of MMI in Ukraine, our study has a number of advantages in comparison with the cited publications. Among the key achievements, it is worth highlighting the development of elements for the modernization of MMI and the transition to the V technological mode. Its main priorities are electric arc steel production, continuous casting of billets, automation of technological process control systems, adoption of digital solutions for monitoring production and energy consumption, and the expansion of scrap metal recycling.

Our paper formalizes the vector of transformation of the development of the MMI associated with the transition to V–VI technological modes, which includes the introduction of low-carbon and hydrogen technologies; the development of electrometallurgy; deep processing of raw materials; closed cycles of resource use (circular economy); the activation of international technology transfer; digitalization of production and management processes based on Industry 4.0.

Unlike current approaches, the proposed ones are focused on updating outdated industrial technologies of MMI based on innovative elements. It is shown that the further development of the industry requires structural modernization, focused on the transition to higher technological modes, which could ensure increased efficiency, environmental safety, and competitiveness under the conditions of the global transition to a circular and "green" economy.

Thus, the applied significance of our study is in substantiating strategic directions of MMI transformation through international technology transfer, digital-circular transformation of production, transition to closed material cycles, decarbonization and energy optimization, innovative partnerships. Our recommendations could be implemented in the practice of MMI enterprises, industry regulators, environmental supervision services, investors, engineering companies, territorial communities subject to the preliminary development of pilot projects and implementation roadmaps.

However, the limitations of this study are the disclosure of information on the sales volumes by MMI enterprises within the period 2010–2023, to overcome which, extrapolation of indicators for 2024 and forecasting for 2025 based on the formalization of trends were performed. Another weak point is the limited access to information on the business activity by MMI due to its confidential nature during certain periods, because of the needs of the economic security of the national economy. This is confirmed by the analysis in Table 2, in which gaps in data on the volume of products sold had to be compensated for using averaging, adjustment, and application of additional coefficients. In addition, there is a shortage of open information on international technology transfer in MMI and its subsectors. The quality and persuasiveness of the results could be increased by using micro-level data of individual enterprises; indicators of energy efficiency, carbon intensity and investment structure; comparative statistics of EU countries with a similar industry structure.

Further advancement of the study involves substantiating proposals for improving the institutional support to MMI with a focus on the implementation of priority measures for the needs of the military economy and defense.

7. Conclusions

1. Adaptive strategic management mechanisms of mining and metallurgical enterprises have been theoretically defined as a set of forms, methods, and tools for ensuring dynamic stability, supporting innovative activity, and the ability to maintain competitiveness under conditions of dynamic changes in the internal and external environment. The theoretical principles for the functioning of these mechanisms are based on the intersection of state policy measures, market incentives, technological development, and structural modernization of the industry. The features of the content of the proposed adaptive strategic management mechanisms of mining and metallurgical enterprises are determined by the environment of the circular economy. Their differences, compared to the known ones, are the use of the advantages of the circular economy model, aimed at maximum resource conservation, waste reduction, and reuse throughout the entire product life cycle. Our result is attributed to the application of the laws of evolution and the principles of the circular economy concept. Its components are reuse of resources and materials, reengineering of business processes for the purpose of their modernization, integrated management of all stages of the product life cycle – from its fabrication to the end of operation.

2. An empirical assessment of the business activity of MMI enterprises in the system of strategic development of the circular economy was carried out on the basis of historical data on the volumes of products sold in 2010–2023. They served as an information base for building statistically significant trend models, which were used to extrapolate to 2024 and forecast for 2025. The features of our result are attributed to the synthesis of dynamic and static methods in analyzing the functioning of mining and metallurgical enterprises. It was established that the volume of sales of MMI products during 2010–2025 decreased by 3%, including due to the extraction of metal ores – by 17% (iron – by 16%, non-ferrous metal ores – by 28%). The volume of sales of metallurgical production products increased by 1%, but the production of pig iron, steel, and ferroalloys decreased almost by half. During 2010–2025, the bulk of the sales of MMI products is provided by metallurgical production (with an average value of 75.36%, its share increased from 79.51% to 82.51%). The second largest by average value is the production of cast iron, steel, and ferroalloys (57.89%); however, a significant reduction in the sales volumes of the sub-sector caused a decrease in its share from 66.3% to 34.83%. Unlike existing approaches to the economic interpretation of MMI transformations, the proposed one is based on clear mathematical and statistical reasoning. Metallurgical production is defined as the basis of the entire vertically integrated mining and metallurgical industry through the processing of mined metal ores, providing raw materials and semi-finished products for all subsequent stages of production in the value-added chain. This is reflected in the largest volume of sales of finished products by metallurgical enterprises in the MMI system. Our results are based on an assessment of trends in the volume of products sold at two stages of the formation of business activity of MMI enterprises: the first (2010–2021) – growth, the second (2022–2025) – reduction. They have an important applied aspect since, due to the technical and technological features of metallurgical production, equipment must operate in a continuous cycle and be maintained even under conditions of negative financial results.

3. The results of the formalization of evolutionary processes show that at the first stage (2010–2021) the business activity of MMI enterprises was influenced by a combination of global market cycles, domestic economic crises and slow modernization. It demonstrated cyclicality with three phases: recovery after the global financial crisis (2010–2013), crisis decline (2014–2016), recovery and recovery, including due to favorable price conditions (2017–2021). The advantages of the proposed periodization, compared to the existing ones, are the allocation of key drivers of fluctuations at the specified stage, represented by the geopolitical situation, raw material prices, export orientation, environmental regulation and technological modernization. Our results are based on the determination of external and internal factors underlying the phases of the cyclicality of business activity by MMI enterprises. Among the external factors, the cyclical nature of the world steel market, geopolitical crises, the COVID-19 pandemic, changes in the structure of global demand and supply from leading players, and increased rigidity of international environmental regulation were identified. The main internal factors were the depreciation of fixed assets; dependence on energy resources and coking coal; slow implementation of Industry 4.0 technologies; environmental requirements and social risks. At the second stage (2022–2025), the decline in business activity of the Ukrainian MMI decreased due to military-political factors due to the destruction and damage of assets, loss of control over production facilities in temporarily occupied territories. The basis of economic destructive factors is the disruption of traditional logistical connections and the emergence of logistical restrictions, damage or destruction of the industry's infrastructure, a sharp increase in energy costs, a drop in exports, and the technical and technological backwardness of MMI enterprises. The result of the study was the substantiation of ways to transform the circular economy into a driver of the recovery and growth of the MMI over the next five-year period (2026–2031).

4. Ways have been proposed to increase the adaptive capabilities of the mining and metals industry to the changing conditions of the circular economy based on the international transfer of modern technologies. Its main forms are systematized: commercial transfer, investment transfer, scientific and technical (intellectual) transfer, institutional transfer. Unlike existing approaches, the main modern technologies in the system of international transfer of MMI enterprises are identified, its promising objects are substantiated, and the advantages, obstacles and challenges of use are identified. Ways have been proposed to adapt MMI enterprises in the areas of technological modernization, the introduction of circular-type equipment, energy, the use of low-carbon technologies, processing and circulation of secondary raw materials, organizational and managerial innovations, and personnel and educational support. Our research results are justified on the basis of PESTEL – an analysis that allows one to systematically assess the macroenvironmental factors that determine profitability, investment decisions, and technological trajectory. The components of the method are P (Political), E (Economic), S (Social), T (Technological), E (Environmental), L (Legal). The main political, economic, social, technological, environmental factors that influence the business activity of mining and metallurgical enterprises in the framework of a circular economy are systematized. The advantages of using PESTEL analysis are substantiation of conclusions regarding the need for mining and metallurgical enterprises to transition to proactive investment strategies

in low-carbon and digital technologies. It should be accompanied by specifying efforts to gain access to "green" financing and premium markets to transform regulatory requirements into a competitive advantage. The applied significance of our research is in substantiating the strategic directions for MMI transformation through international technology transfer, which include digital-circular transformation of production, transition to closed material cycles, decarbonization and energy optimization, as well as innovative partnerships.

The prospects for further research include compiling recommendations for the development of vertically integrated structures within mining, metallurgical, and machine-building enterprises.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The manuscript has associated data in the data warehouse.

Use of artificial intelligence

To prepare the paper, the artificial intelligence (AI) tool GPT-5 was used in section 4 "Materials and Research Methods" for the preliminary development of the methodology and generation of methodological approaches for the initial proposal of alternative management strategies for MMI enterprises. They were subsequently tested by the authors when investigating the adaptive capabilities of MMI enterprises in the framework of a circular economy by critically evaluating scientific literature and summarizing the results of statistical research.

Authors' contributions

Tetiana Kosova: Conceptualization, Methodology; **Larisa Raicheva:** Supervision, Project administration; **Stanislav Cherednichenko:** Writing – original draft, Visualization, Validation; **Kateryna Nesterova:** Software, Formal analysis, Writing – review & editing; **Natalia Yakobchuk:** Resources, Data Curation.

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