



THE FUTURE OF METALLURGY: INTELLIGENT TECHNOLOGIES, DIGITAL TWINS, AND SUSTAINABLE DEVELOPMENT

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Abstract

Modern metallurgy increasingly relies on innovative approaches such as digital twins, intelligent technologies, and automation to enhance production efficiency. This article explores the significance of new technologies in ensuring energy efficiency, optimal resource utilization, and sustainable development. Additionally, it discusses the potential for process optimization through the implementation of digital twin models and the opportunities for a technological revolution in the metallurgical industry.

Keywords: Metallurgy, intelligent technologies, digital twins, sustainable development, energy efficiency, automation, innovations..



Introduction

In the modern era, metallurgy is undergoing a significant transformation driven by the rapid advancement of intelligent technologies and digitalization. The integration of artificial intelligence (AI), machine learning, big data analytics, and digital twins has revolutionized production processes, optimizing efficiency, reducing costs, and minimizing environmental impact.

Additionally, the principles of sustainable development play a crucial role in shaping the future of metallurgy. The industry's focus on energy efficiency, emission reduction, and resource optimization aims to minimize the environmental footprint while maintaining high production standards. Automation and innovation further enhance these efforts, ensuring continuous improvement and competitiveness in a rapidly evolving global market.

This article explores the impact of intelligent technologies, digital twins, and sustainable development on the metallurgical sector, highlighting their significance in creating a more efficient, eco-friendly, and technologically advanced industry.

The main part

The modern management paradigm focuses on analyzing demand and identifying new customer needs, which contributes to the growth of companies' innovation activity. In organizational management, increasing emphasis is placed on strategic planning and long-term goals, as innovations radically transform the industrial and technological foundation of businesses. This approach facilitates a deeper understanding of the market and allows companies to adapt effectively to changes, leading to sustainable growth and development.

The concept of the term “innovation” first emerged in the 19th century in the context of cultural studies, describing the process of transferring components from one culture to another. In the modern world, the term “innovation” encompasses several actions: creating, disseminating, and implementing new ideas to enhance a company's efficiency. Based on this, innovations play a crucial role in improving operational efficiency and accelerating business process transformation.

The Latin word “novator” translates to “destroyer”, implying a person who rejects traditional ideas, methods, or principles in a particular field and seeks radical changes. The English word “innovate” means “to introduce new ideas” and “to bring about change”, while “innovator” refers to a company that develops new products and



employs modern technologies. In English-language economic literature, the term “innovation” has long been widely used, forming a set of established expressions that highlight the breakthrough nature of new developments. These include terms such as “capital-saving innovation”, “design innovation”, “factor-saving innovation”, “financial innovation”, and “manufacturing innovation” – each representing different directions in the field of innovation, aimed at optimizing resources and improving processes.

Joseph Schumpeter, in developing his theory of innovation, identified two key categories of economic actors that play an essential role in the innovation process. The first category includes manufacturing companies, which focus on developing and implementing new technologies and products, actively integrating innovation into their operational processes. The second category consists of investors, who provide the necessary financial resources and support for the realization of innovative projects, thereby facilitating their successful implementation. Together, these two categories form the foundation for a dynamic and efficient innovation process, driving competitiveness and economic growth.

Innovation, or a new development, is the result of creative activity associated with the creation of new or improved products and technologies that find practical application and meet specific needs. This process involves the introduction of new ideas and knowledge aimed at their effective use to satisfy consumer demands.

Picture 1 presents a matrix illustrating the relationship between different categories of managers and companies regarding their readiness to implement innovations. This matrix also includes a classification of innovation types based on their level of novelty. Companies classified as innovators demonstrate high innovation activity, largely due to their effective management. Such organizations are capable of implementing innovations of varying complexity – from large-scale industry-wide changes to the development of new products and improvements to processes that may be unique to a specific company.



Picture 1. Matrix of the relationship between types of managers and companies by readiness for innovation, as well as by types of innovation depending on the degree of novelty

Companies, unlike digital champions, which are at the forefront, are managed by skeptically minded and less proactive participants (according to Everett Rogers' classification) and are only capable of adapting to innovations that have already become widely accepted in the industry. This means that they work only with technologies and products that have been recognized as traditional and well-established at both the global and national levels. These organizations do not strive to implement more radical or innovative changes, which limits their potential for growth and development. Thus, the difference in approaches between innovators and laggards becomes evident: the former actively seek and utilize new opportunities, while the latter prefer to adhere to established solutions.

Digital champions are companies that have become leaders in global digital transformation. They have managed to form highly efficient ecosystems that encompass four main levels: customer solutions, personnel management, operational processes, and technology. These organizations offer relevant digital products and services that meet modern market demands.

The most significant growth of digital champions is observed in the automotive and electronics industries. Approximately 20% of companies in the automotive sector and 14% in the electronics industry implement innovations in their operations, highlighting their commitment to continuous improvement and adaptation to rapidly



changing conditions.

Currently, the concept of the “green economy” is perceived by society in various aspects. Some people see it as new economic sectors that contribute to improving the environmental situation in the country. Others emphasize innovative technologies and ecosystems that should benefit the environment. A third group interprets the “green economy” as a transition to a new stage of development focused on producing environmentally friendly goods. All these perspectives reflect the multifaceted nature of this concept and its deep significance.

Innovation plays a key role in economic development, enabling entrepreneurs to transform production methods and improve the quality of goods and services. According to Schumpeter’s claims, innovation not only introduces new technologies for creating new products but also rethinks existing methods, finds new sources of raw materials, and opens new markets. This can lead to the reorganization of existing industries and the creation of entirely new ones, which, in turn, contributes to increasing competitiveness and economic dynamism. Innovation performs several key functions: it serves as a channel for implementing intellectual achievements, helps maximize consumer satisfaction, promotes resource efficiency, and ensures balanced development.

Digitalization, like informatization and automation, represents a crucial megatrend in economic development, according to J. Naisbitt’s definition. It is based on cybernetic methods, big data analysis tools, and artificial intelligence. When the level of digitalization in a business process or company reaches a critical point, it leads to a qualitative transformation characterized by increased efficiency. Success in innovation is neither accidental nor magical but a result of consistent and purposeful actions. This can be expressed with a simple formula: $\text{Innovation} = \text{Invention} + \text{Implementation}$.

Innovation arises at the intersection of invention and implementation processes. True innovations are the result of the gradual adaptation of human experience, taking into account new approaches, processes, and technologies. In this concept, invention means creating a new solution that meets consumer needs, while implementation is associated with applying this new solution to change human behavior and interactions. To achieve an optimal balance between invention and implementation, it is essential to iterate, make data-driven decisions, and continuously learn and develop critical thinking. Modern technologies are also necessary as they open up numerous



opportunities for learning in the digital economy.

To better understand a company's innovation activity and develop effective measures to improve it, it is important to identify different categories of employees involved in innovation processes. These categories include:

Developers – specialists engaged in analyzing new ideas and researching their practical applicability. They play a key role in shaping the content and main aspects of innovations and are responsible for protecting their intellectual property rights. Developers not only generate and evaluate innovation proposals but also ensure their implementation, making them the central part of the company's innovation ecosystem.

Producers – a group of specialists directly involved in the practical implementation of innovative solutions. They are responsible for integrating new technologies and methods into production enterprises, ensuring their incorporation into existing production processes. These employees play a crucial role in turning ideas into real products or services, requiring deep knowledge and skills in change management.

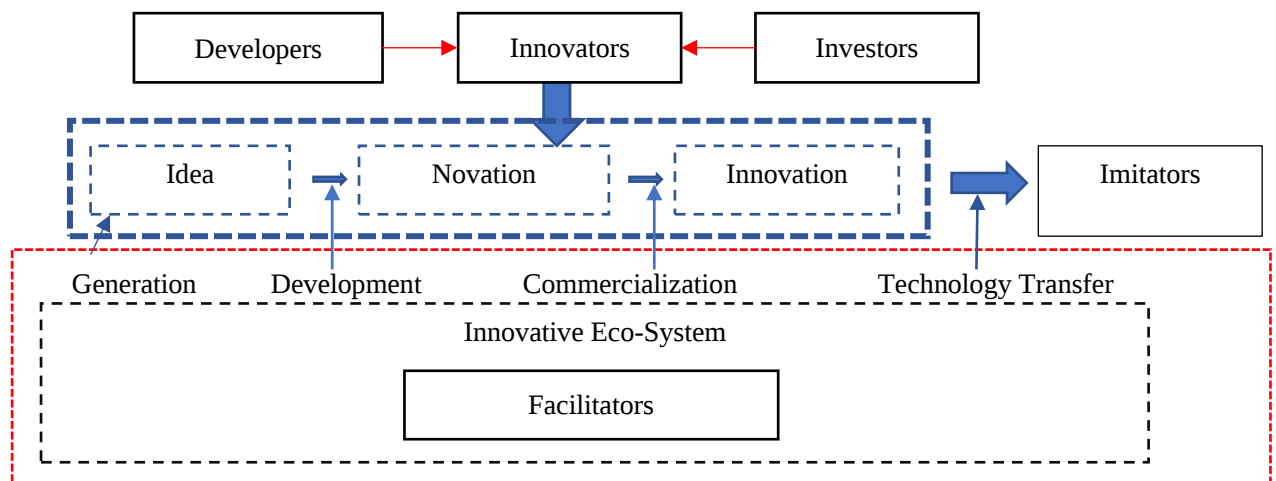
Investors – they occupy an essential position in the innovation process. They actively seek opportunities to fund new ideas or invest their own capital in innovative projects. The main task of investors is to provide the necessary financial resources for implementing these ideas. Their support often becomes a decisive factor in allowing startups and companies to successfully develop and implement innovations.

Innovators – act as a connecting link between all participants in innovation processes. This group includes technology brokers, entrepreneurs, and innovation-driven business leaders who facilitate effective interaction and collaboration between different parties. Their main task is to organize the exchange of ideas and interactions, which contributes to the faster and higher-quality development of new solutions.

Facilitators – organizations and institutions that create the necessary conditions for implementing innovations and forming a full-fledged innovation ecosystem. This ecosystem involves interaction between businesses, the scientific community, and government structures aimed at creating, transferring, and implementing research developments. Facilitators, including government bodies, development institutions, and educational organizations, do not directly engage in innovation activities but provide support and infrastructure for their successful realization. However, their role in ensuring the infrastructure and resources necessary for the successful implementation of innovations is critically important.

The interaction of these groups can be visualized using a diagram where each category

is represented as a separate block (Pic. 2).

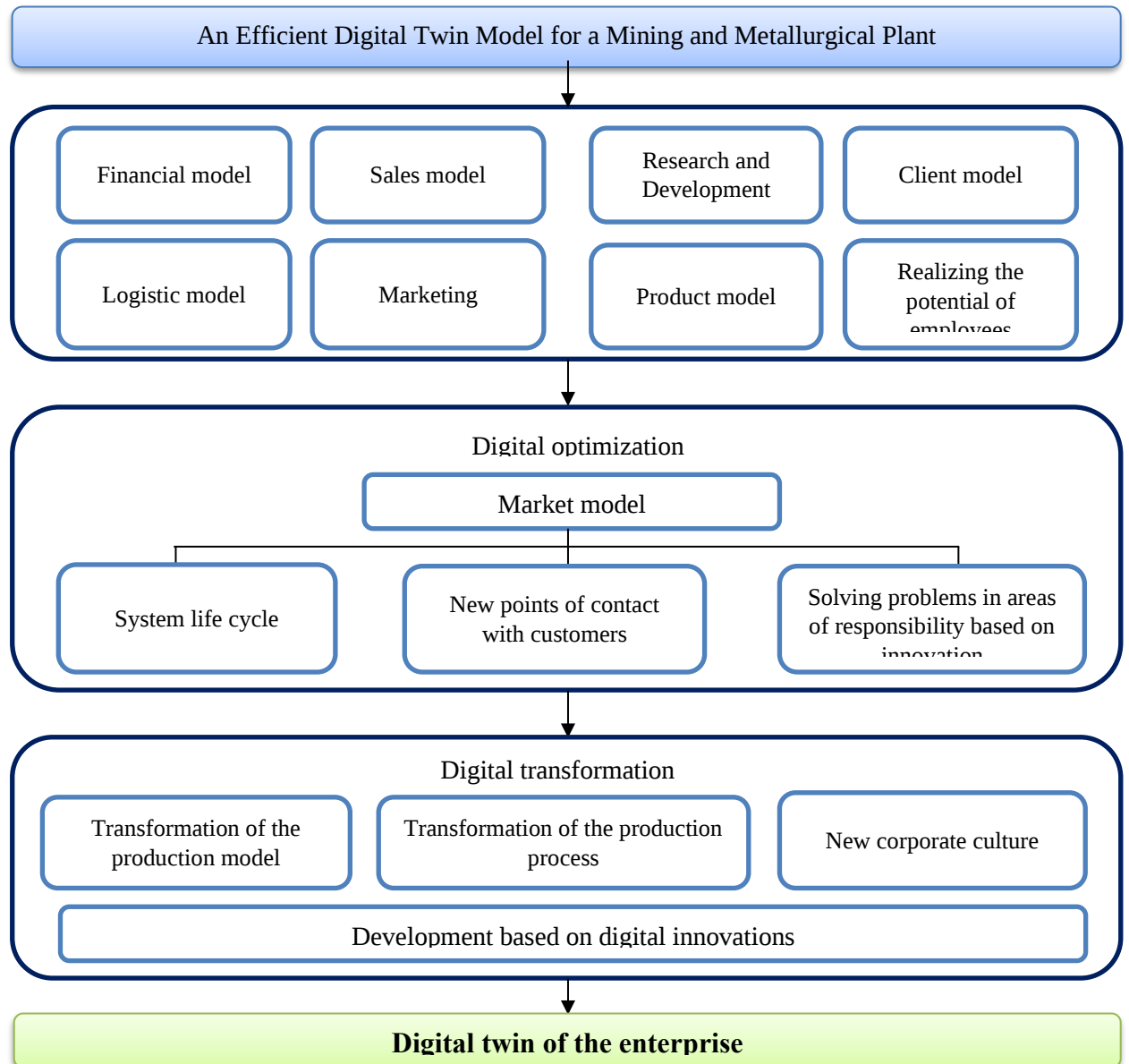


Picture 2. Generalized diagram of the innovation process

During the innovation process, developers generate new ideas and concepts, while manufacturing companies focus on their practical implementation. Investors provide the necessary financial and resource support to bring these ideas to life. However, at the core of this process is the innovative entrepreneur. They act as a key link between all participants, coordinating their interactions and ensuring synergy between developers, manufacturers, and investors. The innovative entrepreneur not only generates ideas but also formulates the strategy for their implementation, making them a crucial player in the successful adoption of innovations. They initiate the initial steps and provide support at every stage of the innovation process.

Analysis section

A **digital twin** is a high-tech virtual model that accurately replicates the characteristics and behavior of real objects, systems, processes, or even people. This model is designed to precisely recreate not only the physical form of the original but also its functional dynamics under various conditions.



Picture 3. Implementation of digital “twins” based on the sustainable development model of JSC Almalyk MMC¹

Digital twins utilize real-time data, enabling them to adapt to changes and predict the behavior of an object more accurately. As a result, they become a powerful tool for analyzing and optimizing processes, allowing for well-informed decision-making based on precise information. Thus, the digital twin acts as a bridge between the physical world and its virtual counterpart, opening up new opportunities for

¹ Compiled by the author based on data from the Altai Mining and Metallurgical Plant.



innovative research and development across various fields while ensuring synchronization between them.

The primary goal of a digital twin is to simulate possible impact scenarios on the original under different conditions. This capability significantly reduces time and financial costs, particularly in cases involving complex and expensive equipment. Additionally, it helps prevent potential harm to human health and the environment.

To reduce costs and take measures to decrease energy consumption, a model for implementing digital twins at the enterprise has been introduced. Energy efficiency initiatives can also lead to significant reductions in emissions.

The planned modernization, aimed at lowering natural gas consumption, will focus on the filtration process of zinc and lead cake in the waelz kiln shop. Additionally, upgrading the compressor station in the energy workshop by installing modern, energy-efficient compressors will provide an opportunity to significantly optimize energy consumption.

This improvement will not only reduce overall energy costs but also enhance the reliability of the equipment. The implementation of energy-efficient solutions will help cut carbon emissions and minimize the negative environmental impact, marking an important step toward the sustainable development of the enterprise. As a result, these measures will contribute to the overall efficiency of production processes and improve the company's economic performance.

Another crucial aspect is the professional development of engineering and technical personnel (ETP) and plant workers, who oversee and actively participate in technological processes. Their competent actions and deep understanding of production operations are essential for the efficient use of energy resources, reagents, materials, and raw materials, ultimately affecting the overall efficiency and competitiveness of the enterprise.

Automation systems in metallurgical production have a long history, but their application has undergone significant changes over the years. Initially, automation was primarily focused on individual units and equipment. However, with the advancement of information technology, automation has expanded to cover not only machinery and equipment but also the entire production cycle, including the business processes of the enterprise.

Experience from both domestic and global metallurgy demonstrates that increasing the capacity of metallurgical equipment presents new technical and economic



challenges related to the specifics of the technologies used. When failures occur in large-scale metallurgical furnaces or rolling mills, the consequences for the production process can be far more severe than the breakdown of lower-capacity equipment.

Conclusion and Suggestions

The evolution of metallurgy, driven by intelligent technologies, digital twins, and sustainable development, marks a significant shift toward a more efficient, cost-effective, and environmentally responsible industry. The integration of automation, artificial intelligence (AI), and big data analytics has revolutionized metallurgical production, enhancing process control, reducing waste, and optimizing resource consumption. Digital twins have emerged as a transformative tool, enabling real-time monitoring, predictive maintenance, and improved decision-making.

Sustainable development remains a key priority, with energy efficiency, carbon footprint reduction, and waste minimization playing a vital role in modern metallurgical strategies. The adoption of innovative solutions not only improves economic performance but also aligns with global environmental goals, ensuring long-term industrial viability.

Suggestions

1. Expansion of Digital Twin Technology – Companies should invest in digital twin solutions for enhanced operational efficiency, predictive analytics, and process optimization.
2. Strengthening AI and Automation – The integration of AI-powered systems in metallurgy can improve quality control, reduce human error, and increase productivity.
3. Sustainability and Energy Efficiency – Implementing energy-saving technologies, renewable energy sources, and waste management strategies will contribute to greener production methods.
4. Investment in Workforce Training – Training and upskilling employees in digital technologies and data-driven decision-making will ensure smooth adoption and utilization of new advancements.
5. Collaboration with Research Institutions – Partnering with universities and research centers can accelerate innovation, providing access to cutting-edge



developments and best practices in metallurgical processes.

By embracing these technological advancements and sustainability initiatives, the metallurgical industry can ensure continued progress, competitiveness, and a positive environmental impact in the future.

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