

V International Scientific and Technical Conference Actual Issues of Power Supply Systems

Digitalization as a tool for innovative development and efficiency improvement of industrial enterprises

AIPCP25-CF-ICAIPSS2025-00405 | Article

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Digitalization as a tool for innovative development and efficiency improvement of industrial enterprises

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Abstract. This study explores the concept of innovation and the role of digital twins in modern industrial and organizational practices. Innovation is understood as a complex process involving technological, applied, and market-oriented aspects, which may occur simultaneously or sequentially, rather than as an isolated event. Digital twins are virtual models of physical objects, systems, or processes that replicate the behavior and characteristics of their real-world counterparts in real time. They are widely applied in various sectors, including manufacturing, energy, construction, medicine, transport, and urban planning. By integrating sensors and advanced simulation technologies, digital twins enable organizations to optimize processes, reduce risks, enhance operational efficiency, and support decision-making.

INTRODUCTION

In the contemporary global economy, innovation is no longer merely an occasional competitive advantage but a fundamental condition for the long-term survival and sustainable development of enterprises. Originally emerging in the 19th century as a term describing the transfer of cultural elements between societies, the concept of “innovation” has evolved into a complex, multifaceted process of creating, disseminating, and commercializing novel ideas, technologies, and organizational solutions that directly contribute to increased efficiency, profitability, and market leadership. [1]

A key characteristic of modern innovation is its systemic nature: it rarely arises from a single breakthrough but rather from the interconnected transformation of technology, applications, markets, and organizational structures. This interconnectedness turns innovation into a continuous chain of successive changes rather than an isolated event.

One of the most vivid and practically significant manifestations of contemporary technological innovation is the Digital Twin (DT) concept, including its organizational-level extension, the Digital Twin of Organization (DTO). A digital twin is a dynamic virtual replica of a physical object, system, process, or even an entire enterprise that mirrors the form, behavior, and condition of its real-world counterpart in real time. By integrating data from IoT sensors, advanced simulation models, and analytical algorithms, digital twins enable companies to test scenarios, predict failures, optimize operations, and make informed strategic decisions without risking physical assets, human safety, or the environment. [2].

First theoretically formulated by Michael Grieves in 2002 and officially introduced in NASA’s 2010 technology roadmap, digital twin technology has rapidly moved from aerospace and large-scale engineering into virtually all sectors of the economy: mining and oil & gas, energy, manufacturing, construction, transport, healthcare, agriculture, retail, and urban development. Leading international corporations (GE, Siemens, Schneider Electric, ADNOC, and others) [3] have already achieved multibillion-dollar savings and dramatic improvements in operational reliability through digital twin deployment.

In the mining and metallurgical industry, where equipment is extremely capital-intensive, operating conditions are harsh, and any unplanned downtime entails colossal financial and environmental risks, digital twins offer particularly high potential value. The ability to predict equipment degradation weeks or months in advance, to virtually test new process chains, and to optimize the entire production system from a single control center transforms traditional reactive maintenance into proactive, data-driven management.

The present research examines digital twin technology as a modern innovation tool and evaluates its potential impact on the operational efficiency and competitiveness of a large industrial enterprise, using the Almalyk Mining and Metallurgical Combine (JSC “AGMK”, Republic of Uzbekistan) as a practical case. The study combines theoretical analysis of innovation and digital twin concepts with empirical assessment of their influence on key business processes and financial performance of the enterprise. Through construction and analysis of a multifactor econometric model, the work aims to quantify the contribution of digital twin

implementation to net profit growth and to formulate practical recommendations for its adoption in heavy industry under emerging-market conditions. [4].

Thus, the research not only contributes to the academic discussion on the nature and components of innovation but also provides a concrete roadmap for transforming one of the strategic enterprises of the Uzbek economy through cutting-edge digital technologies.

EXPERIMENTAL RESEARCH

The term “innovation” was first used in the 19th century in cultural studies and referred to the introduction of certain elements of one culture into another. The meaning of the term “innovation” (from the English innovation) refers to a developing, complex process of creating, disseminating, and using new ideas or technologies that contribute to the growth and increased efficiency of entrepreneurial firms. [5]

It should also be noted that the Latin word “novator” means a renewer, that is, a person who introduces and implements new, progressive principles, ideas, or methods in any field of activity.[6] The English term “innovate” means to introduce innovations, make improvements, or bring about changes, while the term “innovator” refers to a company that creates new products or applies new technologies.

In English-language economic literature, the term “innovation” has long been in everyday use, which has led to the formation of several established expressions emphasizing the breakthrough and highly significant nature of the changes described by this term, such as:

- capital-saving innovation – innovations that save capital;
- design innovation – changes in the design of a machine;
- factor-saving innovation – innovations that reduce the cost of a production factor (labor or capital);
- financial innovation – development of new financial methods;
- manufacturing innovation – a new method of production;
- product innovation – a new product. [7]

A Digital Twin (Digital Twin of Organization, DTO) is a software-based counterpart of a physical device that models the internal processes, technical characteristics, and behavior of a real object under the influence of external disturbances and environmental conditions. An important feature of a digital twin is that its input parameters are formed using data received from sensors installed on the real device operating in parallel. The digital twin can function both online and offline. It is then possible to compare the information from the virtual sensors of the digital twin with the sensors of the real device, identify anomalies, and determine their causes. [8]

A digital twin is a digital (virtual) model of any objects, systems, processes, or even people. It accurately replicates the form and behavior of the original and is synchronized with it. Digital twins are needed to simulate what will happen to the original under various conditions. This helps, first, to save time and resources (for example, when dealing with complex and expensive equipment), and second, to avoid harm to people and the environment.

The concept of a digital twin was first described in 2002 by Michael Grieves, a professor at the University of Michigan. In his book “*The Origin of Digital Twins*”, he identified three core components:

1. A physical product in the real world
2. A virtual product in the digital space
3. Data and information that connect the virtual and the physical product

According to Grieves, “under ideal conditions, all information that can be obtained from a physical object can be obtained from its digital twin.” [9]

The term “**Digital Twin**” was officially first mentioned in NASA’s 2010 modeling and simulation report. It referred to a highly realistic virtual copy of a spacecraft that reproduces its construction, testing, and operational phases.

Digital twins can be categorized into:

- **Prototype (DTP)** – a virtual analogue of a real object that contains all necessary data for manufacturing the original.
- **Instance (DTI)** – contains data on all characteristics and operational parameters of the physical object, including a 3D model, and operates in parallel with the original.
- **Aggregated Twin (DTA)** – a computational system consisting of multiple digital twins and real objects, all managed from a single control center with internal data exchange. [10]

For example, in the Middle East, digital twin technology enabled ADNOC to integrate 20 oil production and refining facilities into a unified control center and standardize all processes.

The optimal acceptable deviation between a digital twin and its physical prototype is considered to be **5%**.

Tasks Solved by Digital Twins

1. Conduct test launches of processes or production chains quickly and with minimal investment.
2. Detect problems or vulnerabilities before production starts or before an object is put into operation.
3. Increase the efficiency of processes and systems by identifying malfunctions in advance.
4. Reduce risks – including financial risks and risks to personnel safety and health.
5. Improve business competitiveness and profitability.
6. Build long-term forecasts and plan the company’s or product’s development for years ahead.

7. Improve customer loyalty by accurately predicting demand and product performance characteristics. [11]

Applications of Digital Twins

Mining and Oil & Gas Industry. Digital twins reduce risks during the extraction and processing of oil and gas, helping protect employees, preserve the environment, and save large financial resources. At one European oil refinery, Schneider Electric's predictive analytics system forecasted a compressor failure 25 days before it occurred, saving the company several million dollars.

Large-scale Manufacturing. Digital twins allow the creation of individual components and entire production chains, enabling virtual testing and preventing equipment failures. [12]

Energy Sector. Digital twins optimize power plant performance, prevent power outages, and improve energy efficiency. GE has saved its customers more than **\$1.5 billion** through digital twin solutions.

IT Infrastructure. Digital twins can model individual devices or entire networks, calculating peak loads and designing cybersecurity protections.

Construction. Digital twins can simulate buildings or entire districts to predict environmental integration, structural loads, and sustainability under various conditions.

Design. 3D virtual models of interior and decorative objects help visualize their appearance and make design adjustments.

Retail. Digital twins model customer flows, employee movement, store occupancy, lighting levels, and temperature optimization.

Transport and Logistics. Digital twins optimize transportation routes, technical services, and passenger flows. A digital baggage-handling simulation at a major airport predicted the need for an additional transport line for emergency situations.

Education. Digital environments support the study of physical objects and processes using AR, VR, and mixed reality technologies.

Space Industry. Digital twins are used to design, test, and launch spacecraft and missions. The digital twin of Apollo 13 in 1970 helped engineers and astronauts save the mission during an emergency.

Medicine. Digital twins of patients enable real-time monitoring, personalized treatment, and surgical planning.

Sports. Teams can test strategies, and athletes can run training simulations on digital models. In Formula 1, digital simulations help refine the performance and characteristics of racing cars.

Urban Development. Digital twins of entire cities exist — for example, Singapore and Kronstadt (Russia). They track transportation systems, utilities, construction, environmental conditions, and energy consumption.

Agriculture. Digital twins help forecast climate conditions and crop yields, making agriculture more efficient.

How a Digital Twin Is Created

Digital twins can be developed in different ways:

- Graphical 3D modeling
- IoT-based models
- Integrated mathematical models such as CAE systems (Computer-Aided Engineering)
- Visualization technologies including holograms, AR, and VR

As can be seen from the given definitions, in the foreign (international) understanding, innovations for the largest organizations are not so much a means of survival as a philosophy of corporate ethics and an integral part of organizational activity. However, it should be noted that the organizations mentioned are major companies of international scale.

Such a classification most fully reflects the entire diversity of innovations, but it is difficult to apply it when determining the scope of innovation activity. Therefore, when considering innovation as the commercialization of something new, the following components can be identified. [13]

T (technology) – new technology	A (application) – a new application in the form of new products, services, or processes
“INNOVATION”	
M (market) – a new market or market segment	O (organization) – a new organizational form or a new approach to management.

Fig. 1. Main Components of Innovation

Thus, any innovation possesses at least one of the following aspects:

- technological;
- applied;
- market segmentation or consumer grouping.

The example above demonstrates how markets are connected with organizational achievements, technology, and its direct application. It should be noted that, in fact, there is no direct dependency between technology and applications, between applications and markets, between markets and (external or internal) organizational structures, or between external and internal organizational structures and technology. Nevertheless, these four coordinates are indirectly interdependent; for instance, a certain technology has a limited number of applications.

Therefore, an innovation can result from the introduction of a new technology, the use of a new application, the development of new markets, or the implementation of new organizational forms. In most cases, it is a combination of multiple factors introduced both simultaneously and sequentially. Consequently, innovation is not an isolated event but rather a chain of successive transformations consisting of a series of events. For this reason, it is difficult to pinpoint the exact moment when a particular innovation emerged or to determine a single definitive cause of the innovation.

RESEARCH RESULTS

A digital twin is a digital (virtual) model of any objects, systems, processes, or people. It accurately reproduces the shape and behavior of the original and is synchronized with it.

A digital twin is used to simulate what will happen to the original under various conditions. This helps, first, to save time and resources (for example, when dealing with complex and expensive equipment), and second, to avoid harm to people and the environment. [14]

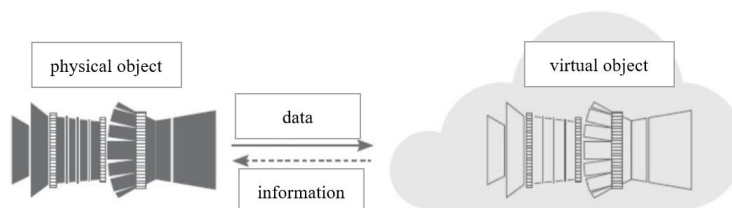


Fig. 2. Basic concept of a digital twin

The idea is that sensors are integrated into the physical object to collect information about its condition over a certain period of time. This information is transmitted to the virtual digital twin, thereby refining the digital model. The digital model takes into account all changes in the physical object and accumulates information about these changes.

Thus, as the virtual model is refined, it becomes an accurate copy of the physical object and can adequately describe and predict its behavior.

It should be noted that the digital twin of equipment has the greatest impact on the main business process of an industrial enterprise – production. In addition, the study proved the influence of implementing a digital twin on other business processes of the enterprise and on the overall performance of the company.

Summing up, the figure below presents the impact of digital twins on the business processes of an industrial enterprise.

Based on the research objectives, the following factors were selected for the multifactor econometric model: the resulting factor is the volume of net profit from product sales at the enterprise, thousand soums (Y). The influencing factors are: cost of goods sold, thousand soums (X_1); long-term investments, total in thousand soums (X_2); value of fixed assets, thousand soums (X_3); and the average annual profit of the enterprise, thousand soums (X_4). Since the units of measurement of the data included in the multifactor econometric model developed on the basis of data from JSC “AGMK” differ, we apply logarithmic transformation to them.

It should be noted that skewness is the skewness coefficient, and if it equals zero, this indicates that the distribution is normal and symmetric. If this coefficient significantly differs from zero, then the distribution is skewed (i.e., not symmetric). If the skewness coefficient is greater than zero, meaning it is positive, the normal distribution curve for the studied factor shifts to the right. If it is less than zero, meaning it is negative, the normal distribution curve for the studied factor shifts to the left.

All the factors follow a normal distribution. It should be noted that $\ln Y$, $\ln X_3$, and $\ln X_4$ have negative skewness values; consequently, the “left tail” of their graphs is longer than the “right tail,” and it is evident that the distribution curve is shifted to the right. Since the skewness coefficients of the factors $\ln X_1$ and $\ln X_2$ are positive, the “right tail” on their graphs is longer than the “left tail,” and therefore, the distribution curve shifts to the left.

CONCLUSIONS

Overall, digital twins provide powerful tools for improving efficiency, enhancing quality, and reducing costs in the mining and metallurgical industries. The implementation of such technologies at the Almalyk Mining and Metallurgical Combine could significantly increase its operational efficiency and competitiveness. Innovation is a multifaceted and continuous process that cannot be attributed to a single factor or moment. It arises from the interaction of new technologies, applications, market development, and organizational structures. Digital twins exemplify the practical application of innovation, providing a bridge between virtual and physical worlds. They allow companies to simulate, predict, and optimize the performance of products, systems, and processes, leading to significant savings in time, resources, and costs. Furthermore, digital twins improve safety, support strategic planning, and enhance customer satisfaction. As industries continue to digitalize, the integration of digital twins into business processes becomes a key factor for maintaining competitiveness, fostering innovation, and achieving sustainable growth.

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