Article


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Abstract: The relevance of the study is dictated by the growing role of the fuel and energy complex of developing countries in the decarbonization of the economy. The article discusses the digital transformation of mining enterprises in Kazakhstan, taking into account the transition to CRIRSCO international standards and growing competition in the global mineral market. The purpose of the study is to assess the current level of digitalization of the mining industry in Kazakhstan and to deepen the methodological apparatus of the geological and economic assessment of enterprises based on the factual base of deposits. The role of the transformation of the mining sector in achieving the sustainability of the poorly diversified economy of Kazakhstan is shown. The importance of digitalization of the industry to complete the transition to CRIRSCO international standards and improve the assessment of the financial provision of enterprises in order to optimize their financial and economic policies is argued. It has been established that, at present, most of the enterprises in the investment-attractive mining sector have a low potential for the transition to a new technological paradigm. A methodological approach to the geological and economic assessment of these enterprises has been developed. To maintain high standards of management transparency through the digitalization of key business processes, along with well-known practices of economic analysis, the IDEF1 methodology was used. In order to expand the software ecosystem, the formats of electronic geological and economic databases are integrated into the digital infrastructure of the enterprise. It is substantiated that the introduction of high technologies in the mining industry requires institutional changes and coordinated interaction between the state, business, and universities as equal partners.

Keywords: transition economy; decarbonization; international CRIRSCO standards; mining enterprise; geological and economic assessment

1. Introduction

In the coming years, mining enterprises will face various trends that can reduce the demand for their products: a post-industrial economy, a declining population, and an increase in the cyclical use of resources. The transition to a low-carbon and sustainable economy is under way. Leading mining companies are committed to achieving zero emissions by making social responsibility and corporate governance (ESG) the core of their organizational strategy. To adapt to increasingly complex conditions, it is necessary to digitally transform existing business models and improve approaches to assessing the
readiness of industrial enterprises for digitalization and the impact of digital solutions on competitive positions.

One of the main factors in the competitiveness of the mining industry in Kazakhstan, which accounts for 13% of the country’s gross domestic product, is digitalization. Kazakhstan is adopting the experience of Singapore, South Korea, Denmark, and China, where the state, with the participation of business and private investors, regulates the implementation of digital solutions. The practice of Australian and North American companies was taken into account, where the introduction of information systems helped to reduce operating costs, reduce risks and accidents, and generally improve the efficiency and quality of management decisions. Kazakhstan considers international dialogues on the consolidation of energy policy and adaptation of advanced foreign experience.

The country plans to become a central digital hub in a significant part of the Eurasian region; therefore, the use of modern digital technologies and the introduction of innovative approaches and environmentally friendly technologies for the transition of industrial production to a low-carbon economy is extremely important.

At the same time, it should be noted that one of the key brakes on the decarbonization of the mining sector compared to the best world practices is the fact that the problem of climate change remains a low priority for the state, businesses, and citizens. The economic model of Kazakhstan is still poorly adapted to international environmental standards; there is no strategic environmental assessment of development programs and concepts in the state planning system.

Kazakhstan supports innovative research in the field of technology, creating conditions for industrial diversification and increasing value added in the primary industries and knowledge-intensive products. Like other countries in transition, Kazakhstan is considering the introduction of digital solutions to enhance its export activities, infrastructure development, and social sphere.

As part of the new industrial policy, approaches to information processing have changed to a large extent to improve the reliability of the geological and economic assessment of mineral deposits, which is primarily due to the emergence of new digital and analytical tools. However, at present, in most cases, enterprises use several information systems with redundant functions; there is still no unified methodology for the geological and economic evaluation of deposits. In addition, in the short and medium term, the task of assessing the consequences of digitalization of the mining industry from the standpoint of its growing role in the decarbonization of the economy of Kazakhstan is being solved, the transition to international standards CRIRSCO (Committee for Mineral Reserves International Reporting standards) will become more difficult.

The foregoing actualizes for Kazakhstan the issue of choosing a methodological apparatus for solving geological and economic problems and its information and analytical support in the context of the digital transformation of the mining industry. The demand for this study and the feasibility of an in-depth study of the issues under consideration are predetermined by the desire of city-forming enterprises for digitalization as a key factor in strengthening competition in the mining market.

The purpose of the study is to assess the current level of digitalization of the mining industry in Kazakhstan and to deepen the methodological apparatus of the geological and economic assessment of the enterprise based on the factual base of deposits.

The structure of the manuscript consistently reflects the stages of research. Section 2 provides an overview of recent research in the field of digital transformation of manufacturing enterprises in general and mining enterprises in particular, taking into account the factors of innovation, decarbonization processes, and approaches to managing different stages of mining. Section 3 presents the methodological approach to the geological and economic assessment of the enterprise, which formed the basis of the study. To maintain high standards of management transparency through the digitalization of key business processes, along with well-known practices of economic analysis, the IDEF1 methodology was used. Section 4 presents the results of assessing the effectiveness of the digital
transformation of the mining industry in Kazakhstan, the directions for improving the geological and economic assessment of enterprises in Kazakhstan, as well as the specific results of calculating reserves for ore bodies of the Kusmuryn deposit for 2022 and 2023 based on the author’s approach using Micromine Origin 12.5 software. Section 5 contains the conclusions, limitations, and recommendations of the study: it is substantiated that the introduction of high technologies in the mining industry requires institutional changes and coordinated interaction between the state, business, and universities as equal partners. Section 5 also presents directions for further research based on the results obtained.

2. Literature Review

The discussion about digital transformation as a need for further progress touches on its most diverse aspects. A. Cahyadi and R. Magda [1] focus on the importance of achieving progress in innovation activities of the institutional component, staff competence, and developed infrastructure. The growing role of digital platforms from the standpoint of the formation of sustainable business communications between partners that have a direct impact on the innovative activity of the subject is the subject of study D. Trabucchi, L. Muzellec, S. Rondeau and T. Uganza [2]. In “Latecomer Economies and National Digital Policy: An Industrial Policy Perspective”, C. Foster and Sh. Azmeh [3] study the specifics of digitalization in developing countries, show the role of digital solutions in overcoming the technological backwardness of these countries, and identify problems that hinder the advancement of advanced technologies.

According to a study by M. Bas and V. Strauss-Khan [4], imported resources have a positive effect on productivity and exports. This is achieved not only through the sharing of resources but also through the transfer of new technologies from industrialized countries to developing countries. D. Castellani and C. Fassio [5] also explore the role of new imported resources that open up access to new technologies and enable a rational combination of already used resources. The main conclusion of the research is that, in this case, both completely new and modernized export-oriented products may appear. As shown by P. L. Hsieh [6], the influence of trade agreements for the domestic legal regulation of financial integration and digital trade on the integration processes of the countries of the Asia-Pacific region and the construction of a new economic order on a regional scale is invaluable. The formation of new businesses in innovative industries is largely predetermined by historical trends typical for knowledge-intensive industries. M. Fritsch and M. Wyrwich come to this conclusion in their research [7].

A study by S. Park and I. Park [8] proved that the diversification of the national economy and participation in the global value chain stimulates the creation of intra-country value chains, which positively affects international state positioning.

As demonstrated by G. K. Adarkwah and T. P. Malonæs [9], in general, scientific interest in emerging large-scale markets with a huge geographical distribution has not subsided over time.

In many studies, the emphasis is on the growing role of innovation in mining management. The study by O. Bazaluk et al. [10] proposes to take into account the level of organization of innovation activity according to the criteria of optimality of innovation management. J. A. Aznar-Sánchez et al., in the study “Innovation and technology for Sustainable Mining Activity: a worldwide Research Assessment” [11], study the role of innovations from the standpoint of achieving sustainable operation by a mining enterprise, increasing its contribution to the environmental and socio-economic spheres of its activities. This approach deepens the study of the specifics of decarbonization processes in the coal industry and their growing role in the diversification of the economy.

To expand the understanding of the importance of digitalization in the mining industry, it is of undoubted interest to assess the factors influencing the introduction of innovations, which are the subject of research by the scientists and specialists J. H. Gruenhagen and R. Parker [12]. The results obtained made it possible to identify such reasons as the
competence of employees, the underdevelopment of the innovation infrastructure, and the organizational component.

The specifics of the work of mining enterprises largely determine the feasibility of making specific digital decisions. M. Kopacz et al. [13] draw attention to the role of the reliability of primary geological data on the economic parameters of the deposit and the possibility of solving this problem using advanced equipment and technologies.

In light of the above, studies [14–17] are of interest, revealing the essence of methodological means for improving production processes as the most important resource of an enterprise. In their study, S.-I. Cioacă, S.-E. Christache, M. Vută, E. Marin, and M. Vută [14] assess the impact of information and communication technology indicators on the achievement of sustainable development goals. Research [15,16] is devoted to project management for supply chains from the position of making digital decisions.

Various aspects of mining management in the context of lean manufacturing are discussed in a study by A. F. Klippel, C. O. Petter, and J. A. V. Antunes [17], which proves the possibility of introducing a new form of management in the mining industry.

Increasing uncertainty in the energy markets actualizes the assessment of the financial and economic condition of mining enterprises. A study by E. Kharabadze and M. Jikia [18] substantiates the importance of assessing the rational ratio of equity and debt capital in the analysis of the financial stability of an entity. The importance of enterprise sustainability in terms of making scientifically based strategic decisions to maintain a stable market position is shown in the work of D. Hackbarth, R. Mathews, and D. Robinson [19], where the authors prove the impact on the profitability of the development of mineral deposits of science-based approaches to assessing the economic efficiency of mining operations.

The study by Y. Uteshoat et al. [20] is devoted to the digitalization of the technological and organizational processes of mining. The authors focus on the integrated use of generated energy and substantiate the feasibility of using new technologies by power-generating enterprises. The rise of sustainability issues in the coal industry is highlighted in a study by P. Saik et al. [21]. The expediency of deepening the research of diversification processes in this area is substantiated.

The impact of innovative solutions on the sustainable development of industry remains the object of close attention of scientists and practitioners. S. Zhironkin and M. Cehlár [22] proposed a new approach to managing different stages of mining based on decision-making methods using software products. A study by A. Khorolskyi et al. [23] is devoted to the expediency of deepening international research in the field of innovation.

Nwaila et al. [24] and Song et al. [25] make an invaluable contribution to studying the digitalization of the mining industry and adjusting the policy of enterprises in the field of resource use. The works of Miao et al. [26] and Ericsson et al. [27] reveal opportunities to improve resource efficiency through green technology innovation.

Given the high attractiveness of the mining industry in Kazakhstan for potential investors, scientific studies on the possibilities of the mining industry in the context of strengthening the country’s international positioning and decarbonizing the economy are of interest. Azadi et al.’s study [28] focuses on the growing role of green technologies in the mining industry. Social and environmental obligations arising from the development of minerals and various aspects of the growing role of innovative solutions in achieving competitive advantages are studied by Svobodova et al. [29]. The work of Shah et al. deepens the discussion of quantifying the role of natural resources in national economic growth [30].

Numerous studies have been devoted to the digitalization of the mining industry, taking into account the specifics of both production and management processes. Thus, the work of Pfeiffer S. [31] substantiates the role of Industry 4.0 in creating new business models and solving social problems of the industry through the formation of links between exogenous and endogenous factors that affect the production process. The need to optimize business processes that allow an enterprise to improve its results is indicated in a study by
Subramanian and Ramanathan [32]. Hofmann and Rüsch [33] establish the influence of Industry 4.0 on the development of industries, accompanied by various effects.

Brandmeier et al. [34] explore the potential of machine learning to enable enterprises to build three-dimensional models that are used in analytical studies of deposits in the forecasting of geological exploration. Contributors Fu et al. [35] demonstrate how 3D mining prediction can improve the efficiency of ore discovery, and digital cards and geoinformation models, on which geoinformation systems (GIS) are based, can evaluate and predict resources deposits and plan the costs of prospecting and survey work. The modern studies considered in this section formed the basis of the methodological approach to the geological and economic assessment of the enterprise, developed by the authors for the study and considered in Section 3.

3. Methods

The methodological basis of this study is a functional approach that takes into account the rapidly changing business environment. The methodological apparatus of the study is based on the main provisions of the methodology for constructing indicators that assess the readiness of enterprises for the digital economy. The methodology used is the analytical study Integration Definition for Information Modeling (IDEF1) is based on well-known concepts of retrospective and comparative assessment of the overall performance of mining enterprises in Kazakhstan in achieving sustainable development. In recent years, interest has increased in theoretical and applied research in the field of economic modeling and information technology used in the mining sector. This is especially true of the methodology for conducting a high-quality geological and economic assessment, which determines the possibility and expediency of continuing the preparation for the industrial development of deposits in hard-to-reach areas with the participation of junior companies and establishing the level of reserve reliability. The task is complicated by the fact that the deposit model is transformed in accordance with the economic situation, the technology used, the morphology of the ore bodies, and geological and analytical information. The demand for the identified problems is supported by the continuing high dependence of Kazakhstan’s enterprises on foreign software and the lack of its own digital products for geological modeling, data collection, and analysis. Low technology and patchwork automation do not provide real-time information about the field. The authors’ methodological approach to conducting a geological and economic assessment of a deposit is based not only on the possibility of converting primary data into digital form, reducing the time of their processing and digitizing retrospective materials. It is proposed to integrate geological and economic information in electronic database formats into the existing digital infrastructure of the enterprise. Digitization and identification of geological and economic information and its systematization into a single database will expand the enterprise software ecosystem. The scientific and methodological apparatus includes a causal and current analysis of the statistical information on the economy of Kazakhstan and the prospects for its development. The limiting factor of the study was the lack of correct statistical data, disclosing, for example, information about the costs of enterprises for digitalization, security, and environmental protection. However, due to the transparency of individual indicators and open access, results were obtained that, according to the authors, will deepen the understanding of the digital transformation of mining enterprises in Kazakhstan. The main sources of information are information and analytical materials from the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan [36]; reports from the Kazakhmys Corporation LLP, Kusmuryn and Akbastau fields according to the standards of the Kazakhstan Association for Public Reporting on Exploration Results, Minerals and Mineral Resources (KAZRK), which is part of the CRIRSCO family, together with the Australian Code for the preparation of reports on exploration results, minerals, and reserve ores of the Joint Ore Reserves Committee (JORC); publications on designated topics in scientific journals; authors' own research.
Digital formatting of information about the enterprise acquires new information qualities, as it allows not only assessing the current state of existing fields but also substantiating the strategy of subsequent exploration works. For the geological and economic assessment of the field and the choice of strategy, exploration works need information about spatial objects, both deposits and mining workings (underground and open). For example, economic information has a spatial component represented as an information map. To this end, enterprises not only implement a mining and geological information system (GGIS) but also strive to combine its functionality with IT solutions developed by their own efforts, taking into account the nuances of each field.

To take into account the indicators of the geological and economic assessment of the enterprise, two schemes are used that describe its interaction with the external environment—object-functional and process-functional. The authors believe that when constructing a system of indicators for the geological and economic assessment of an enterprise from the standpoint of the international activities of subjects, emphasis should be placed on quantitative and qualitative indicators reflecting the impact of production processes on social and environmental aspects, assessing the quality and availability of ESG information in public reporting of enterprises. In addition, business entities will be required to provide characteristics for integrating sustainable development into the existing corporate governance system. To assess enterprises according to the criteria for analyzing sustainable development and social responsibility, the level of disclosure of ESG information is taken into account. In the case of the adoption of the ESG agenda and the real transformation of the business model, the enterprise can integrate the ESG strategy into the overall strategy of its development, determining which of the many aspects of sustainable development have the highest priority, as suggested by the authors in the developed methodological models in Figure 1.
Figure 1. Methodological approach to the geological and economic assessment of the enterprise. Compiled by the authors.
4. Results and Discussion
4.1. Evaluating the Effectiveness of the Digital Transformation of the Mining Industry

Kazakhstan’s transition to a low-carbon and sustainable economy against the background of deepening global competition and the growing importance of geopolitical risks can be accelerated through the digitalization of business processes.

In order to reduce the low-carbon footprint and to phase out thermal coal, mining enterprises in Kazakhstan are moving to the international CRIRSCO standards, implementing management, health, and safety systems that comply with international standards ISO 45001, ISO 9001, ISO 14001, ISO 50001, and support the UN Sustainable Development Goals 8. In their annual integrated reports, enterprises report on the key environmental indicators and disclose their impact in the ESG areas. They show how resource consumption is changing due to the use of digital solutions and the introduction of rational management approaches.

The mining industry, which has a low level of redistribution and insufficient technological equipment compared to the world leaders and, as a result, low labor productivity and competitiveness, is in dire need of digital solutions. The integration into the world economy of the largest enterprises of the quasi-public sector obliges them to meet a high level of efficiency, to actively transform their production activities, and to form digital development strategies with an emphasis on their own technologies and competencies, social responsibility, and cybersecurity.

For the mining and energy industries, the effectiveness of digital transformation is measured in terms of the total cost of diversifying the economy. This compares the costs associated with the digital transformation of technological chains of production, transport, transformation, and consumption of resources (including external supplies) and the resulting savings in operating and capital costs in each industry.

The scale and depth of digital technologies penetration in the mining industry are determined by the cost-effectiveness of additional investments (taking into account subsequent maintenance costs) in the digitalization of processes. When developing new, unconventional, possibly expensive mineral deposits or increasing the productivity of old deposits, the economic feasibility of realizing the digital potential, along with reducing the time and cost of development and production, will be determined by the price environment for specific resources and the cost of their extraction.

In the macroeconomic assessment of the effectiveness of digital transformation, additional costs arising in the sectors of the fuel and energy complex are compared not only with the local benefits but also with the benefits that arise along the entire chain of input-output balance in industries (for example, construction, IT-sphere, communications). There should be taken into account not only the multiplier effect of additional investments in digital technologies directly in the fuel and energy complex but also the price effect for all consumers associated with decreasing the cost of energy supply.

This approach to efficiency assessment is objectively necessary since the same assessment components provide benefits for some industries, but other industries may incur increased costs or losses. At the same time, an optimal system for promoting new areas of investment is formed through, for example, regulatory or tax mechanisms. As a result, the risks of large losses for certain groups (for example, consumers, energy companies) are minimized. The maximum effect is achieved both for the sectors of the fuel and energy complex and for the economy of Kazakhstan as a whole.

The costs of digital transformation are the costs of changing the functional characteristics of traditional technological chains, primarily through investments in systems for collecting, analyzing, and monitoring information, high-speed communications, and adaptive control of the modes of energy facilities and consumers (Table 1).
Table 1. Components of digital transformation costs of mining enterprises.

<table>
<thead>
<tr>
<th>Component A</th>
<th>Component B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost components:</strong></td>
<td>Capital and operating costs associated with the additional development of new energy technologies that expand the technical potential of their use through digital transformation:</td>
</tr>
<tr>
<td>- Capital expenditures for “digital saturation/re-equipment” of the existing and new energy facilities with measurement systems, automation, and intellectualization of process control;</td>
<td>- In the electric power industry, they are renewable energy sources (RES), storage, and distributed generation technologies of all types;</td>
</tr>
<tr>
<td>- Operating costs for maintaining the efficiency of the new information and communication infrastructure.</td>
<td>- In the oil and gas sector, they are technologies for the development of hard-to-reach hydrocarbon deposits, increasing the productivity of old fields.</td>
</tr>
</tbody>
</table>

The electricity and gas industry must take into account the costs of end-users of electricity and gas supplied through the grid and affecting the operating modes of the entire infrastructure.

Compiled by the authors.

However, so far in the mining segment, due to the high cost of the equipment used and the length of its depreciation period, projects related to major digital changes at enterprises are being implemented slowly. In general, the level of implementation of digital solutions in production and economic activities is low and heterogeneous. In 2021, the share of large- and medium-sized enterprises in Kazakhstan using digital technologies was only 9.9% and increased by only 4% compared to 2019; local enterprises do not yet show much enthusiasm for new technologies (Table 2) [36].

Table 2. Indicators of using IT technologies in the mining sector.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
</tr>
</thead>
<tbody>
<tr>
<td>The total number of enterprises surveyed of which the number of enterprises:</td>
<td>1347</td>
<td>1365</td>
<td>1339</td>
</tr>
<tr>
<td>- Using computers,</td>
<td>1121</td>
<td>1154</td>
<td>1111</td>
</tr>
<tr>
<td>- Having access to the internet;</td>
<td>1087</td>
<td>1124</td>
<td>1087</td>
</tr>
<tr>
<td>- Using cloud IT services;</td>
<td>127</td>
<td>135</td>
<td>159</td>
</tr>
<tr>
<td>- Using digital technologies in production;</td>
<td>79</td>
<td>72</td>
<td>88</td>
</tr>
<tr>
<td>- Analyzing big data.</td>
<td>17</td>
<td>29</td>
<td>26</td>
</tr>
<tr>
<td>The number of IT specialists</td>
<td>1562</td>
<td>1377</td>
<td></td>
</tr>
<tr>
<td>Expenses for information and communication technologies, total million KZT including:</td>
<td>62,926.1</td>
<td>61,516.2</td>
<td>67,742.1</td>
</tr>
<tr>
<td>- The cost of acquiring software used on the basis of a license agreement;</td>
<td>4899.1</td>
<td>6910.0</td>
<td>13,508.1</td>
</tr>
<tr>
<td>- The cost of independent software development within the enterprise;</td>
<td>6489.7</td>
<td>3879.4</td>
<td>3748.1</td>
</tr>
<tr>
<td>- The cost of training employees working with IT technologies;</td>
<td>387.2</td>
<td>312.3</td>
<td>343.7</td>
</tr>
<tr>
<td>- Costs for paying for the services of third-party organizations and specialists related to IT services.</td>
<td>17,321.7</td>
<td>15,744.3</td>
<td>17,609.5</td>
</tr>
<tr>
<td>The number of large and medium enterprises using robotics, total including:</td>
<td>36</td>
<td>25</td>
<td>14</td>
</tr>
<tr>
<td>- Collaborative robots;</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>- Industrial robots;</td>
<td>12</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>- Service robots.</td>
<td>33</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>The number of enterprises receiving orders for goods and services via the internet</td>
<td>9</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>The number of enterprises ordering goods and services via the internet</td>
<td>84</td>
<td>73</td>
<td>67</td>
</tr>
<tr>
<td>The number of businesses using social media to interact with customers and partners</td>
<td>206</td>
<td>220</td>
<td>217</td>
</tr>
</tbody>
</table>
Initially, enterprises covered operational activities to streamline corporate processes and reporting, make management decisions, and digitalize material and information flows. Enterprise resource planning (ERP) systems and production management systems (MES) were introduced as the initial base for the use of digital information technologies. Then, with the development of digital communications and Internet of Things technologies, enterprises began to create digital production models and introduce fundamentally new automated tools, using new methods of technological optimization based on software platforms to analyze all the data coming from the facility.

Despite the difficulties, thanks to digitalization, capital investments at the initial stage (sensors, infrastructure, digital platforms) and the risks of innovative projects are significantly reduced. Enterprises initially purchased ready-made digital platforms, mostly universal, introducing digital mechanisms to ensure security and optimize technological and business processes. Along with the speed and quality of the processes, the enterprises sought to increase the speed of data transfer and their availability. The use of local technologies for specific tasks made it possible to improve the complexity of production and management processes. Automated processes for accounting for equipment and standards, performance indicators, repair planning, personnel management, and work management were additionally integrated with the resource management systems operating at the enterprise.

The most common digital solutions implemented at mining enterprises are automation of business process management of the main activities (extraction and transportation of rock, mining); computer modeling of geological objects based on the results of geological exploration for calculating reserves and planning their development; digitization and storage of the collected geological information and data obtained in the course of geological exploration; projects for the implementation of resource management systems and positioning of personnel and equipment; introduction of “smart mines”; big data analysis.

From 2015 to 2018, enterprises were mainly focused on the usage of big data technologies, mathematical modeling, and the creation of big data warehouses. In 2019–2020, the focus shifted to the use of machine vision and virtual reality (VR) technologies to improve industrial safety in production and Internet of Things digital advisors to reduce production costs and minimize scrap. The most important catalyst for the efficiency of technological processes (drilling, blasting, transportation, plowing, etc.) was the rapid exchange of information inside and outside the mines. To this end, financial investments in technological projects aimed at the digitalization of underground infrastructure were increased. A study by S. Galiyev et al. [37] considered the issues of ensuring industrial safety and providing comfortable conditions for workers in production, in particular, the introduction of industrial robots. As part of scientific and technological development, enterprises entered contracts for the implementation of research and development work (R&D) with scientific organizations and filed applications for intellectual property.

From 2021 to 2022, the main focus of the enterprises was on the automation and digitalization of key business processes. Digital twins and digital platforms were introduced, including the Kazakhstani information system eKAP, the enterprise resource planning program System Analysis Program Development Enterprise Resource Planning (SAP ERP),

<table>
<thead>
<tr>
<th>Indicators</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internet portal;</td>
<td>2127</td>
<td>571</td>
<td>523</td>
</tr>
<tr>
<td>Internet resource;</td>
<td>244</td>
<td>218</td>
<td>187</td>
</tr>
<tr>
<td>Automated internal business processes;</td>
<td>138</td>
<td>146</td>
<td>139</td>
</tr>
<tr>
<td>Radio Frequency Identification (RFID) technology;</td>
<td>53</td>
<td>41</td>
<td>39</td>
</tr>
<tr>
<td>3D printers.</td>
<td>4</td>
<td>7</td>
<td>14</td>
</tr>
</tbody>
</table>

Compiled by the authors based on source [36].
and the full-featured HR, SAP ERP Human Capital Management (SAP ERP HCM) HR process optimization system. Automation of customer interaction processes based on the Customer Relationship Management (CRM) platform was activated. Due to state regulation of the mechanism for motivating the innovative activity of enterprises, improving the system of financing innovative projects, and intensifying public–private partnerships that stimulate technology transfer, in 2022, labor productivity in the mining industry was expected to grow by 38.9% compared to 2016. From 2018 to 2020, the state, together with businesses, conducted a survey of 107 enterprises to identify the level of implementation of digital technologies (Table 3) [38].

Table 3. Results of digitalizing the mining and mining-and-smelting sectors of Kazakhstan.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Number of Enterprises by Level of Digitalization</th>
<th>Barriers Preventing Digitalization</th>
<th>Digitalization Indicators</th>
<th>Implemented Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining</td>
<td>Low level—7 enterprises;</td>
<td>Absence of financial resources for digitalization and infrastructure;</td>
<td>The number of enterprises that provide for the cost of training personnel in the field of digitalization—7.</td>
<td>Dispatch Control System (DCS); Automated System of Commercial Accounting of Energy Resources (ASCAE); Digital geological model; Computer-aided design (CAD); Computer-aided manufacturing (CAM); Computer-aided engineering (CAE); 1C—a programming language that is used in the 1C: Enterprise Program family; Automated Process Control System (APCS); System for collecting, processing, displaying and archiving information (SCADA); Additive technologies or 3D printing; Production data collection system; Maintenance and Repairs (MRO); Laboratory information management system (LIMS); ERP system; Robotic process automation (RPA)—automation of the same type of business processes through software and acceleration of tasks.</td>
</tr>
<tr>
<td></td>
<td>Medium level—4 enterprises;</td>
<td>understanding of the benefits from the introduction of digitalization among the management of enterprises;</td>
<td>The number of enterprises that provide for the cost of training personnel in the field of digitalization—7.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Above medium level—2 enterprises</td>
<td>Absence of qualified personnel and suppliers of digitalization solutions for the enterprise.</td>
<td>The number of enterprises that provide for the cost of training personnel in the field of digitalization—7.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Barriers related to insufficient cybersecurity, data confidentiality, unauthorized access to data, and data leakage.</td>
<td>The number of enterprises where there is a service responsible for digitalization—10.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The number of automated business processes—24.</td>
<td></td>
</tr>
<tr>
<td>Mining and smelting</td>
<td>Low level—5 enterprises;</td>
<td>Absence of digitalization solution providers for the enterprise.</td>
<td>The number of enterprises that provide for the cost of training personnel in the field of digitalization—3.</td>
<td>APCS; SCADA; ASCAE; LIMS, ERP, MES, DCS, MRO; Digital geological model; CAM; CAE; Artificial intelligence (AI)/machine learning (ML)—(artificial intelligence, the use of data tools and predictive analytics to obtain a quality recommendation).</td>
</tr>
<tr>
<td></td>
<td>Medium level—2 enterprises;</td>
<td>Absence of understanding of the benefits of introducing digitalization.</td>
<td>The number of implemented systems/software—11.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Above medium level—1 enterprise</td>
<td>Absence of sufficient infrastructure for digitalization.</td>
<td>The number of enterprises where there is a service responsible for digitalization—6.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Absence of qualified personnel.</td>
<td>The number of automated business processes—6.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Absence of funds for investment in digitalization.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compiled by the authors.

In general, the results of the survey revealed the low level of digitalization of enterprises: low level—59% (63 enterprises), average level—22% (24 enterprises), above average—19% (20 enterprises). There were 13 enterprises in the mining industry with a predominance of a low level of digitalization, and in metallurgy, 8 enterprises.

The most acute problems of digitalization implementation are related to the lack of financial resources for investments in digitalization, the necessary infrastructure (this is one of the main factors), low return on investment, low level of digital literacy of staff (the importance of the human factor in the context of studying the digitalization of enterprises remains one of the most significant).

Digitalization is constrained by barriers related to digital standards, regulations, certificates, lack of cyber security, data privacy, unauthorized access, and data leakage. One of the brakes on the introduction of digital solutions is patchwork automation and the lack of unified hierarchical structures and unified classifiers that allow one system to cover a maximum of business processes and optimize various IT systems.

The most common obstacles are caused by high cost and scarcity of all kinds of resources, the unwillingness of staff to make changes, including the lack of understanding
that the implementation of IT solutions of varying degrees of complexity without an integrated approach to changing business processes and involving business units will not lead to an increase in profits.

New opportunities in the technological transformation of the enterprise affected the management of various types of work, for example, repair work, including improvement and change (optimization) of current business processes, increasing the efficiency of accounting for the condition of equipment and reliability in further operation, the introduction of risk-based repair management in the future, and the use of mobile applications to improve the efficiency (speed and accuracy) of work. However, the goals of transformation still remain separate, with an emphasis on process optimization rather than its complete change.

With the help of digital solutions, objects that have been operating for several decades but still have the potential for further development were supported. Technologies aimed at the development of end-to-end automation and the integration of production and management processes into a single information system have become relatively promising.

In general, the results of the study allow us to conclude that against the backdrop of growing demand for the use of digital technologies in production processes, the surveyed industries of Kazakhstan overcame the stage of basic production automation during 2016–2021. Currently, they are at the stage of active implementation of tools for executing local processes when one-time decisions are made for specific tasks and ready-made solutions are used. This takes into account the industry specifics, which is manifested in the low speed and accurate of the introduction of new technologies, as well as the constant investment in the development and optimization of digital solutions, both by the state and business and by private, including foreign, investors.

4.2. Improving Geological and Economic Assessment of Enterprises

The conducted studies established that digital transformation has directly affected the information openness and social status of enterprises. In this regard, digital solutions are especially relevant for enterprises, starting with the introduction of advanced technologies in internal business processes and the formation of digital competencies among staff and ending with the development of external digital channels.

The digital transformation of a company’s internal business processes covers both operational activities and operations in the financial markets in order to attract investment for exploration and increase the resource base. In this aspect, the role of digital contracts is growing as a tool for financing investment projects that involve direct contractual relations between an enterprise and investors and the promotion of communication channels with them.

In particular, this is the development of a digital public reporting standard as a further development of local public reporting standards recommended by CRIRSCO. Having overcome the isolation of the Soviet standards of closed geological reporting on reserves, Kazakhstan moved into the field of public geological reporting on resources and mineral reserves and was the first in the post-Soviet space to mark the transition to international CRIRSCO standards from 2019 to 2024. Due to the electronic form of the report on geological exploration, resources, and mineral reserves, the integration of information collection software into the internal automated business process management system, and the transition from discrete expertise to expert monitoring is being carried out. At the same time, the processing results are available to investors online.

With the transition to a low-carbon economy, there is growing awareness among businesses that the quality of ESG disclosure is becoming a critical condition for accessing finance and boosting export activity. The study identified factors that created difficulties for enterprises in presenting ESG information, including lack of uniform standards and methodology, unavailability of ESG data directly at the enterprise due to the underdevelopment of business processes and difficulties in interacting with suppliers and buyers, and low transparency and quality of primary data.
To solve these problems, enterprises are adopting the experience of the mining and metallurgical concern RioTinto with ESG-blockchain data by developing the stages of work with ESG data, focusing on the definition of a methodology for working with primary data for the analysis of ESG activities, setting a target in the field of ESG data management, integration with suppliers and customers of the enterprise and their information systems for collecting data along the entire value chain using digital tools.

An analysis of the digital transformation of mining enterprises made it possible to find an approach to the development of an information–analytical model of a geological and economic assessment involving the connection of the accumulated digital potential of an enterprise to advanced solutions to economic problems (Figure 2).

<table>
<thead>
<tr>
<th>Assessment of the stochastic nature of the enterprise environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>The enterprise technical level achieved</td>
</tr>
<tr>
<td>Justification of variations in the activities of the enterprise</td>
</tr>
<tr>
<td>Selection of digital solutions</td>
</tr>
<tr>
<td>Justification of selecting the IDEF1 methodology for building the model of geological and economic assessment of the enterprise</td>
</tr>
<tr>
<td>Generation of the target task of the effectiveness of the enterprise functioning</td>
</tr>
<tr>
<td>Establishment of exogenous factors and the possibility of countering them</td>
</tr>
<tr>
<td>Modeling variations of increasing the effectiveness of the enterprise through digital transformation</td>
</tr>
<tr>
<td>Conclusion on the work effectiveness in the stochastic environment</td>
</tr>
<tr>
<td>Regulation of the enterprise activities in the context of digital transformation</td>
</tr>
</tbody>
</table>

Figure 2. The approach proposed for modeling geological and economic assessment of a mining enterprise. Compiled by the authors.

Making scientifically based management decisions requires objective and operational primary information and their subsequent structuring, which ensures a high level of information flow management. Both the geological knowledge and the investment attractiveness of the enterprise depend on the quality of geological and economic information. At the moment, most of Kazakhstan’s enterprises use mainly foreign software products, which become more difficult to work with every year due to the technological and geological specifics of a particular field and the increasing complexity of developing new fields.

Taking into account the complexity of the fields and the uncertainties of the external environment, the development of digital technologies, the integration of industrial platforms, and the development of independent operating systems and software products are of decisive importance. This will make it possible to move from disparate geological documents to structured data arrays in order to create a single digital space where not only information about the enterprise’s resources will be stored, but at the same time, business intelligence tools will be formed covering all interested divisions of the enterprise.
To solve the identified problems in the construction of an information system, especially at the initial stage, when it is required to identify weak links in the existing structure of information flows, in our opinion, it is advisable to apply the IDEF1 methodology. In combination with functional analysis and assessment of the specific needs of each field, the IDEF1 methodology will allow for structuring information flows and identifying problem areas in the information and analytical work of the enterprise. As an analytical method, the IDEF1 methodology makes it possible to determine for a geological and economic assessment a specific array of initial data, the structure and movement of information flows, and the relationship between them at the enterprise level. This will allow for establishing the level of reliability of the reserve’s future assessment and determine the feasibility of continuing work on the preparation of the industrial development of the deposit. It is also important that this approach shortens the processing time of the initial information and the time of calculation of geological and economic indicators for the options for field development.

One of the city-forming enterprises of Kazakhstan was chosen as the object of study for this approach: the vertically integrated holding LLP Corporation Kazakhmys and the promising fields of Kuzmuryn and Akbastau (Figures 3 and 4).

![Figure 3. Current state and prospective assessment of the deposits taking into account the reserves categorization increasing. Compiled by the authors.](image)

Calculations for the geological and economic assessment under consideration were performed by the authors using 1C:Enterprise software system, including “1C:Enterprise 8. Management of our company for Kazakhstan. Basic version”; Based on the holding’s primary data, Statistica and Excel were integrated with the holding’s innovative intellectual platform SAP ERP. In 2021, the holding put into commercial operation the modules of the ERP system based on Microsoft Dynamics 365 for Finance & Operations 10.0.0. Such studies, supplemented by these calculations, increase the level of analytical and predictive study of the external and internal environment of the holding, allowing obtaining quantitative characteristics of the impact on the final result of a combination of factors [39,40].

In studies modeling geological and economic evaluation, G. Aubakirova and F. Isatayeva [40] and G. Aubakirova et al. [41] take into account the components of the economic assessment of the Kusmuryn and Akbastau deposits. At the same time, compliance with the international system of reporting standards on mineral reserves is achieved, taking into account the obligations of Kazakhstan to implement the Extractive Industries Transparency Initiative and the international set of standards of the Global Reporting Initiative (GRI) [42–47].
During the geological and economic assessment, uncertainties were taken into account, which is typical for the estimation of ore reserves, which can change the estimates of mineral reserves. Consideration is given to assumptions in effect at the time of the assessment, which may change significantly when new geological and economic data are used.

When assessing the life of the Kusmuryn and Akbastau deposits, the reserves of mineral resources were taken into account on the basis of a high degree of confidence in their economically viable extraction. The economic status of existing reserves and their revaluation were affected by the rate of mining, projected prices for products, the exchange rate, and operating costs.

Corporation “Kazakhmys” from 2020 in stages during 2021–2023 moves to reserve valuation and mineral resources under the JORC Code, 2012, with the involvement of independent consultants. In accordance with the JORC Code, the reports reflect total ore reserves, proven ore reserves and probable ore reserves, total mineral resources, measured mineral resources, and inferred mineral resources.

To assess the economic viability, ore reserves and mineral assets are classified into groups:

- Mining asset (“YES”): a mineral asset for which a current ore reserve is declared, and mining and processing has commenced and is ongoing;
- Asset under construction (“CA”): a mineral asset for which an ore reserve is declared and substantively justified at a level not lower than a preliminary feasibility study, which demonstrates on a multidisciplinary basis that the development of the asset is technically feasible and economically viable;
- Detailed exploration asset (“ADR”): a mineral asset for which only mineral resources are declared;
- Exploration asset (“RA”): a mineral asset for which no mineral resources have been declared.

As of 1 January 2023, the corporation plans to complete verification drilling, study of hydrogeological and geotechnical conditions. In the first half of 2023, to estimate mineral resources, and by the end of 2023, to estimate mineral reserves and prepare a summary report in the last quarter of 2023.

It is planned to transfer 27% of the reserves to the measured category (B) and 7% to the verified category (C1). In 2024–2026, another 24% of the reserves will be transferred to the measured category (B) and 10% to the verified category (C1). For 2027–2029, 18% of the reserves are planned to be transferred to the measured category (B) and 6% to the verified category (C1).
As a result, over 80% of resources and reserves will be categorized as measured (B) by confidence. Thus, the explored and put-on-balance reserves allow for production and capacity utilization (concentration plants) for a period of more than 40 years.

As a strategic priority of the corporation, an annual increase in ore mining volumes of up to 35 million tons is indicated. To reach the planned volume, it is assumed:
- Commissioning of new deposits, modernization of already functioning mines (in 2027, the reconstruction of the Nurkazgan mine with an increase in productivity of up to 6.5 million tons; in 2028, the achievement of annual productivity of up to 8 million tons of ore at the Zhilandinsky mine; in 2026, the construction of shafts “Ventilation-2”, “Air-supply—Cletevoy-2”, “Skipovaya” at the Nurkazgan mine).
- Achieving the maximum workload of existing factories (in 2024, the increase in the annual productivity of the Karagaily concentrator to 1.9 million tons of ore; in 2027, the increase in the annual productivity of the Nurkazgan concentrator to 6.5 million tons of ore).
- Bring the newly built concentrating plants to the planned capacity (in 2024, it is planned to build a new concentrating plant with an annual capacity of 1.2 to 1.5 million tons at the Shatyrkul-Zhaysanskoye field).

The forecast values of the indicators will be affected by changes in prices for minerals, the rate of depletion of deposits, and the delay in bringing new large-scale, low-cost projects to the planned capacities.

In many ways, the implementation of the proposed approach to modeling the geological and economic assessment is determined by the presence of a basic infrastructure component in the holding. This is the organization of high-speed, uninterrupted, and reliable network data transmission channels; the use of optical fiber, which made it possible to organize up to 100 Mbps of information traffic, regardless of external factors; functioning of the ERP system, including financial, sales and supply management modules.

Currently, Kazakhstan lacks standards for specialized, critically important mining and geological information systems; its own or adapted foreign information systems are being implemented slowly (Figure 5).

Figure 5. Information systems introduced by enterprises in 2021. Source: compiled by the authors according to the Agency for Strategic Planning and reforms of the Republic of Kazakhstan [36].

Most often, enterprises transform a fully functional MINEFRAME MGIS to solve geological, economic, and technological problems in the virtual space. This platform...
provides external developers with access to the GIS functionality, which speeds up the process of developing new tools with subsequent integration into digital technology.

Therefore, enterprises are faced with the task of mastering international standards for data exchange between various mining and geological information systems using the OMF format, support for reading and writing open exchange standards (CSV, DXF). In addition, enterprises are required to professionally support these standards at all stages of the life cycle of the product being created and after-sales cooperation with developers. That is, along with the development of their own software, enterprises solve the problem of “seamless” integration of third-party software into an already formed digital infrastructure.

To improve the geological and economic assessment of the enterprise under study, the authors used open file formats dxf/dwg, shp, csv, and xml, which simplifies the construction of a block model of the field (csv format) and improves the quality of mining and geological graphics (dwg/dxf format).

Kusmuryn deposits for 2022 and 2023 were calculated using a specialized program, Micromine Origin 12.5 software (Tables 4–6).

Table 4. Calculation of reserves by ore bodies 1 January 2022.

<table>
<thead>
<tr>
<th>Ore Bodies</th>
<th>Ore, Thousand Tons</th>
<th>Copper %</th>
<th>T</th>
<th>Gold g/t</th>
<th>Silver kg</th>
<th>T</th>
<th>%</th>
<th>Zinc T</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT 1</td>
<td>1,138,159.0</td>
<td>3.43</td>
<td>39,027</td>
<td>2.19</td>
<td>2496.9</td>
<td>34.02</td>
<td>39</td>
<td>3.4</td>
</tr>
<tr>
<td>RT 2</td>
<td>21,638,586.8</td>
<td>3.02</td>
<td>652,748</td>
<td>0.71</td>
<td>15,285.9</td>
<td>13.32</td>
<td>288</td>
<td>0.59</td>
</tr>
<tr>
<td>RT 3</td>
<td>2,505,455.4</td>
<td>1.82</td>
<td>45,591</td>
<td>0.23</td>
<td>565.7</td>
<td>4.5</td>
<td>11</td>
<td>0.31</td>
</tr>
<tr>
<td>Lens 4</td>
<td>1,562,573.4</td>
<td>2.20</td>
<td>34,375</td>
<td>0.25</td>
<td>397.2</td>
<td>5.18</td>
<td>8</td>
<td>0.09</td>
</tr>
<tr>
<td>Total:</td>
<td>26,844,774.6</td>
<td>2.87</td>
<td>771,741</td>
<td>0.70</td>
<td>18,746</td>
<td>12.90</td>
<td>346</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Compiled by the authors.

Table 5. Calculation of reserves by ore bodies 1 January 2023.

<table>
<thead>
<tr>
<th>Ore Bodies</th>
<th>Ore, Thousand Tons</th>
<th>Copper %</th>
<th>T</th>
<th>Gold g/t</th>
<th>Silver kg</th>
<th>T</th>
<th>%</th>
<th>Zinc T</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT 1</td>
<td>851,827.49</td>
<td>3.68</td>
<td>31,313.44</td>
<td>1.18</td>
<td>1008.24</td>
<td>24.33</td>
<td>20.72</td>
<td>3.29</td>
</tr>
<tr>
<td>RT 2</td>
<td>23,582,652.34</td>
<td>3.03</td>
<td>714,050.12</td>
<td>0.65</td>
<td>15,343.32</td>
<td>11.51</td>
<td>271.40</td>
<td>1.39</td>
</tr>
<tr>
<td>RT 3</td>
<td>2,536,577.03</td>
<td>1.68</td>
<td>42,544.42</td>
<td>0.17</td>
<td>443.14</td>
<td>5.57</td>
<td>14.13</td>
<td>0.18</td>
</tr>
<tr>
<td>Lens 4</td>
<td>1,784,380.59</td>
<td>1.74</td>
<td>31,125.34</td>
<td>0.20</td>
<td>363.66</td>
<td>3.57</td>
<td>6.38</td>
<td>0.06</td>
</tr>
<tr>
<td>Total:</td>
<td>28,735,437.45</td>
<td>2.85</td>
<td>819,033.32</td>
<td>0.60</td>
<td>17,158.36</td>
<td>10.87</td>
<td>312.63</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Compiled by the authors.

Table 6. Change in stocks.

<table>
<thead>
<tr>
<th>Ore Bodies</th>
<th>Ore, Thousand Tons</th>
<th>Copper %</th>
<th>T</th>
<th>Gold g/t</th>
<th>Silver kg</th>
<th>T</th>
<th>%</th>
<th>Zinc T</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT 1</td>
<td>–286,331.5</td>
<td>0.03</td>
<td>–7713</td>
<td>5.20</td>
<td>–1489</td>
<td>0.06</td>
<td>–18</td>
<td>37.42</td>
</tr>
<tr>
<td>RT 2</td>
<td>1,944,065.6</td>
<td>0.03</td>
<td>61,302</td>
<td>0.03</td>
<td>57</td>
<td>–0.01</td>
<td>–17</td>
<td>102.55</td>
</tr>
<tr>
<td>RT 3</td>
<td>31,121.6</td>
<td>–0.10</td>
<td>–3046</td>
<td>–3.94</td>
<td>–123</td>
<td>0.09</td>
<td>3</td>
<td>–95.04</td>
</tr>
<tr>
<td>Lens 4</td>
<td>221,807.2</td>
<td>–0.01</td>
<td>–3250</td>
<td>–0.15</td>
<td>–34</td>
<td>–0.01</td>
<td>–2</td>
<td>–1.29</td>
</tr>
<tr>
<td>Total:</td>
<td>1,910,662.9</td>
<td>2.48</td>
<td>47,292</td>
<td>–0.83</td>
<td>–1587</td>
<td>–17.62</td>
<td>–33.7</td>
<td>9.70</td>
</tr>
</tbody>
</table>

Compiled by the authors.

The following information was taken as the initial data for calculating the reserves:
- Tabular data coordinates of wellheads, sampling, and well inclinometry;
- Geological sections along the lines of profiles at a scale of 1:1000 (Figure 6).
The use of the block model has increased the effectiveness of drilling operations, increased the reliability of information about the boundaries of ore bodies, their thickness, depth of occurrence and content of the main and associated components in them, the morphology of ore bodies and rocks has been refined, and new ore bodies have been identified.

For Kazakhstan, where the lack of a highly developed infrastructure is one of the most important deterrents in the way of the decarbonization of the economy, the international practice of introducing new equipment into the mining industry is very important. Therefore, Young’s and P. A. Rogers’ [48] work is interesting. It examines the environmental impact of mining and justifies the need to improve the infrastructure to account for greenhouse gas emissions by mining enterprises. According to the results of M. Lufin and J. Soto-Díaz [49], new technologies are accelerating the creation of integrated production organizations that solve the most important industrial problems of the mining industries while highlighting the problem of a shortage of qualified engineering personnel with digital data management skills and knowledge of industry specifics (M. Breul and M. Atienza [50]).
It should be noted that in the initial stages of the holding’s digitalization, it was the high wear and tear of equipment, which required significant operating costs, combined with the low level of use of integrated processing technologies and difficulties with the digitalization of technical solutions, that led to large losses of valuable components of the extracted minerals. This kind of problem has been pointed out in studies by J. Joaquin Jara et al. [51], R. Al Rawashdeh and G. Campbell [52], and G. Hillson [53]. However, at the moment, when the holding is focused on building a digital model of an enterprise and is one of the leaders in digitalization in Kazakhstan and plans to introduce elements of Industry 4.0 into all business processes by 2025, the loss of valuable components is not so significant.

For mining companies in Kazakhstan, international experience is important, showing the importance of investing in energy projects. J. Guo [54] shows their impact on achieving sustainability in the energy sector along with T. Menzel and T. Teubner [55].

The Kazakhmys Corporation holding is interested in using domestic digital solutions; therefore, it cooperates with the state, businesses, investors, reputable foreign experts, and local scientific and educational institutions. This is due to two reasons. First, the state has obliged subsoil users of Kazakhstan to finance research and development work in the amount of one percent of extraction costs. Following foreign best practices, the mining sector is obliged to use these funds to cooperate with enterprises that offer relevant technological solutions. Secondly, the pandemic has shown that it is easier to work with national suppliers, and it is easier to adapt their digital products and receive technical support 24/7. Foreign providers of IT solutions are both more expensive and more difficult to adapt to the needs of the customer, and there are problems with after-sales service.

5. Conclusions

The approach developed by the authors to information and analytical modeling of the geological and economic assessment of the Kazakhmys Corporation holding contributes to deepening the relationship between production and management business processes due to their consistent digitalization. The proposed management model, presented as a set of interrelated components, is based on digital solutions that can be used to coordinate the relationship of an enterprise with external counterparties and increase demand for the product being developed.

In general, the study allows us to draw conclusions.

1. The emerging digital ecosystem of Kazakhstan is dominated by the point distribution of new technologies, and the nature of their distribution is fragmented. There is no holistic approach to digital transformation as a complex undertaking. Due to the lack of a systematic approach to the development of the “digital enterprise” and the conflict between traditional approaches to work (budgeting, procurement, security) and modern agile practices, there is a lag in the transition of the mining industry from research to the implementation of viable solutions in real production conditions, subsequent scaling from the purpose of obtaining financial benefits, approaching the zero level of industrial injuries. The foregoing complicates the interpretation and evaluation of the effectiveness of technological changes. However, as Kazakhstan integrates into global digitalization trends, largely due to government regulation, mining enterprises are experiencing a consistent increase in digital competencies, accompanied by the development of digital platforms and optimization of their own infrastructure, which contributes to the development of a favorable digital environment.

2. A variety of technologies being introduced will accelerate Kazakhstan’s entry into the advanced markets of global networks in the field of advanced production and will allow realizing the accumulated comparative advantages. Studies show that sustainable economic growth is determined not so much by the scale of high-tech industries and foreign exchange earnings of the state but by the growing capabilities of enterprises in various industries, coordination of joint actions of the state, business and educational structures to the constant complication of production and exports. In
recent years, there has been a growing interest in Kazakhstan in studying indicators of economic complexity that predict differences in economic growth, as shown in the works of F. Neffke and M. Henning [56] and CA Hidalgo [57]. According to a study by Z. Miao [58], this can improve comparative advantages in the export of goods and make progress in the integration of the digital economy and the value chain [46].

3. The study found that there are numerous barriers to the digital transformation of the mining industry in Kazakhstan, but none of them are insurmountable. Digital transformation processes should be systemic and should increase technological independence in key digital technologies, which will accelerate adaptation to a dynamic environment. The accumulated international experience and Kazakhstani practice help to summarize the challenges and realize the opportunities that digitalization opens up for the mining industry.

4. The combination of economic modeling and digital technologies will provide the top management of enterprises with a software tool for long-term predictive calculations of various options for the development of deposits. Medium- and long-term ESG goals of enterprises, coordinated with the UN sustainable development goals, will allow establishing mutually beneficial contacts with stakeholders (state, society, owners, customers, suppliers, personnel), not only demonstrate the impact of an enterprise on society and the environment but also prove the existence of positive changes, in particular, the availability of financial and organizational capabilities to achieve corporate goals, including long-term guidelines in the field of ESG principles.

As noted earlier, this study has limitations due to the confidential nature of information about deposits since most of the information about minerals in Kazakhstan is still classified. Also, in Kazakhstan, not all of the largest mining entities annually report on sustainable development in the format of the international set of GRI standards, although they are experiencing growing pressure from investors, customers, and suppliers to improve the quality of disclosed data. This is explained by the lack of methodological support, the difficulties of collecting, adequate measurement of reliable primary information, and its interpretation and subsequent systematization of the results. In general, the quality of the mentioned reporting remains low, and the mechanism for presenting data, both in theory and in practice, has not yet been worked out. However, despite the difficulties, the priorities of enterprises are the issues of minimizing greenhouse gas emissions, improving the climate strategy, and safe work of personnel.

The practical significance of the study lies in the fact that the proposed information and analytical support for the geological and economic assessment will make it possible to digitize the key functions of the enterprise on the scale of the vertical value chain, reduce the cost of production by optimizing the business processes and increase business margins, as well as to diversify the client base.

In addition, the practical significance of the study lies in the possibility of combining geological and economic models into a single complex. Subsequently, it becomes possible to analyze the adequacy of the decisions, conduct a comparative analysis of the technical and economic indicators of deposits, and evaluate the correctness of operational costs by optional field development. Taking into account the constant increase in the volume and complexity and the need to automate geological information, this approach will improve the quality of decisions made.

The authors are aware that the presented approach is only the beginning of the forthcoming scientific and practical work, which involves the establishment of interdependencies between the process parameters, the formation of the initial base of analytical functions, and the limiting parameters of their values.

In their future studies, the authors plan to focus on improving the geological and economic assessment based on the constant updating of information about the geological and technological features of the deposit, accounting for mineral reserves according to international CRIRSCO standards (KAZRC Code) in the light of Kazakhstan’s commitments to implement the Extractive Industries Transparency Initiative (Extractive Industries Trans-
parency Initiative) and compliance with the international set of GRI standards and ESG principles. Emphasis will be placed on the structuring of economic calculations, their change depending on the degree of knowledge and exploration of the deposit, and the scale and content of primary geological, technological, environmental, and economic information.

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