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Mining Industry 4.0 – Opportunities and Barriers

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Abstract
Safety, development, and efficiency are the main slogans that guide modern mines. At the beginning of the fourth industrial revolution, they are familiar with innovations and modern technologies that allow them to create innovative solutions and build an environmentally friendly mining sector. The aim of the paper was to assess the feasibility of implementing the assumptions of the industrial revolution 4.0 in the mining industry. Based on the author's own research and literature research, a set of scenarios for the transformation process was developed. After the verification, three alternative scenarios related to the transformation process 4.0 in mines were used for the research. The transformation scenarios were assessed from the perspective of individual stakeholder groups. The NAIADE (Novel Approach to Imprecise Assessment and Decision Environments), which so far has not been used in the mining industry to assess development scenarios, the method was used to assess the transformation scenarios. The research identified and characterized nine groups of stakeholders. Based on the conducted structured interviews, a set of technical criteria for the assessment of scenarios was defined. The analysis results from the impact matrix and social impact matrix developed for the first time for the mining industry transformation scenarios. Based on the analysis of the impacts of individual factors, it was shown which scenario is the most acceptable for stakeholders and the best from a technical point of view. The research focuses on the deficit of digital competencies and the generational change, as well as the change in the competency requirements of the new type of worker-miner-operator 4.0.

Keywords
Mining 4.0, Industry 4.0, mining engineering, predictive maintenance, digital transformation, multicriteria analysis, smart mining, NAIADE, operator 4.0

Introduction

The mining industry is currently at a turning point and is facing a number of challenges, including the need to improve efficiency, reduce costs and safeguard assets but also decrease its impact on the natural environment (Xie et al., 2018; Wiecek et al., 2019).

High productivity of mining, transport and maintenance systems is becoming one of the main indicators of competitiveness in the mining industry (Li, Wang, & Wang, 2017). Although mining is considered by a significant part of society as a traditional sector of the economy and not very susceptible to changes, technological progress significantly contributes to changes also in this branch of the economy (Sishi & Telukdarie, 2020). The most important changes in mining are improved safety, increased productivity, care for the environment and more efficient use of resources (Beloglazov, Petrov, & Bazhin, 2020). This is essential because the available deposits are increasingly complex, located at great depth and often of reduced quality (low mineral content). There is also a very specific way of the rare earth metals (REM) extraction, which also should be taken into account (Jonšta et al., 2021). Future mining production will be shaped in the context of the need to produce at costs determined by international competition (Lööw, Abrahamsson, & Johansson, 2019). To achieve this aim, most of the processes in the mine should be automated or carried out remotely by operators (Bialy, Grebski, Galecki, & Kaniak, 2020; Burduk et al., 2021) with reduced energy and water consumption and progressive use of clean energy from renewable sources (Ulewicz, Siwiec, Pacana, Tutak, & Brodny, 2021; Kluczek, 2019; Allawi, Mijbil, & Salloomi, 2019). A significant factor is the strong social pressure in the field of environmental protection and innovative activities in this area (Grebski & Mazur, 2022; Cernecky et al., 2015).

Mining of different minerals, i.e. drilling, blasting, loading and transportation, has the greatest potential to improve and reduce environmental impact through innovation in efficiency and productivity (Pałaka, Paczesny, Gurdziel, & Wieloch, 2020). On the other hand, we have unfavourable conditions for the mining sector: depletion of surface resources, decrease in productivity in long-exploited deposits, increase in labour costs, lack of qualified human resources as well as environmental conditions and social resistance to access to new deposits (Dorin, Diaconescu, & Topor, 2014). In order to improve the situation, investments and to obtain the synergy effect of the mine, companies producing mining machinery and equipment as well as research and development facilities (universities and research institutes) are necessary. The issue of a modern mining industry should be approached comprehensively along the extended value chain, which cannot be limited only to mining but should include the technical preparation of mining, transport as well as processing processes.

Each stage of the extended value chain can be subject to a continuous improvement process, and innovative technology can be used to make this stage safer, more efficient and more sustainable (Mazur & Momeni, 2019; Klimecka-Tatar, 2018; Dzhuguryan, Deja, Wiśnicki, & Jóźwiak, 2020, Tirpakova, Blišťanova & Hanak, 2022; Blistan et al, 2020). A wide range of modern technologies will be used in modern mines based on the Industry 4.0 concept to achieve efficiency, safety and economic goals.

ABI Research, a global consulting company dealing with the technology market, has prepared a report "Digital Transformation and the Mining Industry", which shows that the spending of the mining sector on digital technologies will grow this decade at an average annual rate of 5.2% and will reach the level of 9.3 billion dollars in 2030. ABI Research analysts indicate that the key investments of the mining industry will concern 4G/5G networks, which are to provide the support necessary for the implementation of data collection projects for mapping places or the use of drones to generate images of the entire area. Data analysis software will help miners, for example, to avoid unplanned downtime and also to predict, for example, the effect and consequences of individual mining activities. The example of the COVID-19 pandemic showed that mines equipped with remotely controlled or autonomous equipment were able to continue working with the same efficiency as before the pandemic, which was shown in the report of PWC Global (2021). According to an analysis by the World Economic Forum in collaboration with the International Finance Corporation and McKinsey & Company (2009), the digitization of the mining sector in the world by 2025 could save 373 billion dollars. At the same time, we can identify at least three areas with the greatest potential for digitization: increasing productivity, safety and recycling of production waste.

Mining 4.0 offers one more possibility; as a result of the continuous monitoring process and having large data sets, it is possible to create operational and economic models taking into account not only geological and operational data but also fluctuations in the sale (price) of the mined mineral product, on the basis of which so-called assessment of economically mined reserves can be conducted.

The aim of transformation 4.0 in mining is everything that is to ensure that this industry can function profitably in the long term (Mitra, Musingwini, Neingo, & Adam, 2018) with the lowest environmental impact (Wang, Xu, & Ren, 2019). It is based on the consolidation of systems and the integration of people with digitally-controlled machines that make extensive use of the wireless network, information and communication technologies. It means integrating devices with the virtual world. This gives full control over the production process to enterprises that use Industry 4.0 solutions (Dardzinska & Zdrodowska, 2020), allowing the identification of bottlenecks and their elimination and consequently allowing them to increase their competitive advantage (Sishi & Telukdarie, 2020; Rojek, 2021).

The most important technologies of the transformation process are automation and robotics, artificial intelligence, the internet of things, drones, digital twins, virtual reality and the use of excavations for energy storage (Wachnik, 2022; Pałaka et al., 2020).

The aim of the paper was to develop and assess scenarios related to the implementation of Mining 4.0 and the further development of the mine in Poland and Europe. Based on the literature research, different alternative scenarios related to implementing the above-mentioned changes in mines were developed, and three of them were chosen after their verifications. The NAIADE methodology (Novel Approach to Imprecise Assessment and Decision Environments) was used in order to assess them. Within this method, nine stakeholder groups have been identified and characterized. Based on a personal interview with representatives of these groups, a set of technical criteria for the assessment of scenarios was defined. Based on a structured interview with representatives of all groups of stakeholders, a set of technical criteria for the assessment of scenarios was defined. Subsequently, the same group of stakeholders assessed the developed scenarios on the basis of a nine-point scale; then, with the use of the same scale, the scenarios were assessed by authors according to a set of defined and expected effects (criteria). Based on the adopted assumptions, it was shown which scenario is the most acceptable to stakeholders and is the best from a technical point of view. The authors wanted to check what Scenarios for the implementation of Mining 4.0 in mines can be dealt with and how the individual solution (scenario) is perceived among stakeholders. The NAIADE method is often used to assess various types of urban solutions (Nicolini & Pinto, 2013). In the paper, the authors showed the possibility of using this method also for the mining industry in the areas of assessment of mining transformation scenarios.

Literature review, the analytical framework

Until recently, the mine was associated mainly with narrow corridors, a pickaxe or wagons. However, looking at the momentum with which further advanced solutions are implemented, digital technologies will soon become the main attribute of this type of objects, and the view of a foreman with a tablet in his hand will not surprise anyone. Will this scenario work? What opportunities and barriers do we face in the process of transforming Industry 4.0 in mines? Mining 4.0 - this is the idea of Industry 4.0 transferred to the field of mining. Professor Urlich Paschedag at the Bergbau 4.0 conference in Aachen (Paschedag, 2017) described this idea as follows:

- Mining machinery, equipment, sensors and people can connect and communicate with each other.
- The data from the sensors feed the IT systems of the digital mine, creating its VR image.
- Technical support systems help miners by providing aggregated, visual and understandable information to enable quick, fact-based decision-making. Miners are physically supported in difficult, awkward or dangerous jobs

During the conference Society of Mining Professors Annual Meeting & Conference in Torrino Weber-Youngman (Weber-Youngman, 2017) defined the mine of the future in six points:

1. Remote control of most mining activities.
2. Reducing the risk associated with the human-machine interface through the use of modern solutions in the field of robotics and autonomous devices.
3. Virtual and augmented reality applications.
4. Real-time monitoring and analysis of mine production through scanning and monitoring and real-time decision-making based on incoming data.
5. Planning and optimization of the mine project in real-time (digital twin concept).
6. The holography of the mine design.

Presented technologies (Fig. 1) will enable a fundamental change in the method of mining minerals in the past, as well as the potential use of mine excavations for energy storage. Variation in decision-making will be significantly reduced, and automated operations will be more centralized (Mitra et al., 2018).

In papers (Palka & Rizaoğlu, 2019; Palka, Brodny, & Stecuła, 2017), special attention was also paid to the issue of vertical and horizontal integration of the used systems in particular in the field of data exchange. Digitization of processes enables, among others, increasing knowledge about the production process through real-time measurement and analysis (Big Data), including the use of potential cloud activities (Clouds), additive technologies, augmented reality and virtual reality technologies, cyber-physical systems using artificial intelligence and neural networks, widely understood cybersecurity (Ślusarczyk, 2018; Tiep, Oanh, Thuan, Tien, & Ha, 2020) and intelligent logistic systems (Deja, Dzhuguryan, Dzhuguryan, Konradi, & Ulewicz, 2021). In mining 4.0, the importance of information about the operation and condition of facilities in transport systems will increase. The conveyor belt generates up to 60% of transport costs. Its failure not only entails high repair costs but can also cause high production losses related to long-term emergency shutdowns. (Jurdziak, Błażej, & Bajda, 2018). Data from automation and scale systems allow for more precise measures of belt life and optimization of scheduled maintenance.

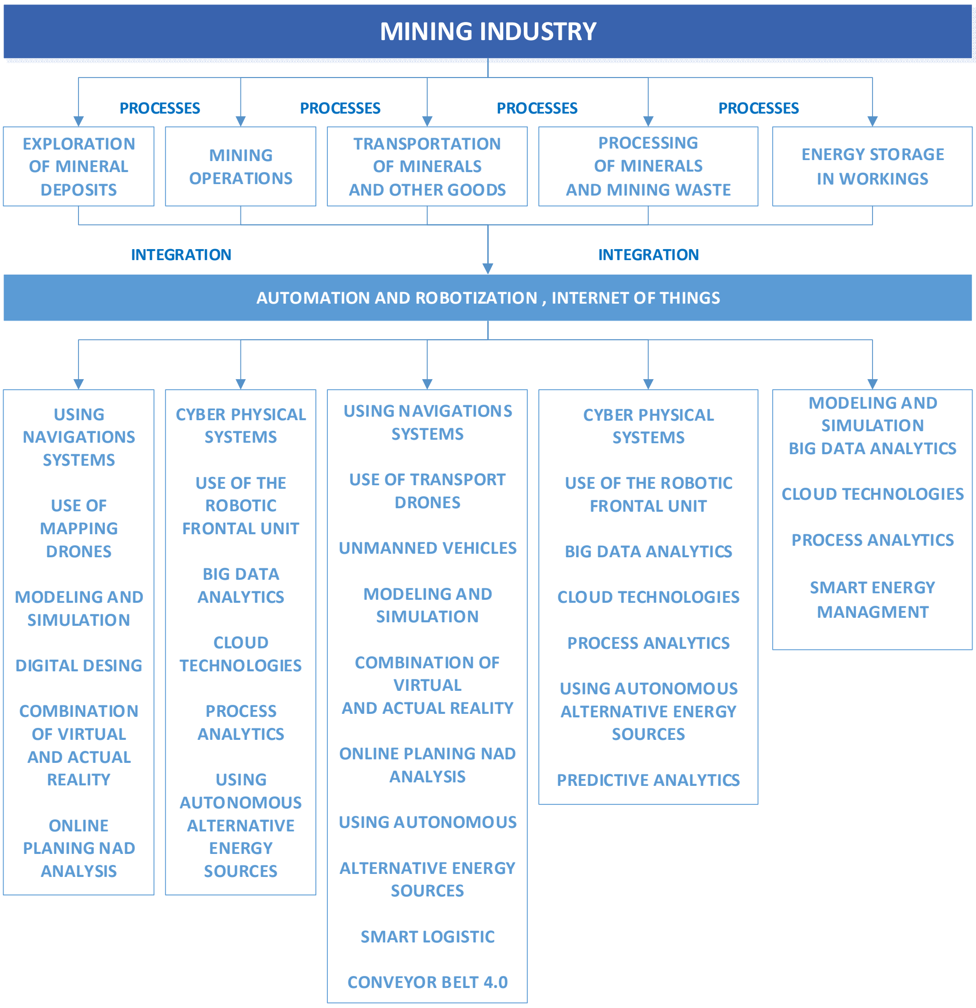

Fig. 1. Diagram of modern technologies 4.0 for the mining industry

Based on the conducted literature studies, potential industry 4.0 technologies that can be implemented in the mining industry were presented (Palka & Rizaoğlu, 2019; vKawalec, 2019; Beloglazov et al., 2020; Bertayeva, Panaedova, Natocheeva, Kulagovskaya, & Belyanchikova, 2019; Weber-Youngman, 2017; Paschedag, 2017; Zdrodowska, Dardzinska, & Kasperczuk, 2020). The presented solutions will be based on IT solutions, which will change the demand for new miners' competencies. A miner of the future working in mine 4.0 will have to have completely different competencies and skills compared to the current competencies of a miner. The competencies of the new Miner-Operator 4.0 will be directly related to automatization, digitization and interoperability. In Poland, Serbia, and other countries, we are dealing with a change in the age structure of employees. The current workforce is ageing, and the work of the traditionally understood miner is not attractive to young workers (Lööw et al., 2019). It is clearly visible in the quantitative structure of students at universities with subjects related to mining. This is related to many factors, including the negative attitude of society to mines and their impact on the environment, e.g. the blockage of the opening of a lithium mine in Serbia in 2021. Objection to the project to build a lithium mine in Serbia is being replicated around the world. Local communities believe that the job offers and taxes associated with the development of new mining projects are not worth the inevitable environmental impact. There is a very important problem in the field of preparing future staff for a miner of the future (Lööw et al., 2019; Mitra et al., 2018). The lack of appropriate specialists in the field of digitization of industrial processes is one of the main difficulties in the implementation of Industry 4.0 (Ingaldi & Ulewicz, 2020; W. Grebski & Grebski, 2018; M. Grebski & Grebski, 2019). Authors of papers (Romero et al., 2016; Lööw et al., 2019) developed and modified the typology of Miner-Operator 4.0 based on eight assumptions:

1. The use of biomechanical support for work that requires effort.
2. The use of augmented reality to operate the mining infrastructure of machines and devices as well as for maintenance works.

3. The use of Virtual Reality for simulation and training.
4. The use of sensors to monitor the health of the miner and his location.
5. The use of personal communication systems between a database miner and mining equipment.
6. Cooperation of a miner with robots in repetitive tasks.
7. The social miner uses enterprise social networking services for interaction between operators and between operators and the Internet of Things.
8. The analytical miner uses big data analytics to discover useful information and predict relevant events.

In order to achieve a positive effect of the transformation 4.0 in the mining industry, taking into account the paradigms "Green mining" or "Sustainable mining" (Miao & Qian, 2009; Dutta et al., 2016), it is necessary to obtain a consensus between all stakeholder groups, which include: mines, employees, society, state and local administration, mining machinery manufacturers, industry and scientific institutions.

Materials and Methods

Based on the literature research, a set of alternative scenarios related to the digital transformation of mining enterprises were determined and verified. These scenarios were assessed in two stages:
1. The main stakeholders interested in the implementation of selected Industry 4.0 solutions in the mining industry were indicated, and the focus groups, which were taken into account in the research, were created. A structured interview with representatives of individual groups was the basis for indicating the criteria for assessing alternative scenarios related to the digital transformation of mining enterprises.
2. The NAIADE method was used to assess the collected qualitative and quantitative data, taking into account selected alternative scenarios.

The NAIADE method (Novel Approach to Imprecise Assessment and Decision Environments) refers to the Multi-Criteria Analysis (MCA), which is a part of the Social Multi-Criteria Evaluation approach. It was developed by Mund in 1995 as a framework for applying social choice to complex political problems to focus on stakeholders and their specific interests (Marta & Giulia, 2020). It has been used in various contexts, e.g. urban planning or urban regeneration (Nicolini & Pinto, 2013; Della Spina, 2019), environmental management (Ramírez, Hagedoorn, Kramers, Wildenborg, & Hendriks, 2009; Gamboa, 2006), natural resource management (Garmendia & Gamboa, 2012) or protected area management (Oikonomou, Dimitrakopoulos, & Troumbis, 2010). The authors did not find any publications describing its use in the mining industry.

Due to the NAIADE method, individual scenarios were analyzed on the basis of specific criteria defined by all stakeholder groups. This allowed for two types of analysis (Dinelli et al., 2022):
1. multicriteria analysis based on the impact matrix in terms of decision criteria,
2. equity analysis (alternative criteria matrix) that will allow analyzing possible alliances and conflicts of interest between stakeholder groups in relation to the proposed scenarios, measuring their acceptability.

Due to the assumptions of the NAIADE methods, it was possible (Marta & Giulia, 2020):
1. Technical assessment, which is based on the scoring assigned to criteria for each alternative scenario and is performed using an impact matrix (alternatives vs criteria). Due to this analysis, the final score was obtained by the ranking of alternatives and determined according to a set of technical criteria.
2. Social assessment, due to which conflicts between various stakeholders can be examined. Additionally, it is possible to explore likely coalitions between different stakeholders using an equality matrix that ensures that each group of them assesses each alternative scenario.

The research presented in the paper was carried out according to the following:
1. Identification of the main stakeholder groups and selection of stakeholders from each of the focus groups who will take part in the initial structured interview and express their opinion on the Mining 4.0 transformation in the main structure review.
2. The initial structure interview with selected stakeholders.
3. The analysis of the responses of the individual stakeholder groups, which will enable the identification of the scenario assessment criteria.
4. Define alternative scenarios and their verification.
5. Criteria assessment of scenarios.
6. Construction of the alternative criteria matrix.
7. Assessment of scenarios using the matrix of criteria of alternatives and their acceptability.
8. The structure interview with selected stakeholders in order to assess alternative scenarios.
9. Creation of the dendrogram of coalitions.
10. Comparison between technical and social ranking and an indication of the most preferred scenario.

Nine stakeholder groups were identified as the main stakeholder groups. In table 1, the characteristics of individual groups of stakeholders were presented. Each of the potential participants was acquainted with scientific and educational materials on technological solutions that can be used in mining 4.0, especially the digitization of mining processes. The participants were selected on the basis of short structured interviews with individual candidates that took place in May 2021 (opinion on the Mining 4.0 transformation). Then, two series of structured interviews took place: June-July 2021 (discussion on the Mining 4.0 transformation in order to indicate assessment criteria) and September-October 2021 (assessment of alternative scenarios). Participants were selected in the form of stratified samples to form homogeneous groups. The structure of stakeholders participating in the structured interview was presented in Table 2.

Tables 1. Characteristics of individual groups of stakeholders

No	Stakeholder	Level	Category	Resource	Objective	Role
S1	European Union	International	Political	Political	Cohesion of the territory of Europe	Granting financial resources in economic terms
S2	mines	Local	Specific interest	Economic	Maximize the economic income.	Implementation of new solutions related to the digitization of mining processes.
S3	employees	Local	Specific interest	Economic	Improvement of employment conditions.	Gaining new competencies of Miner 4.0.
S4	recipients/ customers	Regional	Special interest	Economic	Minimizing the price of mined products	Negotiating the quantity of purchased products and the amount of selling prices
S5	society	Regional	Special interest	Cognitive	Improvement of both residential and employment conditions.	Respond to the transformation related to the research topic.
S6	environmental organizations	International	Special interest	Cognitive	Protection and improvement of the natural environment	Control of mining facilities in terms of the impact on the natural environment
S7	state and local government administration	Regional	Political	Political	Improvement of the condition of the regional territory and political consensus.	Control of mining facilities in terms of compliance with various types of legal regulations.
S8	mining machinery manufacturers	International	Experts	Economic	Maximize the economic income.	Searching for new solutions related to digitization and automation of machines.
S9	industry and scientific institutions	International	Experts	Cognitive	Possibility of scientific and technological development.	Research on the level of digitization of mining and the use of new, potential solutions in this field.

Tab. 2. Categories of stakeholders participating in a structured interview on innovation in mining in the field of digital transformation

No	Stakeholder	Percentage fraction [%]
S1	European Union	2
S2	mines	4
S3	employees	5
S4	recipients/ customers	4
S5	society	4
S6	environmental organizations	3
S7	state and local government administration	3
S8	mining machinery manufacturers	4
S9	industry and scientific institutions	4

The structured interview was conducted with a selected group of stakeholders in the June-July 2021 period. The purpose of the interview was to provide information and opinions on the perception of the possibilities and limitations of the use of digital mining solutions in relation to individual scenarios for analysis.

Synthetic guides on transformation 4.0 have been developed with relevant explanations and comments. Their aim was to familiarize individual groups of stakeholders with the subject under research. In this way, misinterpretation of concepts was avoided, and space was obtained for creating ideas and stakeholder opinions on individual scenarios.

Based on the assumptions made and the data obtained, several scenario warrants were developed and verified. Three scenarios for the implementation of Mining 4.0 were selected for further research. These scenarios are presented in Table 3. The names of individual scenarios are related to the possibility of implementing Mining 4.0 solutions in them.

Tab. 3. Description of selected scenarios for the Mining 4.0 implementation

	Description	Influence
Scenario 1 (positive)	Increased interest in mining processes, in particular rare earth metals. General cost reduction through higher production with less production resources used. Cost reduction through vertical and horizontal integration of ERP, MRP II in the enterprise (mine) systems. Productivity improvement. Widespread use of cyber-physical systems (CPS). Monitoring of the current effectiveness through, e.g. KPI. Logistic integration of suppliers - machines, spare parts, lubricants, consumables etc. and integrated customer chains. Increase in the interest in the work of a miner due to the development of an appropriate educational system that gives the opportunity to search for a new employee with operator competencies and remote work. Change of the image of a miner's work (resignation from manual work in favour of operator work).	Positive: – Limitation of environmental impact. – Mining 4.0 develops mining companies into learning organizations that require learning in the workplace and continuous education. – Production control can even be performed in the form of the "digital twin", away from the factory. – Change in the competency requirements into more abstract and theoretical ones, rather than physical possibilities of the employee, which opens the possibility of working as a miner also for women. – Improvement of working conditions. Negative: – The potential lack of employment opportunities for employees from a given environment and the need for high 4.0 competencies, which may cause anxiety in the local community. – Possibility of employing employees from countries with low labour costs for remote operator work (employment outsourcing).
Scenario 2 (neutral)	The need to use autonomous and automated systems. Machine manufacturers provide autonomous equipment to the mine, but due to the low interest in the work of a miner, there is a problem with qualified staff, there is a problem with the integration of individual systems. The devices function as autonomous islands without horizontal and vertical integration, which is ineffective. There is also a problem with the automation of the new processes. When a manual task is automated, typically, the former manual operators are the operators of the new automated system. These operators can function well in the system because, having previously worked, they have basic knowledge and experience of mining operations and the technology they control; they need to learn how to use the new equipment. However, the difficulty of transferring such skills to younger employees was defined, in particular to an intelligent mining system programmer who, from the IT point of view, will have appropriate competencies but will not have mining experience and knowledge, which is often required for direct work in the mine. It may turn out that in the case of many machines used, there will be a problem with maintenance or their efficient operation, or with the improvement of the efficiency of their use, which will directly impact the total efficiency. Lack of interest in mining studies and work.	Positive: – The connection between the economy and the development of the construction of the high innovative mining machines. – Development of innovative mining equipment and further digitization of processes. – An increasing level of integration of horizontal and vertical systems. Negative: – Lack of employees who can acquire the required competencies. – Ageing mining staff with experience of the physical work in a mine. – Extended waiting times for new mining equipment enabling remote work with a high automation factor or with remote operational control.
Scenario3 (pessimistic)	Increasing Social pressure to give up fossil fuels, including coal. Some of the production operations and control will be done remotely, possibly from low-wage countries. Employees and contractors can be located anywhere in the world, but they can be active in the same physical or virtual workplaces. Combined with new forms of employment such as crowdsourcing, this creates what can be described as 'lost employment' in the vicinity of the mine. There may be strikes and social anxiety. This shows that the effect of technological change in the mining industry or individual mining companies will not be limited to the industry or company - it will also significantly impact society. Small mining communities may find it difficult to provide the advanced skills and competencies required by a future smart mine. Lack of interest in the work of a miner. Increase in salary costs. The need to look for new employees and reduce labour costs.	Positive: – Limitation of environmental impact due to mine closures. Negative: – Employees are not willing to acquire new competencies. – Reduction of wages. – Reduction of employment. – Mine closures. – No development of existing mines and no opening of new ones. – Social anxiety.

Results

On the basis of the information obtained from the structured interviews with individual stakeholder groups and the analysis of the obtained responses, the criteria for the assessment of individual scenarios were established.

Measurable criteria were taken into account, which were then divided into five non-parallel groups. These criteria and their description are presented in Table 4.

Tab. 4. List of criteria used for assessment of scenarios

Criteria category	No	Criterion	Unit	Description
Economic	1.	Cost of implementing changes	[€]	Total cost of implementing changes related to the implementation of Mining 4.0
	2.	Costs of purchasing and maintaining machines	[€]	Total cost related to the purchase, use and maintenance of modern machinery
	3.	Cost of employee training	[€]	Total cost of acquiring the relevant "new" competencies by employees
	4.	Total economic value	[€]	Estimating the financial benefits resulting from the implementation of Mining 4.0
Environmental	5.	Air pollution	[%]	Level of air pollution caused by different pathogens
	6.	Mining damages	[m^2]	Size of the area damaged by the mines
	7.	Electricity demand	[kWh]	Demand for electricity needed for the functioning of the enterprises
Process digitalization	8.	Amount of data to be stored and processed	[Gb]	Amount of processed data
	9.	Data cloud	[€]	Cost of maintaining an appropriately sized data cloud
	10.	Cyberattacks	[quantity]	Number of cyberattacks on the enterprise's infrastructure
Production	11.	Productivity	[-]	Total productivity level
	12.	Efficiency	[t/kg]	The efficiency of the mining process
Social	13.	New workplaces	[number]	Number of newly open workplaces
	14.	New job positions	[number]	Number of new types of jobs positions resulting from the introduced changes
	15.	The overall change in employment structure	[number]	Differences in the size of employment-related to hiring and firing of employees
	16.	Social anxiety	[-]	Level of social anxiety in relation to a given event measured by the Parker scale

The combination of so many different criteria indicates a multidisciplinary perception and assessment of the Mining 4.0 by a diverse group of stakeholders, each of whom has their own competencies and experience related to this subject.

Tab. 5. Assessment criteria and scenarios of digital transformation according to the chosen criteria (impact matrix)

Criteria category	No	Criterion	Scenario 1	Scenario 2	Scenario 3
Economic	1.	Cost of implementing changes	more or less bad	bad	very good
	2.	Costs of purchasing and maintaining machines	very bad	more or less bad	very good
	3.	Cost of employee training	bad	moderate	good
	4.	Total economic value	very good	more or less good	Very bad
Environmental	5.	Air pollution	good	more or less bad	very bad
	6.	Mining damages	more or less good	bad	more or less bad
	7.	Electricity demand	more or less bad	moderate	moderate
Process digitalization	8.	Amount of data to be stored and processed	bad	more or less good	good
	9.	Data cloud	moderate	very good	very good
	10.	Cyberattacks	bad	more or less good	more or less good
Production	11.	Productivity	very good	good	more or less bad
	12.	Efficiency	very good	good	more or less bad
Social	13.	New workplaces	more or less good	more or less good	bad
	14.	New job positions	very good	more or less good	more or less bad
	15.	The overall change in employment structure	more or less good	moderate	bad
	16.	Social anxiety	good	more or less bad	bad

After identifying the criteria to be applied when assessing the listed scenarios, the first step of the research was to develop an impact matrix. To create this matrix, scenarios were assessed according to the NAIADE methodology (Munda, 2004; Marta & Giulia, 2020); the considered scale is composed of nine qualitative points that are (1) perfect, (2) very good, (3) good, (4) more or less good, (5) moderate, (6) more or less bad, (7) bad, (8) very bad, and (9) extremely bad, and were presented in Table 5. This table, which is also called the impact matrix, was created on the basis of the three previously described scenarios and 16 evaluation criteria. The values of the impact matrix (assessment of scenarios for decision criteria) were presented in a qualitative form (linguistic expressions) based on previously collected quantitative data.

According to the chosen technical criteria and the analysis presented in the impact matrix, it was found that the best scenario is Scenario 1, and then Scenario 2. Assessments of Scenario 3 differ significantly from the assessments of other Scenarios.

Several important criteria contributed to the positive assessment of Scenario 1. First, these are the production criteria that were rated very good. Changes related to the digitization of mine processes, and above all, the implementation of Mining 4.0, will allow the mine to improve their efficiency and productivity, which should be reflected in their future revenues. The criteria from the social group were also assessed positively. Social anxiety related to the reduction of employment and the reduction of the environmental impact of mining processes will decrease. Due to the digital change, new job positions will be created that will be a challenge for the young generation of employees. The overall change in employment structure and workplaces may be partially threatened by greater automation of production, but workers will still be needed; however, their job profile will change. Also, from the point of view of environmental criteria, this scenario is assessed quite positively. Mining 4.0 will make it easier to know where and to what extent mining damage will occur, and it will also be possible to reduce it partially. Air pollution related to the activities of mines will also decrease. Unfortunately, the increased amount of data related to the digitization of processes and their full automation will result in an increased demand for electricity. That is why Scenario 1 was negatively assessed in the group of criteria of the process digitization. This is related to the increase in the amount of data to be stored and processed, which may increase the cost of maintaining the data cloud. In addition, this data will be exposed to an increased number of cyberattacks concerning not only the data itself but also the functioning of mines.

As for Scenario 2, it was also positively assessed in terms of production and social criteria. Unfortunately, the situation is different when it comes to environmental criteria. In this case, according to the criteria, the natural environment will still be exposed to mining damage and air pollution. In the group of the criteria of processes digitization, this scenario was assessed better than Scenario 1. It requires fewer data to be stored and processed, and thus the cost of their storage is lower, and mines are less likely to be exposed to cyberattacks.

Scenario 3 was assessed quite high in terms of process digitization and economic criteria, although in the case of the second group, the criterion of total economic value deserves special attention, although the mines will not incur high costs related to the implementation of Mining 4.0, because such solutions will not be used, but on the other hand, it means no financial gain from it. The positive assessment also applies to the criteria of the process of digitization, but it is related to the lack of implementation of such solutions and the partial closure of mines. Social criteria were assessed the worst. Closure of mines related to the giving up mining fuels, but also limiting the work of some mines, will reduce employment and thus increase social anxiety. The economic criteria related to the limitation of the work of mines and the environmental criteria related to the further impact of the mines, which will continue to operate, were also poorly assessed.

Next, the same scenarios were generally assessed by representatives of individual stakeholder groups (Table 6). For the assessment, the same rating scale that was used to assess the scenarios according to the criteria was also used this time.

Tab. 6. Assessment criteria and Scenarios of digital transformation according to the individual groups of stakeholders (social impact matrix)

No	Stakeholder	Scenario 1	Scenario 2	Scenario 3
S1	European Union	bad	bad	good
S2	mines	very good	more or less good	bad
S3	employees	good	very good	bad
S4	recipients/ customers	good	good	more or less bad
S5	society	more or less good	good	good
S6	environmental organizations	moderate	bad	good
S7	state and local government administration	good	more or less good	bad
S8	mining machinery manufacturers	very good	more or less good	bad
S9	industry and scientific institutions	very good	good	more or less bad

All scenarios received a very different assessment from individual stakeholder groups, which means that they had different expectations for the further development of the mines. Scenario 1 was the highest assessed by all stakeholders (sum of all ratings). The most frequently given grades were very good (stakeholders S2, S8, S9) and good (stakeholders S3, S4, S5). Only two groups of stakeholders are not convinced of it; these are environmental organizations (S6) and the European Union (S1), which are fighting to give up fossil fuels and close mines due to the damage and pollution they cause. Scenario 2 was well assessed by individual groups of stakeholders; however, it was assessed slightly worse than the previous scenario. It is related to the less advanced development of mines and the used solutions. Scenario 3 was assessed well only by two stakeholder groups, i.e. environmental organizations (S6) and the European Union (S1), for the same reason why scenario S1 was assessed poorly. However, for the remaining groups, the closure of a mine and giving up fossil fuels may result in job loss and reduction in revenues, the lack of opportunities for development work, and the creation of new solutions for this industry.

The responses from the structured interviews with representatives of individual stakeholder groups, which were presented in Table 6, were analyzed in accordance with the assumptions of the NAIADE method in order to detect any alliances or conflicts between the interested parties. Figure 2 illustrates the process of creating 'alliances' between stakeholders corresponding to different levels of consensus.

Such a juxtaposition avoids undermining the assessments of individual stakeholders by the emergence of "scenario leaders" who would like to influence the responses of other respondents and avoids undermining the results of surveys aimed at determining their acceptance of the proposed scenarios.

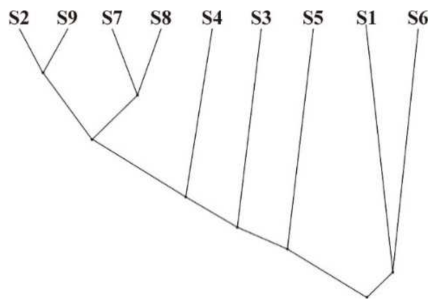

Fig. 2. Dendrogram of coalitions

In Figure 2, a dendrogram that can be used to visualize the proximity of the involved stakeholders was presented. The first coalition is formed by mines (S2) and industry and scientific institutions (S9) because both of these groups strive for the further development of mines, the technologies used in them and their digitization towards Mining 4.0. Another very credible coalition is formed by state and local government administration (S7) and mining machinery manufacturers (S8). Both of these groups care about the development of the mine; the state and local administration treat mines as a source of various types of minerals, and thus earning opportunities, but also jobs for the local community, while for mining machinery manufacturers, mines are the main recipient of their products. Subsequently, the two coalitions merge into a bigger form of the coalition, including groups S2+S7+S8+S9. These are groups that care about the further development and modernization of the mine. Then the coalition is joined by recipients/ customers (S4) for whom mines are a source of raw materials and energy materials, which means that they want the mines to exist and develop and continue to supply them with the ordered raw materials. Employees join the coalition as the next group (S3). For them, mines are a workplace, a possibility to earn money, they are afraid of changes because it involves the need to acquire new skills and competencies, but they know that due to this, mine can survive. Then the coalition is complemented by society (S5). It is a group that feels the operation of mines and their impact on the natural environment, but it is also a group, especially the local community, for which mines are a potential place of employment and livelihood. Thus, There is the coalition S2+S3+S4 +S5+S7+S8+S9. There is also a coalition of two important groups, i.e. the European Union (S1) and environmental organizations (S6). These are the two groups that oppose the excessive development of mines, especially when it comes to fossil fuels. However, they understand that the digitization of mines will, at least partially, improve their impact on the natural environment. Finally, this coalition joins the coalition of the other stakeholders.

It is essential to combine the social impact matrix analysis with a dendrogram in order to interpret the results and indicate the preferences of the stakeholders for particular scenarios. For the groups: mines (S2), state and local government administration (S7), mining machinery manufacturers (S8) and industry and scientific institutions (S9), which created the first bugger coalition; Scenario 1 is the most preferable. For groups of industry and scientific institutions (S3) and society (S5), Scenario 2 gives better possibilities. Additionally, the group of recipients/customers (S4) assessed Scenario 1 and Scenario 2 at similar levels as the most significant. Probably the reason for this is that they feel connected to the mines through the products they buy, but it is not critical to them how those products are produced. Groups of the European Union (S1) and environmental organizations (S6) have indicated that the best solution is Scenario 3, which involves the abandonment of fossil fuels, including coal, which means the liquidation of this type of mine.

Discussion, main limitations, and future studies

Based on the analysis, the scenarios were ranked (Fig. 3). It was possible to create two rankings, i.e. a technical ranking based on a criterion assessment and a social ranking based on the assessment of individual stakeholder groups.

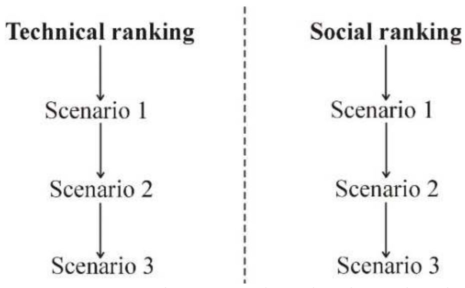

Fig. 3. Comparison between technical and social ranking

When analyzing both rankings, it should be emphasized that both the criteria and the stakeholder assessments showed that Scenario 3 is the least preferred one. This is due to the limitation of the mine's operations and their possible closures, and hence the reduction of employment, a possible increase in the level of unemployment, and reduced interest in development works in this field among manufacturers of mining machinery or industry and scientific institutions. Scenario 1 was selected as the most preferable one in both analyses, followed by Scenario 2. Scenario 1 allows for a big leap in technical solutions used by mines, which will not only reduce the impact on the natural environment but also open the labour market for social groups previously excluded and improve the work conditions of most employees. Special attention should be paid to the summary scores in the impact matrix and the social impact matrix. Scenarios 1 and 2 obtained similar results in both rankings, with a slight advantage of Scenario 1. The difference between these two scenarios and Scenario 3 is quite significant, especially in the assessments of individual stakeholder groups.

Main limitations

The authors selected three scenarios related to the implementation of Mining 4.0: optimistic, neutral and negative when it comes to the possibility of implementing this solution. These scenarios were described on the basis of literature research, knowledge and experience of the authors. Perhaps some important aspects of the topic under research, which should have been included in individual scenarios, may have been omitted during their creation. Perhaps they chose the wrong scenarios from the one they created, and maybe it was also possible to create other indirect scenarios.

The authors tried to select the research sample as objectively as possible in the form of representatives of individual stakeholder groups with the use of stratified sampling, but it was not entirely possible due to the reluctance of many people to take part in this type of research and devote their valuable time. It should be emphasized that the structured interview was conducted twice (plus the first-round when sampling), and the people taking part in it had to read the information provided to them regarding the possibility of implementing Mining 4.0.

The conducted structured interviews were moderated, and sometimes leading questions were asked to obtain specific types of information, which may have had little effect on the given answers.

It should be emphasized that the selection of criteria was made on the basis of interviews with stakeholders. They indicated what is important to them when it comes to mines, their digitization and implementation of Mining 4.0. For this reason, some criteria essential to other scientists may not have been included in the analysis.

The obtained results are subject to a high level of uncertainty. However, the use of the NAIADE method allowed to reduce this level of uncertainty due to the complexity of the evaluation approach.

Future studies

The presented research has shown that in the mining industry, we are dealing with activities aimed at increasing efficiency and improving work safety. Industry 4.0 is the digitization of manufacturing infrastructure controlled by cyber-physical systems. Further research will focus on the analysis of opportunities and threats related to Scenarios 1 and 2, in particular in human-oriented mining. Computerized control of production (transport, mining, maintenance, processing - extended value chain) requires a human being to deal with complexities that exceed the imagination of the designers of production systems. Therefore, the full potential of Industry 4.0 and the achievement of a socially sustainable manufacturing industry will only be realized if Miner-Operator 4.0 is at its centre and interacts with machines through physical and cognitive means. The authors intend to focus on the issues of human-machine interaction and social integration with technology in the area of the mining industry. Future research is to define specific challenges that will be faced by the educational system, mines and society in the area of the Miner-Operator 4.0.

Conclusions

The mining industry is facing major changes, which are to lead to the achievement of climate neutrality in Europe by 2050. It is expected that the mining industry will transform, which brings with it various challenges, including the need to create new types of jobs as well as change and supplement employees' qualifications. This requires large financial outlays and the implementation of appropriate strategies and action scenarios. Achieving consensus and the synergy effect of individual stakeholder groups is necessary to achieve success in the transformation process. The proposed method of assessing the scenarios turned out to be an effective instrument for supporters.

The use of the NADAIE method to assess scenarios allowed for the determination of the impact matrix and social impact matrix. Due to the second one, it was possible to create a coalition dendrogram. The obtained results turned out to be highly consistent, and the level of acceptance of the developed Scenario 1 was high. The legitimacy of using the NAIADE method in the assessment of the implementation of Mining 4.0 was also shown, with a focus on stakeholders who may be affected by it.

The application of the NADAIE method emphasizes the importance of stakeholder involvement in the Mining 4.0 implementation assessment process. Due to this, it is possible to determine the social consequences of the implemented changes to which stakeholders are exposed. Moreover, it also emphasizes that stakeholder participation is a necessary requirement for reaching a consensus on the choice of an appropriate solution.

A decision-making evaluation process containing a juxtaposition of various methods and techniques is useful for delineating a conscious and collaborative improvement and transformation process that will combine technological evolution with dialogue with stakeholders and the know-how of the local community and experts. It also allows building relationships with stakeholders and taking their system of values and relationships into the improvement process. Only an integrated approach to assessment and integration processes enables building joint long-term activities as well as effective development and building of public decision-making processes.

The methods and techniques covered by the common name of Industry 4.0 have been created for many years, affecting many areas (Pietraszek, Radek, & Goroshko, 2020). Therefore, the observations of this article may be interesting both in the area of management (Pacana & Ulewicz, 2020; Antosz & Pacana, 2018) as well as industry (Baryshnikova, Kiriliuk, & Klimecka-Tatar, 2021) and research (Pietraszek, Gądek-Moszczak, & Radek, 2014), especially in the case of advanced research, e.g. materials, where work automation and distributed measurement of positions are widely used (Dudek & Wlodarczyk, 2010; Szczotok, Pietraszek, & Radek, 2017).

From a technical point of view, it should be noted that the qualitative assessment offers the possibility of unifying the assessment of individual solutions by using the same set of criteria. From a social point of view, coalition-building analysis can play an important role in presenting the relationship between stakeholders and their goals related to the research topic. A combination of social and technical assessments can help to find a compromise solution among conflicting interests to reduce the possible conflict. The authors are aware of the limitations of the methodology used at the stage of scenario development and verification - the geopolitical aspect related to local conflicts and economic sanctions was not taken into account, which may significantly change the approach to the social environment and the government's approach to the issue of hard coal and lignite mining, as well as revise plans for the liquidation of hard coal. It can be a strong drive towards innovative activities in terms of increasing the integration, autonomy and efficiency of mining operations. 4.0.

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