Multifunctional Safety System as a Framework for the Digital Transformation of the Coal Mining Industry

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Abstract. Accidents related with operation of mining equipment is a serious problem in the extractive industries. The accidents can result in damage and downtime of machinery, or even can lead to injuries and fatalities. These problems seem to become more acute in the modern conditions of Industry 4.0 implementation. This paper focuses on applicability of a multifunctional safety system in opencast coal mining, with regard to features of this method and using digital technologies. The authors emphasize essentiality of a business-model of opencast coal mining to reach the wanted results. The first section in your paper

1. Introduction

The energy industries represent the backbone sector in the national economy in Russia. They continue governing the economic advance and foreseeable potency of the country. The fact of the matter is impossibility of economic development mineral resources either in Russia or in the world. The evolution of civilizations is always associated with an implacable and extensive increase in extraction and output of energy resources. Conventional hydrocarbons (coal, oil and natural gas) provide more than 80% of energy consumed in the world up to now. In view of the currently observed depletion of conventional energy resources, reduction in power delivery, drop and volatility of demand and price for the conventional energy sources and the unleashed energy transition to renewable energy sources, it is highly critical to adopt a new intensive model of advance in the energy sector – Energy Outlook 2020 [1].

The coal industry is faced with the most serious challenges in modern conditions. Alongside with tension due to the changed geotechnical conditions of production of energy resources, the coal industry falls out of competitiveness in consequence of the onrushing advent of energy transition to zero-carbon (Prediction of Development of Power Engineering in the World and in Russia 2019) [2]. In this regard, there are two alternatives: reduction in coal production, which can unleash a heavy social and economic crisis in the coal mining regions and, probably, across the whole country; or competitive recovery of the industry by means of transition to a new business-model based on the integrated subsoil management, advanced technologies, new sales market and novel models of business interaction between related sectors, with focus on the internal markets owing to deeper conversion of coal inside the country.

The second scenario, considering the amount of the total proved reserves of coal in Russia, the role of coal in the energy balance and possible social risks, seems to be more sound and efficient. Russia has already witnessed many attempts to switch to the second scenario. Solutions put forward included: rising of coal-driven power generation, evolvement of coal chemistry, import substitution and localization of manufacturers of coal mining equipment. All ideas failed to materialize, regrettably. A unique window of opportunity as of today is connected with digitalization and conversion to Industry 4.0 platform.

No one doubts today that industrial digitalization is a synonym of competitive advantage and can offer access to markets of the time to come. However, the coal industry to enhance prosperity and
competitiveness needs not patch-like introduction of some digital technologies but should launch high-rate and all-inclusive commercialization of digital technologies, capable to update the business-model in the industry and its role in the national economy. Immediacy of integration of digital technologies into the coal sector is proved by the marketing experts and confirmed by the governmental structures in Russia. For example, the Ministry of Energy of the Russian Federation has developed the Digital Energetics Project which is concerned with the coal mining industry among other things. The project is aimed to cut down operating costs and capital expenses, and to increase coal production in underground and opencast mining by 5–7% by 2020.

Accidents related with operation of mining equipment constitute a serious problem in the mining industry. The accidents lead to damage and downtime of mining machines, or even to physical injuries and fatalities in the most serious cases. The application of digital technologies can solve these problems. The central role here should belong to a multifunctional digital system of safety.

2. Previous studies

Digital transformation of any industry is a complex and interdisciplinary theoretical and applied problem, which requires a clear insight (on the level of a concept and a strategy) into the objectives, available avenues, mechanisms and tools of the problem implementation with active participation of all parties concerned, i.e. business, government and science. In this respect, both Russia and the world are extensively making the first though casual steps along this way. The increasing amount of literature on digitalization and Industry 4.0 as a whole, as well as on some individual sectorial details proves the currentness and scientific relevance of the problematics appreciated by the research community. The practical relevance of the defined problem is acknowledged at the largest international conferences and forums (Eastern Economic Forum 2019; Digital Industry of Industrial Russia 2019, 2020), which make a path toward modifications in the line of Industry 4.0, in declarations made by presidents of different countries and top managers of major companies, as well as by development of programs and strategies of digitalization in economy, in its individual industries and in specific regions. It is required to study digital transformation processes in the energy sector, generally, and in the coal industry, in particular, since the pattern and method of use of energy resources at any stage of development of a human society always were and remain both the constraint and the driver for a novel production style and its key components.

The studies into the features of introduction of Industry 4.0 and digital technologies in the mining industries and in the energy sector appeared only in 2017. The challenges of the mining industries in the conditions of economic change to the next wave of innovation have been addressed by Di Silvestre, Maria Luisa & Favuzza, Salvatore & Riva Sanseverino, Eleonora & Zizzo, Gaetano, 2018, Maresova, Svobodová, Soukal, & Hedvicakova, 2018; Digital Transformation in Oil and Gas, 2017; Osvin, 2018; Plakitkin & Plakitkina 2017, 2018; Kryukov & Tokarev 2019, 2020, Nikitenko, Goosen, Kontorovich, 2018, 2019, 2020; Eder, Filimonova, Kontorovich, 2017, 2019 et al. [3-15]Most of these studies are incipient since the mining sector is heavily behind all other industries in terms of digital technologies. However, digitalization of coal production resulted in complication of management, in restructuring of business architecture and in closer cooperation between competitive companies and allied sectors, which enabled studying Value-Added Chains (VAC) in the mining industries and in the energy sector (Meller & Parodi, 2017, Pietrobelli et al., 2018; Goosen, Nikitenko 2017; Goosen, Nikitenko 2019 et al). [3-15]

The analyses use various approaches, including the most popular methodology of VAC, business-models and public–private partnership. The scope of the studies embrace the effect of digitalization on strategies of industrialization and re-industrialization in the business operating regions, breaking of the boundaries between the extractive and allied industries, localization of production, influence of digitalization on technological advance, and on the global and local energy markets, etc. (World Bank, 2017, Meller & Parodi, 2017, Pietrobelli et al., 2018; Goosen, Nikitenko 2017; Goosen, Nikitenko 2019 et al.). The role of outsourcing engineering companies in VAC in the energy sector was examined by Anderson, 2012; Marin et al, 2015; Pietrobelli & Katz, 2018S Pietrobelli et al., 2018, Meller & Parodi, 2017. Recently many researchers focus on VAC upgrading and on features of management within the framework of Industry 4.0 [4.0] (SMC 4.0): Holmström & Partanen, 2014; Parilli, Blazek 2015; Wu et al., 2016; Kersten et al., 2017; Hofmann & Rüsch, 2017, De Marchi, Di Maria &
Gereffi, 2018; Hofman, Sternberg 2019; Avdasheva 2015; Malygin, 2015; Sekerin, Kucherenko 2017, Katukov, Smorodinskaya 2018; Smorodinskaya, 2018; Dementiev, Ustyuzhanin et al., 2018; Kondratiev 2018, 2019; Sergeev, 2017, 2019). The features and the trends of VAC in the fuel and energy sector are described by Goosen, Nikitenko 2017; Goosen, Nikitenko 2019[16-25].

The role of multifunctional safety system in the digital transformation of the coal mining industry remains yet to be studied.

3. Key paths of digital transformation in coal industry

The coal industry has yet unaccomplished previous Industry 3.0 and, thus, Industry 4.0 Revolution is slow and inconsistent, which makes an obstacle for the advance in the coal sector and in the allied industries, as well as in operating regions of mining companies.

Digitalization of the coal sector is based on three concepts:

• Digital Mine, including introduction of innovative technologies, such as robotics, artificial intelligence, computerized systems, and integration of technological innovations with business applications;

• Digital Logistics through digital platforms;

• Tokenization with an emphasis laid on financial management [15,26].

An illustrative example of the first concept is operation of a ‘smart’ coal seam. A ‘smart’ seam can provide shearer cutting drums with data on the current size and strength of the seam, on the presence of unwanted hard inclusions and other essential parameters. Depending on this information, the shearer operation mode can be automatically adjusted in real time, for instance, it is possible to vary angle of picks, drum feed velocity, drum vector in the plane of the cutting face, etc. While communicating with a shearer, the ‘smart’ seam denotes a haulage route and equipment so that coal is shipped to a set point by a required time before beginning of the next production cycle. Furthermore, all properly computerized machines and equipment give warnings on wear of different parts and automatically order the wanted parts from the Internet. Such model of digitalization enjoys active commercialization at Siberian Coal Company SUEK and Siberian Business Union (SDS). The similar technologies are run in Raspadskaya-Koksovaya Mine of EVRAZ. Underground Wi-Fi network allows continuous and online operating control. SUEK exploits automatic dispatch offices in surface and underground mines and automatic optimization system for process flow parameters at processing plants and at ports. Moreover, the mines are equipped with a set of intelligence systems, from underground Wi-Fi capable of accurate operation coordination at high personnel safety, through cap lamp-mounted personal methane sensors, to 3D functional simulators of all mines and various personnel training simulations.

The key areas of application of digitalization in the coal industry are: automation or basic automation, creation of digital infrastructure and introduction of multifunctional safety systems.

Automation is aimed at improvement and standardization of basic production, logistical and financial procedures, and represents preparation of a data array (Big Data). Automation of basic and auxiliary mining processes is a part of the Fourth Industrial Revolution, or Industry 4.0, including also robotization, artificial intelligence (AI) and Internet of Things technology. Prior to introducing an automatic control system in a mine, it is required to possess a clear and distinct business-model of potential objectives and facilities capable to have influence on the wanted results.

Major points of the business-model are: expediency of automatic control; effective maturity level; introduction approaches (slow, by stages or fast); transient phase duration (a real length of time between the stages of early introduction and steady-state operation). Furthermore, the business-model defines financial and operation risks, and automation-related unsafety; identifies beneficial and adverse external factors; analyzes advantages and blind sides as well as capacities and risks of selected technology (SWOT-analysis); sets Key Performance Indicators for the advance assessment and measurement.

Automation ensures technological integration and communication towards higher efficiency and improved productivity. To this effect, such innovative technologies as automatic control need an all-inclusive and comprehensive approach.

The Global Mining Guidelines Group’s (GMG) latest guidelines for the implementation of autonomous systems in mining has presented the model of maturity levels for autonomous mine
operation. The model attributes autocontrol levels used to describe certain units and kinds of machines, as well as maturity levels to reflect the general automatic operation control. These levels are:

- **Level 0**: Zero automatic control. Total manual control by an operator.
- **Level 1**: Operator’s backup. The system possesses certain function-oriented properties of automatic control. An operator ensures control in the whole course of operation.
- **Level 2**: Semi-automatic control. The system performs certain operation in autonomous mode, without direct control. An operator is engaged with other objectives. On this level, remote control is often involved though not obligatory.
- **Level 3**: Conditionally automatic control. The system performs autonomous operation on a special site. The system can control situation and goes into waiting mode in case interference is required. An operator / autocontrol inspector can switch off the system and undertake manual control at any time if necessary.
- **Level 4**: Advanced automatic control. The system performs long-term autonomous operation on a special site and is capable of situation control. The system operates in case of minimal possible risk. Given an elevated risk, the system switches to waiting mode. An operator / autocontrol inspector can require shutting of the system.
- **Level 5**: Completely autonomous operation. The system performs long-term autonomous operation control within and beyond a special site, and is capable of situation control. The system acts in case of minimal possible risk. Given an elevated risk, the system switches to waiting mode. An operator / autocontrol inspector can require shutting of the system.

Levels 0–1 are the manual and continuous control from an operator. Level 2 is a semi-automatic control with variable-level control from an operator. Levels 3–5 are the autonomous and continuous operation. The operating maturity of the autonomous operation of a certain mine can represent:

- The manual control and hand-held equipment (Levels 0–1);
- The composite control and mixed fleet of manual, semi-automatic and automatic machine;
- The advanced automatic control with a fleet of completely automatic or automation-intensive equipment (Levels 3–5). [GMG]

In the framework of basic automation projects, production and auxiliary processes are prepared for digitalization (Digital Ready).

The second digitalization area is creation of the external and internal digital infrastructure, including expert systems, supervision centers, end-to-end quality management and scenario-based planning, and digital mine technologies. In practical terms, technological innovation in the coal industry is associated with development and implementation of governmental assistance to technological modification and upgrading with application of Internet of Things and cyber-physical systems. Government also promotes manufacturing of domestic equipment in coal mining using process control by cyber-physical systems [27].

Digital infrastructure engineering is in many respects connected with a real digitalization tool—intelligence system capable to maintain real-time end-to-end data exchange between applications and data bases, as well as external data acquisition, internal processing and distributed storage with algorithmization of queries from remote users. Amongst all elements of digital infrastructure, the center place belongs to the distributed and combination data collection and storage systems capable of simultaneous modeling and forecasting of digitalization processes in the whole industry as well as of smart digitalization control on a scale of a mine or a region. Many consulting and mining companies in the world (British Petroleum, etc.) and in Russia (SDS-Ugol, SUEK) are highly interested in engineering and application of such systems.

Mines are hazardous production facilities, composed of complex natural and geotechnical systems which exist in continuous interaction and generate interdependent geological, physical, chemical, aerological, technological, productive and social processes capable to initiate industrial hazards, risks and accidents. Enhanced safety is the major advantage of automated control systems in mining. On the other hand, the automated control systems invite new safety risks. Therefore, the third approach to coal mine digitalization is safe and sustainable performance. In this regard, safe digitalization involves introduction of proper technologies and obligatory transformation of a mine’s business-model based on the multifunctional safety system.
4. Multifunctional safety system

Generally a Multifunctional Safety System (MFSS) can be defined as an ‘inter-relation of technological, manufacturing, engineering and information systems, processes and personnel engaged in implementation of project designs at reduction of geological and production risks down to a permissible value [28]. In 2012 MFSS was standardized in coal mines on the national scale, and specification and all subsystems of underground mine safety were incorporated in the national standard of Russia (GOST R 55154-2019) [29]. MFSS is intended for: automation of safety-targeted processes; detection and evaluation of hazards in transition to new technologies; assessment of potential risks of integration; determination of real period of time for overall digitalization given obligatory verification and proof tests.

Coal mine’s MFSS requirements are based on the accumulated experience of automated process control over mining safety as well as the federal code of integration of systems and facilities engaged in mine safety and management [30].

Regarding coal mines, MFSS is understood as a dedicated managerial and engineering system meant to perform safety services and reduce risks from various kinds and/or sources of hazards [31]. A coal mine’s MFSS comprises systems of aerological safety, geodynamic safety, fire safety, communication, warning, personnel positioning and explosion safety.

Considering the critical nature of safety in deeper level opencast coal mining, with complication of geotechnical conditions, in conformity with the new edition of federal code for industrial safety in opencast coal mining, it is urgent to fuse all engineering, manufacturing and information systems into an integrated multifunctional safety system of opencast mining. Such MFSS is to ensure safe operation of equipment, to implement proper and prompt control over production processes in opencast coal mine, as well as to prevent initiation and development of hazardous situations in an open cast [32].

The present-day safety regulation documents oblige opencast coal mines to have MFSS starting from January 1, 2022. At the same time, there are no any rules or standards concerned with the composition of safety systems, or safety parameters to be controlled, or systems of accident prediction and prevention. The Federal Code of Industrial Safety [32] dictates that the list of the safety systems integrated in MFSS is defined by the project documentation, with regard to the hazard analysis and accident risk assessment at a specific opencast coal mine.

MFSS of an opencast coal mine should ensure continuous monitoring of operating safety. The principal objectives of MFSS are reduction and elimination of personnel injury rate, prevention of accidents and equipment failures, and cutting down of downtime of production, which present the economic effect of MFSS introduction. In an opencast coal mine, MFSS is to implement continuous prediction and control of process flow parameters subject to varied geological conditions; to analyze process flow features and make advanced decisions on combating risks and accidents at the hazardous production facilities.

Establishment of regulatory requirements for MFSS of an opencast coal mine first needs to set standard requirements for MFSS composition and characteristics of subsystems toward high-level protection and safety.

The present paper authors propose MFSS to monitor and prevent possible hazards in opencast coal mining, including:
- emergency protection of personnel, mining machines and structures;
- communication and alarm system;
- positioning of personnel, mining and haulage machines;
- avoidance of collisions (autonomous and remote control; positional relationship of opencast machinery);
- physiological monitoring of drivers and operators (driver fatigue control);
- pit wall stability control and monitoring;
- control and monitoring of mining equipment parameters (velocity, loading/overloading, fueling, etc.);
- administration of railway stations and railway transport;
- dust and gas control.
Feasibility study of the list of engineering and information systems integrated in MFSS in opencast coal mining should estimate its performance reliability in terms of safety and efficiency. MFSS should be adaptable to the digital management system of a mine.

5. Conclusions
Digitalization of the coal industry is a synonym of marketability and is an avenue to the future markets. At the same time, efficient advance of the coal sector needs that digital technologies are not introduced discretely, as a patchwork, but as the high-rate and all-inclusive digitalization capable to transform the sectorial business-model and its role in the national economy.

The updated federal code of industrial safety in opencast coal mining, by analogy with underground mines, dictates integration of engineering, manufacturing and information systems into a unified multifunctional safety system to implement appropriate and real-time production process control, and to prevent initiation and development of hazardous situations in opencast coal mines.

Finally, prior to introduction of the multifunctional safety system in an opencast coal mine, it is necessary to shape a business-model capable to meet the objectives set out, with regard to the unique principles of Industry 4.0.

Acknowledgments
The reported study was funded by RFBR, project number 19-35-90075/19

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