Occupational Risk Management Method for Quarry Blasting Operations Based on Modified FMECA Algorithm

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Abstract

Occupational risk assessment is one of the most crucial legal obligation for employers and the basis of accident prevention. In the case of highly repetitive work operations and an almost constant work environment, performing a preliminary risk analysis and checking risk levels periodically may be sufficient. In the case of blasting operations in quarries: the mining and geological conditions, technology, blasting methods, explosives, and initiating agents are variables that affect occupational safety. Moreover they make occupational risk assessment difficult to apply on the operational level. Therefore, occupational risk management followed by a deep analysis of hazards and their associated risks may allow to design and manage blasting works with regard to occupational risk. The paper presents the method for the support of occupational risk management in quarry blasting operations based on a modified FMECA algorithm. The designed method provides a systematic approach to risk identification, and allows to indication of the main occupational hazards that should be prioritized for preventive action. The preventive action which could be implied in the design stage by changes in technology or work organization based on options available for a particular quarry.

Keywords: *occupational risk, risk management, safety, blasting, quarry*

1. INTRODUCTION

The application of explosives in open-pit mining is usually the basic stage of the production process. Explosives are commonly used in quarrying to break a mineral-bearing material. This can be explained by the fact that drilling and blasting operations are the most effective methods of extracting natural aggregates in hard rock quarries. Furthermore it is the cheapest and fastest method to produce a large volume of rock. Despite its benefits, the use of explosives in mining poses several potential hazards to personnel, the natural environment, and the surrounding structures.

Current research on quarry blasting safety focuses mainly on the environmental impact of explosives detonation on the mine surroundings and its mitigation.The occupational health and safety (OHS) of employees who performs blasting works is not a commonly addressed area in research papers. This reflection in lack of research interest may result from the detailed blasting safety procedures in national legislation, and the need to meet rigorous safety requirements when handling explosives, and that does not give much space for innovation.

One of the main tools to evaluate and improve employee safety during work is the occupational risk assessment [1,2,3]. In Poland, like in other European Union countries, occupational risk assessment is mandatory [4,5,6]. Framework Directive 89/391/EEC requires employers to carry out risk assessments as part of the protective measures to improve the safety and health of workers [6]. This fact makes an occupational risk assessment a legally required document for any worker undertaking work in the European Union. The key components of a risk assessment are: the identification of hazards and associated risks, estimation of the risk level, determination of risk acceptance, and implementation of preventive or corrective actions where necessary [7,8]. Awareness of risks and their levels can provide the basis for managing operational activity focused on improving employee safety, which lays the foundation for occupational risk management.

Occupational risk assessment for blasting operations can be both complex and require particular expertise in explosive handling, quarry operations, and workplace safety. Due to varying mining and geological conditions, available methods of blasting works, types of explosives and initiating systems, and the relationship between used technology and materials, occupational risk assessment for quarry blasting operations shouldn't be considered as a single activity, but as a dynamic process of assessing risks for each particular blast. This approach allows to optimization of the process in terms of work safety through the application of risk assessments in existing conditions. Moreover, it includes the assessment results, to select technology or resources that should reduce the level of occupational risk.

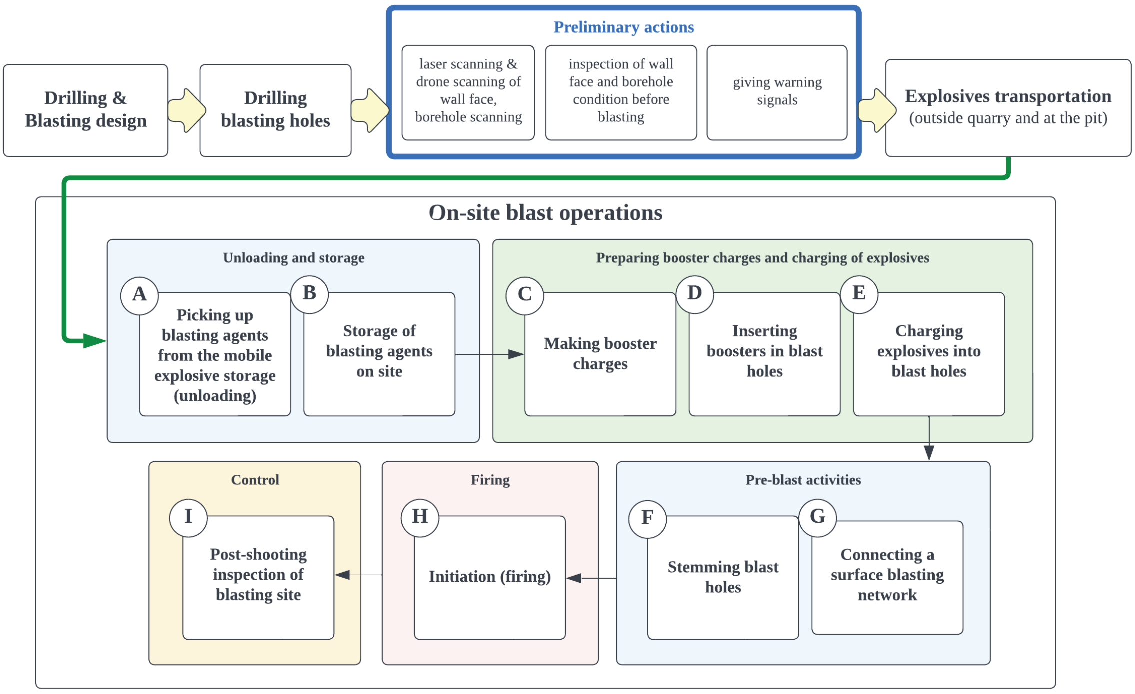
This paper presents an engineering approach to the occupational risk management framework for quarry blasting works based on a modified Failure Mode, Effects & Criticality Analysis (FMECA) method. The presented method aims to provide an intuitive, time-efficient way of managing occupational risks during the design and execution of blasting operations, identifying key safety issues, and helping to prevent negative impacts on the health and safety of workers.

2. QUARRY BLASTING SAFETY

The safety of quarry blasting operations is generally considered in two main areas: the environmental impact of blasting, and occupational health and safety. Both of these aspects are regulated in Poland by legislation.

Polish regulations recognize the following environmental impacts of blasting operations: blast-induced ground vibra-

Fig. 1. Quarry blasting process stages for typical crushed aggregates production blasting (long boreholes blasting method up to 6 m length)
Rys. 1. Proces realizacji robot strzałowych dla typowych strzelań produkcyjnych w górnictwie skalnym (strzelanie długimi otworami strzałowymi powyżej 6 m)



tions, air blast, and flyrock. Their prevention is also considered by establishing safety zones for each selected hazard [9].

Current research work on blasting safety mainly focuses on the environmental impact of blasting. In the case of blast-induced ground vibrations research was done on prediction of intensity and modeling of ground-borne vibration phenomena [10,11,12,13,14,15], the effect of blast-induced vibrations on buildings and structures [16,17,18], and the influence of blasting technology on the seismic effect [19,20,21]. Considering airblast and flyrock, research was mostly made in prediction models of its intensity [22,23,24,25,26]. Blasting operation former studies were also presented by Kiani et al. [27].

Environmental impacts generally affect the mine's surroundings and external people. Given Polish legal obligations, these impacts can have only a minor influence on the safety of the workers carrying out the blasting works because of the necessary safety precautions [9]. The only real hazard that could be identified is the possibility of injury to personnel securing access routes to the flyrock safety area. Other quarry employees are obliged to stay in the blasting shelters until the signal declaring the end of blasting works is given [9]. Therefore, the proposed approach to occupational risk management does not take into account the environmental hazards resulting from the detonation of an explosive as they are unlikely to affect workers.

In the case of Polish OHS regulations, when performing blasting work in quarries, we can distinguish between general regulations based on the Labour Code [4,5], regulations on safety at work in mines and on the handling of explosives [9,28,29,30], and detailed OHS requirements related to work environment factors and work performance [31,32]. These regulations provide detailed guidelines on how to perform the work safely.

Recent research in quarry safety has focused mainly on measuring, simulating, and reducing selected hazards in mines [33,34,35], safety management & occupational risk assessment [34,36,37,38], and preventive measures [39,40]. In the case of occupational risk assessment in quarry blasting operations research was done by Kiani et al., Seccatore et al., and Ke et al. [27,41,42], suggesting various approaches to risk assessment dedicated to quarry blasting. Kiani et al. identified blasting operations risks and used the Fuzzy Analytical Hierarchy Process (FAHP) to compare and rank them [27]. Seccatore et al. studied the applicability of the HAZOP (Hazard and Operability Study) method to assess occupational risks level in rock blasting [41], and Ke et al. adopt Social Network Analysis (SNA) to find relationships between safety risk factors and occupational accidents [42].

An analysis of the available literature shows that current research on quarry occupational safety focuses mainly on general mine hazards, with blasting as one of the sources of hazards that can affect workers. New occupational risk assessment methods have been proposed for blasting operations, however this subject is not commonly addressed in current research studies.

3. OCCUPATIONAL HAZARDS AND RISKS IN QUARRY BLASTING OPERATIONS

Blasting operations expose workers to several hazards which can have different sources. The root causes of occupational hazards can be divided into four categories: how the work is carried out, work environment and conditions, materials used to perform the work & used equipment.

Due to the specifics of the quarry blasting works operations, the hazards in each category may differ for each blasting even in the same mine. This is due to variable blasting locations, used methods of blasting, geological conditions, types of explosives and initiating agents, and changing weather conditions. Additionally, each stage of blasting operations exposes workers to a different range of hazards. It is therefore

Tab. 1. Quarry blasting occupational hazards and risks [*W - the way in which work is carried out; EC - work environment and conditions; M - materials used to perform work; E - used equipment.]

Tab. 1. Zagrożenia I ryzyka zawodowe w robotach strzałowych w odkrywkowym górnictwie skalnym [*W - sposób wykonywania pracy; WE – środowisko i warunki pracy; M - materiały użyte do wykonania pracy; E - sprzęt używany.]

Blasting operations stages	Root cause of hazards*	Occupational hazards	Occupational risks	Technological, organizational and environmental variables	
Unloading and storage on site	W	Manipulation of heavy & fragile objects	Static and dynamic load during lifting & manual transportation, tripping, stress due to time pressure	Type and packaging of used explosives (bulk, cartridges), type of mobile explosive storage unit	
	EC	Dust, noise, weather conditions (hot, cold, rainy), sun exposure	Exposure to negative work environment factors, sunstroke, dehydration, exposure of the skin and eyes to UV radiation	Location of machines in operation, weather & wind	Staff awareness and experience, safety culture level of the company
	M	Explosives, boosters, initiating agents	Uncontrolled detonation, damage to the initiating agent (detonation or misfire), exposure to chemical agents (explosives)	Type of used explosives, boosters and initiating agents	
	E	Mobile explosives storage car	Hit or run over, hitting on vehicle parts	Type of mobile explosive storage unit, organization of safe unloading	
Preparing boosters and charging of explosives	W	Forced body position, bending torso, precision manipulation of objects, manipulation of heavy & fragile objects, operational errors	Static and dynamic load, overloading of the musculoskeletal system, tripping, falling from the working bench, loss of the blasting line to the detonator, faulty detonator connection, stress due to time pressure	Type and packaging of used explosives, type of initiating agents, number of blasting holes & type of surface network connection, organization of safe work on blasting site & concentration during work	
	EC	Dust, noise, weather conditions (hot, cold, rainy), sun exposure, upper and working bench face	Exposure to negative work environment factors, sunstroke, dehydration, exposure of the skin and eyes to UV radiation, impact from a falling overhanging rock, falling from a working bench	Location of machines in operation, weather & wind, proximity of upper and working bench face, organization of safe work on blasting-site	
	M	Explosives, boosters, initiating agents	Uncontrolled detonation, damage to the initiating agent (detonation or misfire), exposure to chemical agents (explosives)	Type of used explosives, boosters and initiating agents, type and complexity of surface network connection, number of boreholes	
	E	Operating MEMU (bulk explosives production units), use of hand tools	Impacts, vibrations, splashing with explosives (eyes contamination), exposure to exhausts, lifting explosives charging pipe	Type of MEMU device & charged explosives, types of used hand tools (authorization to operate with explosives)	
Pre-blast activities	W	Work with hand tools (shovel), Forced body position, bending torso, precision manipulation of objects, operational errors	Overloading of the musculoskeletal system, tripping, falling from working bench, loss of the blasting line to the detonator, faulty detonator connection, stress due to time pressure	Type of initiating agents, number of blasting holes & type of surface network connection, organization of safe work on blasting-site & concentration during work	
	EC	Dust (from quarry), weather conditions (hot, cold, rainy), sun exposure, upper and working bench face	Exposure to negative work environment factors, impact from a falling overhanging rock, falling from working bench, exposure of the skin and eyes to UV radiation	Weather & wind, proximity of upper and working bench face, organization of safe work on blasting-site	
	M	Dust from stemming material, initiating agents in explosive column	Exposure to dust containing crystalline silica, faulty detonator connection, accidental initiation of an explosive charge, stress due to time pressure	Type of initiating agents, number of blasting holes & type of surface network connection, organization of safe work on blasting site & concentration during work	
	E	Use of hand tools and initiating system devices (i.e. logger)	Injury due to tool failure or uncontrolled detonation by an equipment malfunction	Type of used tools and devices	
Initiation (firing) and post-blasting control	W	Entering the blasting shelter	Hit against blasting shelter elements, scuffs and scratches	Condition of blasting shelters, time pressure	
	EC	Detonation effect, dust and post-blast fumes, unstable ground, weather conditions, sun exposure, upper and working bench face	Hearing damage (noise), inhalation of post-blast fumes with carbon and nitrogen oxides, tripping, falling from unstable working bench, exposure of the skin and eyes to UV radiation	Explosives volume, wind, time between blasting and control, blasting technology & output	
	M	Explosives and detonators	Uncontrolled detonation of misfires	Type and quality of used explosives & detonators, quality of blasting operations	
	E	-	-	-	

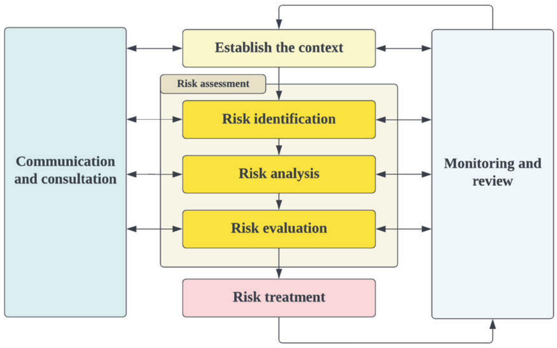


Fig. 2. Risk management process [45]
Rys. 2. Proces zarządzania ryzykiem [45]

necessary to identify the hazards not only in terms of root cause but also considering the potential variable conditions and technologies, for each stage of the blasting work. For hazard identification, the quarry blasting process for typical crushed aggregates production blasting (for blastholes longer than 6 m) was mapped as shown in Figure 1.

Through a systematic approach to hazard identification based on quarry site investigations and literature review, hazards & occupational risks have been identified for each stage of the blasting process, in each hazard root cause category, and by pointing the variable factors that affect the nature and level of hazard for typical production blasting in Polish quarries. For this paper's purpose, the results are presented in condensed form in Table 1 for aggregated blasting operations.

Concluding upon the identified hazards and risks (tab. 1), it can be pointed out that blasting workers in quarries are exposed to wide range of hazards including safety hazards (tripping, falls, impacts), physical hazards (explosion, noise, vibration, UV radiation), chemical hazards (explosives, dust), psychosocial hazards (working under time pressure, the stress of working with hazardous materials) and they are strongly affected by many ergonomic risk factors (heavy lifting and manual handling, static and dynamic loads, forced body position). Due to the changeable on-site and geological conditions, various available methods to execute blasting works, as well as different materials and initiating agents that can be applied, only periodically revised occupational risk assessment may not be sufficient to keep workers safe. A risk assessment based on all detected occupational risks is formally acceptable [5], but does not allow to manage work safety at an operational level. Therefore, the use of an occupational risk management tool can improve safety and help to make technological choices with a focus on employees' safety.

4. OCCUPATIONAL RISK ASSESSMENT AND MANAGEMENT

Risk assessment is an essential part of the risk management process. It consists of three steps: risk identification (finding, recognizing, and describing risks), risk analysis (comprehending the nature of risk and determining its level), and risk evaluation (comparing assessed risk levels with risk criteria to determine whether the risk is acceptable or not) [43]. Legal obligations [4,5] as well as the requirements of the health and safety management system [44] imply the need to assess occupational risks. ISO 45001 standard also includes risk-based approach, which lay the foundation for occupational risk management [44]. Through the outcomes of the risk assessment, it is possible to manage the work process concerning existing risks using risk management methodology. Figure 2 shows the concept of the risk management process based on [45] and the role of risk assessment in managing the risk. The relevant publications detail the stages and requirements of risk management [45,46,47].

Risk assessment could be conducted using various qualitative, quantitative, and semi-quantitative methods, and regarding occupational safety, there are also recognized dedicated methods for specific types of hazards [48]. Good practice and legal requirements [5] indicate, that the choice of assessment method should be tailored to the type of analyzed hazard. Also, different methods may be used for each step of the risk assessment, depending on their applicability [8].

Risk management is a set of coordinated activities to direct and control an organization with regard to risk [45]. According to the definition, risk management in occupational safety could be the basic tool to improve safety as risk is the fundamental concern of OHS. Risk evaluation can indicate the necessity of risk mitigation, which is one of the available options at the risk treatment stage.

Evaluation and dealing with risk is the most common way to conduct legal-based occupational risk assessment in the practice of industrial companies. Ways of meeting the need for communication and consultation, as well as monitoring and review are also implemented in the Polish regulations, although they do not provide any specific guidance beyond the general requirements of involving employees in the risk assessment process, communicating risks to workers and periodically reviewing the validity of the occupational risk assessment [5].

Despite the availability of numerous algorithms enabling a detailed and quite objective assessment of occupational risks, there is a lack of methods to minimize the risk by deliberate choice of safer operations. In the case of blasting operations with different available technologies, materials, and equipment, such a tool can improve safety not only by implementing protective and corrective measures but also by selecting the work technology and its organization from a safety point of view at the design stage.

5. FMEA METHOD

Failure Modes and Effects Analysis (FMEA) was first applied in 1949 by US Army to study the risks of malfunction of

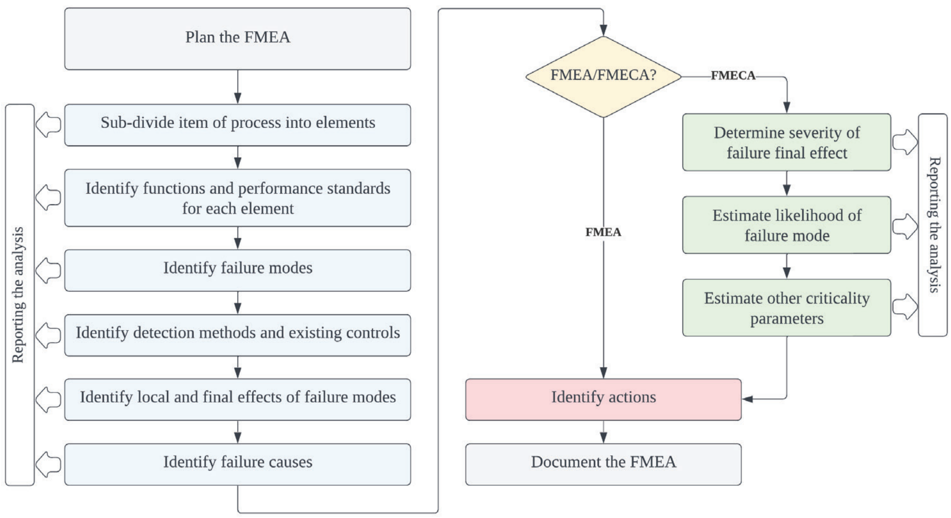


Fig. 3. FMEA/FMECA analysis steps [50]
Rys. 3. Etapy analizy FMEA/FMECA [50]

the military systems [49]. This method is widely used in various industries to evaluate how products or processes might fail, providing a systematic approach for identifying modes of failure, and possible effects and could include identification of the causes of failure modes. FMECA (Failure Modes, Effects and Criticality Analysis) as an extension of this method provide moreover ranking of the failure modes in terms of criticality [50]. The general steps of FMEA/FMECA method are shown in Figure 3, and the full description of the method was described in [50].

One of the advantages of this method is its process-based approach, which is essential in today's management systems based on ISO standards. The requirements of the FMEA method are not dogmatic, therefore this analytical approach can be tailored, adapted to different scopes, and applied in different ways. It can therefore be used as a framework for managing occupational risks to which blasting staff is exposed.

6. METHODOLOGY

The proposed method for the support of occupational risk management in quarry blasting operations is based on the general concept of FMECA analysis. A detailed investigation of the particular steps and requirements of the method was carried out. To adapt this framework to the problem of occupational risk management in quarry blasting, necessary changes have been made. They considered:

- the state of the art in occupational health and safety,
- a set of legal requirements related to the safety of blasting operations,
- the various nature of occupational hazards arising at blasting operations,
- different types of occupational risk assessment techniques.

The suggested method of risk management does not intend to estimate risks according to a single unified method. Good practice strongly recommends that occupational risks should be estimated using the method most appropriate to the risk in question. For the risk assessment stage the FMECA suggests a qualitative or semi-quantitative parametric method, in which the severity is determined, and likelihood is estimated along with selected criticality parameters (like detectability) [50]. Not all occupational risks can be accurately assessed using parametric methods, for instance, ergonomic hazards for which dedicated risk assessment methods exist. Therefore, the presented approach does not guide the selection of the risk estimation method but indicates the possible types of methods and the formulation of their results in the occupational risk management procedure. The methodology allows using most suitable method of estimating risk level based on accuracy, available data, and resources, as well as experience and knowledge of the personnel.

To make fully informed decisions about blasting operations in terms of health and safety, the method provides a ranking of the identified risks using the Pareto principle. It can be used to identify the main occupational hazards that should be prioritized for preventive action which could be implied in the design stage by changes in technology or work organization based on options available for a particular quarry. Therefore the main aim of the presented tool is to combine the process of occupational risk assessment and its outputs with the design stage and quarry blasting at the operational level.

7. RISK MANAGEMENT FOR QUARRY BLASTING OPERATIONS

The main purpose of the presented method is to provide a precise design toolkit which will improve decision making process on technology, work organization, or resource changes to minimize occupational risk on the employee. A diagram of the risk management method was presented in the figure 4. The method involves five main stages:

a. hazards and risks identification stage,
b. selection of risk assessment techniques for each identified risk,
c. estimation of risk level and its standardization,
d. ranking the risks depending on risk level,
e. analyzing risks for scenarios including change of technology or resources.

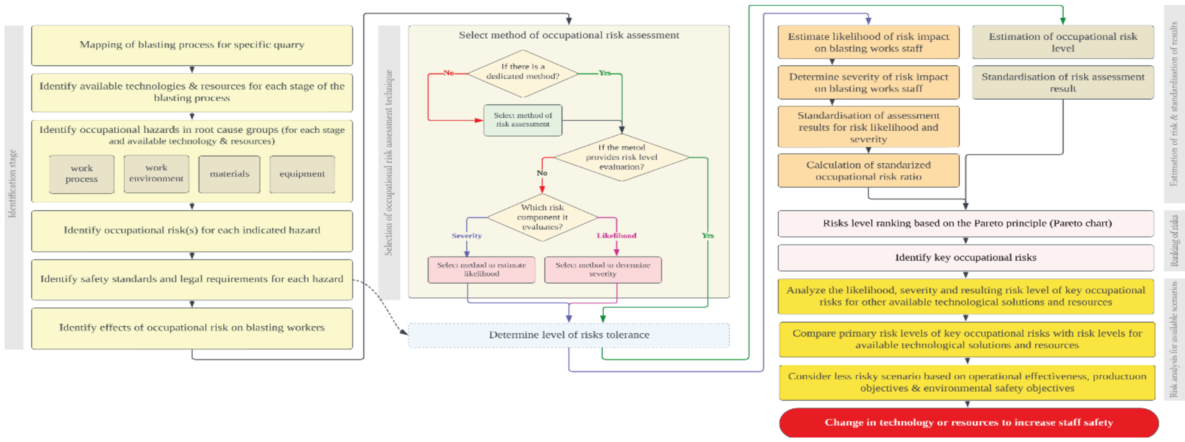


Fig. 4. Occupational risk management method for quarry blasting operations
Rys. 4. Metoda zarządzania ryzykiem zawodowym dla prac strzałowych w odkrywkowym górnictwie skalnym

The first stage starts by detecting all operations for quarry blasting depending on the specifics of the analyzed quarry. For each operation it should be identified all available methods, technologies, equipment, materials and work performance options that could be used. This stage allows to identify all available alternatives, the application of which may improve safety. Then the occupational hazards are identified in four categories, depending on their origin: the way work is executed, work environment (natural and quarry environment), used materials & equipment. This approach allows to make systematic identification of safety hazards depending on the sources identified in the next step risks. For each identified risk analysis of standards and legal requirements should be made, to comply with limit values if they are relevant. If a legal limit exists, it can be used to determine the acceptable level of risk. To understand the possible impact of risk on the employee's health or life, an analysis of risk scenarios should be made. Its results can provide useful insight into the severity of the risk.

For each identified risk it should be considered if there is any dedicated technique to assess risk level, or which method will provide the most accurate estimation result. Selection of the method could be based on [8], and can be proceeded by assessing risk level or each of its components separately. In this method, the classic definition of risk was used, where risk is a function of the likelihood and severity of consequences. Therefore these two risk parameters could be assessed individually and with different methods, to obtain more accurate estimation results. Determining the level of risk acceptance could be applied to combine this methodology with occupational risk assessment in legal terms.

The estimation of the occupational risk level could be carried out depending on whether the technique used makes it possible to assess the risk level or whether separate methods are used to estimate the likelihood and severity. Results at different scales are obtained by different risk assessment methods. To compare and rank risk levels, it is necessary to standardize the results of risk assessment. It has been suggested that simple outcome scales should be used: 0 – 100 for both likeliness and severity, and 0 – 10000 for risk level (equivalent to the result of the multiplication of risk components ratios). Standardization of results can be made by comparing two scales and determining the level in the proposed scale through the use of aspect ratios.

To determine which assessed occupational risks should be prioritized for preventive action, the Pareto principle was used. It implies, that 80% of consequences come from 20% of causes, and is commonly used in occupational safety issues to hazard prioritization [51]. Prioritization can be made according to the operations of the blasting process, root cause groups for hazards, or all risks in a process. Various approaches to prioritization allow to identification of critical areas for which the level of risk can significantly affect employees' safety.

For identified key risks or critical safety areas should be considered the change of technology, materials, tools, or work methods. The available resources, technologies, and materials identified in the first step should be considered by analyzing the level of risk as they are been used. Comparing the obtained risk level with the risk level for selected key occupational risks allows for a selection of available modifications in blasting operations which should have a positive impact on worker safety. It should be also considered if applied changes do not negatively affect the operational effectiveness, production objectives, and environmental safety objectives. If the modification of the blasting process does not affect the production or the environment, the results based on the presented methodology should make it possible to control the occupational risks at the stage of the blasting works design and to take preventive measures through a conscious choice of technology, materials, and work equipment.

8. CONCLUSION

Risk assessment is one of the fundamental legal obligations of the employer. By carrying out an occupational risk assessment for a particular position and regularly monitoring the level of risk, this requirement can be met. However, this approach does not allow the use of occupational risks analysis at the design stage of blasting operations daily. Quarry blasting is often carried out under varying mining and geological conditions, using a range of blasting methods, explosives, and initiating agents, and can be organized differently in the same quarry. To benefit from the awareness of recognized occupational risks, they should be considered about the conditions of the blasting operation for a particular blast.

The application of risk management methodology can allow to apply a piece of information about occupational risk levels to make informed technological and organizational decisions at the design phase of blasting in the quarry. A methodology based on the assumptions of the FMECA algorithm has been proposed for the management of occupational risks in quarry blasting operations. The algorithm itself has been extended to include the option of adopting various methods of evaluation of occupational risk level, taking into account the variable nature of occupational hazards in blasting operations. A risk ranking method based on the Pareto principle has been proposed to enable the selection of critical stages, work activities, resources, or hazards regarding to employees' safety. The application of the proposed procedure requires both time and a detailed analysis of the blasting process and the factors affecting workers directly and indirectly.

To verify the potential to improve workers' safety by applying the occupational risk management method to blasting work operations in quarries, a pilot study on a quarry with its own blasting works staff and for the contracted blasting company is planned. The results of the forthcoming analyses, combined with a study of the organization's safety level, will further elaborate on the subject discussed in this paper.

Literatura – References

1. MOREL, G.; PILLAY, M. The occupational risk assessment method: a tool to improve organizational resilience in the context of occupational health and safety management. In Advances in Safety Management and Human Factors, 2020, p. 367-376.
2. FASORANTI, A.J. Occupational risk assessment as a tool for minimizing workplace accidents in Nigeria industries. In International Journal of Education and Research, vol. 3, no. 5, 2015, p. 143-156.
3. BĂBUŢ, G.B.; MORARU, R.I. Occupational risk assessment: imperatives for process improvement. In Quality – Access to Success, vol. 19, issue 166, 2018, p. 133-144.
4. Labour Code of 26 June 1974 (Journal of Laws 1974 no. 24 item 141 as amended).
5. Decree of the Minister of Labour and Social Policy of 26 September 1997 on general regulations of safety and hygiene at work (Journal of Laws 2003 no. 169 item 1650 as amended).
6. Council Directive 89/391/EEC of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work.
7. PN-N-18002:2011 - Occupational health and safety management systems - General guidelines for risk assessment.
8. IEC 31010:2019 - Risk management - Risk assessment techniques.
9. Decree of the Minister of Energy of 9 November 2016 on the particular requirements for the storage and use of blasting agents and equipment in the mining plant's operation (Journal of Laws 2016 item 321).
10. YAN, Y.; HOU, X.; FEI, H. Review of predicting the blast-induced ground vibrations to reduce impacts on ambient urban communities. In Journal of Cleaner Production, vol. 260, 2020.
11. DING, X.; HASANIPANAH, M.; RAD, H.N.; ZHOU, W. Predicting the blast-induced vibration velocity using a bagged support vector regression optimized with firefly algorithm. In Engineering with computers, vol. 37, 2021, p. 2273-2284.
12. CHOI, Y.; LEE, S.S. Predictive modelling for blasting-induced vibrations from open-pit excavations. In Applied Sciences, no. 11, vol. 16, 2021.
13. MATIDZA, M.I.; JIANHUA, Z.; GANG, H.; MWANGI, A.D. Assessment of blast-induced ground vibration at Jinduicheng molybdenum open pit mine. In Natural Resources Research, vol. 29, 2020, p. 831-841.
14. AKYILDIZ, O.; HUDAVERDI, T. ANFIS modelling for blast fragmentation and blast-induced vibrations considering stiffness ratio. In Arabian Journal of Geosciences, vol. 13, 2020.
15. GORAI, A.K.; HIMANSHU, V.K.; SANTI, C. Development of ANN-based universal predictor for prediction of blast-induced vibration indicators and its performance comparison with existing empirical models. In Mining, Metallurgy & Exploration, vol. 38, 2021, p. 2021-2036.
16. KANGDA, M.Z.; BAKRE, S. Dynamic analysis of base isolated connected buildings subjected to seismic and blast induced vibrations. In Soil Mechanics and Foundation Engineering, vol. 58, 2021, p. 416-424.
17. KANGDA, M.; BAKRE, S. Performance of linear and nonlinear damper connected buildings under blast and seismic excitations. In Innovative Infrastructure Solutions, vol. 6, 2021.
18. KANGDA, M,Z.; BAKRE, S. Performance evaluation of moment-resisting steel frame buildings under seismic and blast-induced vibrations. In Journal of Vibration Engineering & Technologies, vol. 8, 2020, p. 1-26.

19. WANG, P.; MA, Y.; ZHU, Y.; ZHU, J. Experimental study of blast-induced vibration characteristics based on the delay-time errors of detonator. In Advances in Civil Engineering, vol. 2020, 2020.
20. ROY, M.P.; MISHRA, A.K.; AGRAWAL, H.; SINGH, C.P. Blast vibration dependence on total explosives weight in open-pit blasting. In Arabian Journal of Geosciences, vol. 13, 2020.
21. SINGH, C.P.; AGRAWAL, H.; MISHRA, A.K. Frequency channeling: a concept to increase the frequency and control the PPV of blast-induced ground vibration waves in multi-hole blast in surface mine. In Bulletin of Engineering Geology and the Environment, vol. 80, 2021, p. 8009-8019.
22. HASANIPANAH, M.; AMNIEH, H.B. A fuzzy rule-based approach to address uncertainty in risk assessment and prediction of blast-induced flyrock in a quarry. In Natural Resources Research, vol. 29, 2020, p. 669-689.
23. NGUYEN, H.; BUI, X-N.; BUI, H-B.; MAI, N-L. A comparative study of artificial neural networks in predicting blast-induced air-blast overpressure at Deo Nai open-pit coal mine, Vietnam. In Neural Computing and Applications, vol. 32, 2020, p. 3939-3955.
24. ZHOU, X.; ARMAGHANI, D.J.; YE, J.; KHARI, M.; MOTAHARI, M.R. Hybridization of parametric and non-parametric techniques to predict air over-pressure induced by quarry blasting. In Natural Resources Research, vol. 30, 2021, p. 209-224.
25. FANG, Q.; NGUYEN, H.; BUI, X-N.; TRAN, Q-H. Estimation of blast-induced air overpressure in quarry mines using cubist-based genetic algorithm. In Natural Resources Research, vol. 29, 2020, p. 593-607.
26. HAN H.; ARMAGHANI, D.J.; TARINEJAD, R.; ZHOU, J.; TAHIR, M.M. Random forest and Bayesian network techniques for probabilistic prediction of flyrock induced by blasting in quarry sites. In Natural Resources Research, vol. 29, 2020, p. 655-667.
27. KIANI M., HOSSEINI, S.H., TAJI, M.; GHOLINEJAD, M. Risk assessment of blasting operations in open pit mines using FAHP method. In Mining of Mineral Deposits, vol. 13, issue 3, 2019, p. 76-86.
28. Act of 21 June 2002 on explosives for civil use (Journal of Laws 2002 no. 117 item 1007).
29. Decree of the Minister of Economy of 8 April 2013 on detailed requirements for the operation of an opencast mine (Journal of Laws 2013 item 1008).
30. Decree of the Minister of Economy of 18 February 2011 on how to perform work with explosives for civil use and when clearing areas (Journal of Laws 2011 no. 42 item 216).
31. Decree of the Minister of Labour and Social Policy of 14 March 2000 on health and safety at work in manual handling activities (Journal of Laws 2000 no. 26 item 313).
32. Decree of the Minister of Health of 2 February 2011 on the analysis and measurement of factors hazardous to health in the working environment (Journal of Laws 2011 no. 33 item 166).
33. ZHENG, X.; YANG, Q.; JIN, L.; ZHENG, Y.; LUO, H.; MA, G. Numerical simulation on spatio-temporal distribution regularities of blasting dust mass concentration in open quarry. In China Safety Science Journal, vol. 30, issue 10, 2020, p. 55-62.
34. DEGAN, A.G.; LIPIELLO, D.; PINZARI, M. Occupational hazard prevention and control in a quarry environment: exposure to airborne dust. In WIT Transactions on the Built Environment, vol. 151, 2015, p. 27-38.
35. CARBONE, S.; DE BRITO, V. A simulation approach to predict workers' exposure to respirable dust in a quarry site: a case study. In International Multidisciplinary Scientific GeoConference SGEM 2, 2016, p. 25-32.
36. EKONG, A.E.; EZEOKORO C.; NWAICHI, E.O.; OBELE, R.E. Occupational health and safety management in selected stone quarries in Akamkpa, Cross River State, Nigeria. In Current Journal of Applied Science and Technology, vol. 39, issue 34, 2020, p. 107-122.
37. TIMOFEEVA, S.S.; DROZDOVA, I.V.; BOBOEV, A.A. Assessment of occupational risks of employees engaged in open pit mining. In E3S Web of Conferences - XVIII Scientific Forum "Ural Mining Decade", vol. 177, 2020.
38. [KOVACS, A.; BORDOS, S.; GARALIU-BUSOI, B.; MIRON, C.; STANILA, S. The analysis of the technological and professional danger factors specific to the works of exploitation of useful rocks from quarries, which can generate risk of accident and/or technological breakdown. In MATEC Web of Conferences - 9th International Symposium on Occupational Health and Safety SESAM 2019, vol. 305, 2020.
39. MELIKA, F.F.; AMER, F.G.M. Proposal guideline for preventive measures toward occupational health hazards for quarries workers. In Egyptian Journal of Health Care, vol. 11, no. 4, 2020, p. 1260-1274.
40. ERSOY, M. The role of occupational safety measures on reducing accidents in marble quarries of Iscehisar region. In Safety Science, vol. 57, 2013, p. 293-302.
41. SECCATORE, J.; ORIGLIASSO, C.; DE TOMI, G. Assessing a risk analysis methodology for rock blasting operations. In Blasting in Mining – New Trends, 2012.

42. KE, L.; CHEN, K.; HU, N.; TAN, M.; ZHANG, G.; MENG, H. Safety risk assessment of blasting in open-pit mine based on SNA. In China Safety Science Journal, vol. 32, issue 10, 2022, p. 48-56.
43. ISO 31073:2022 - Risk management – Vocabulary.
44. ISO 45001:2018 - Occupational health and safety management systems - Requirements with guidance for use.
45. ISO 31000:2018 - Risk management – Guidelines.
46. LALONDE C.; BOURAL, O. Managing risks through ISO 31000: A critical analysis. In Risk Management, vol. 14, 2012, p. 272-300.
47. BJORNSDOTTIR, S.H.; JENSSON, P.; THORSTEINSSON, S.E.; DOKAS, I.M.; DE BOER, R.J. Benchmarking ISO risk management systems to assess efficacy and help identify hidden organizational risk. In Sustainability, vol. 12, issue 9, 2022.
48. KRAUSE M. Praktyczne aspekty doboru metod oceny ryzyka zawodowego. In Zeszyty Naukowe Politechniki Śląskiej, Seria: Organizacja i Zarządzanie, z. 59, 2011, p. 173-190.
49. SPREAFICO, C.; RUSSO, D.; RIZZI, C. A state-of-the-art review of FMEA/FMECA including patents. In Computer Science Review, vol. 25, 2017, p. 19-28.
50. EN IEC 60812:2018 - Failure modes and effects analysis (FMEA and FMECA).
51. WOODCOCK, K. Safety Evaluation Techniques, Ryerson University, Toronto.

Metoda zarządzania ryzykiem zawodowym dla robót strzałowych w odkrywkowym górnictwie skalnym w oparciu o zmodyfikowany algorytm FMECA

Ocena ryzyka zawodowego stanowi jedno z podstawowych wymagań prawnych stawianych pracodawcy oraz fundament prewencji wypadkowej. W przypadku prac charakteryzujących się powtarzalnymi czynnościami i niewielką zmiennością środowiska pracy, wykonanie oceny ryzyka zawodowego wraz z okresową kontrolą poziomu ryzyka wydaje się wystarczające i spełnia wymaganie stawiane przez prawo. Rozważając prace strzałowe w kamieniołomach, warunki górnicze i geologiczne, stosowana technologia i metody strzelania, środki strzałowe i inicjujące są zmiennymi, które mogą wpływać na poziom bezpieczeństwa pracy. Ponadto zmienne występujące w trakcie robót strzałowych powodują, że ocena ryzyka zawodowego i jej wyniki są trudne do wdrożenia na poziomie operacyjnym. Rozwiązaniem tego problemu może być zarządzanie ryzykiem zawodowym poprzedzone szczegółową analizą zagrożeń i towarzyszących im ryzyk, które może pozwolić na projektowanie i zarządzanie robotami strzałowymi z uwzględnieniem ryzyka zawodowego pracowników.

Artykuł prezentuje metodę wspierającą zarządzanie ryzykiem zawodowym w robotach strzałowych w odkrywkowym górnictwie skalnym opartą na zmodyfikowanym algorytmie FMECA. Zaproponowana metoda pozwala na systematyczne podejście do identyfikowania ryzyk zawodowych i wskazuje na kluczowe zagrożenia zawodowe, dla których powinny zostać w szczególności zastosowane działania profilaktyczne. Ograniczenie ryzyka zawodowego może być osiągnięte na etapie projektowania robót strzałowych poprzez zmianę technologii lub organizacji pracy w oparciu o dostępne możliwości dla danego zakładu górniczego, a wybór charakteru rodzaju zmian jest wspierany przez zaproponowany w niniejszym artykule algorytm.

Słowa kluczowe: *ryzyko zawodowe, zarządzanie ryzykiem, bezpieczeństwo pracy, roboty strzałowe, kamieniołomy*