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Miscellaneous

Application of elements of the theory of events to identify hazards in mining workplaces

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Abstract

This article aims to present the process of identifying hazards as a chain of events in a sequence that leads to injury or equipment damage in the workplace. The events chain can be described as an ordered set of circumstances favorable to the appearance of hazards. The article presents an analysis of elements of events theory in an attempt to identify hazards in the mining industry. A sample analysis of the circumstances favorable to initiating the occupational disease, pneumoconiosis, is also presented using elements of events theory.

Introduction

For risk assessment of mining operations there is a need to identify all potential hazards. In the analysis of such risks, the most difficult to detect are certain sequences of events or conditions that collectively lead to an increased probability of undesirable results. Such a chain of events considers all human factors, as well as environmental parameters at the work site, which are clearly critical to the development of hazardous situations. The use of events theory elements to identify hazards depends on the analysis of a chain of events culminating in the accident or material damage or occupational disease. Analysis of such a chain of events makes it possible to identify conditions favorable for the creation of hazardous situations. That is why a deep analysis of the circumstances preceding the hazardous event must be made.

Environment parameters and occupational safety at work

The work environment is defined as a set of objects associated crew organized to produce specific values in the work process. Parameters of the work environment that relates to its objects have the biggest influence work safety. The direct or indirect effects of work environmental parameters on crew and the operations of the mining plant can be expressed as follows:

- physical parameters associated with a mining environment such as the magnitudes of critical temperatures, pressures, rock mass stresses, voltages and electric currents, noises, vibrations, velocities of ventilation flows, etc.;
- geometrical parameters including the dimensions of the excavation, the heading of the excavation, and the nature and location of mining machinery;
- pollution of the ventilation air stream by gases and/or dusts (Cichowski, 1999).

The nature of the work site is very industry-specific in the mining industry, differing considerably from the typical factory due to the formation, methods of work and the hazard of the environment and the machinery and equipment in use. A mining crew may encounter, directly or indirectly, such environment conditions as surrounding rock walls, machines and energy equipment, and devices needed to control mining dam safety barriers, cars retarder, fire equipment, alarms, spraying equipment and various types of materials, such as blasting agents, coal dust and stone dust, as well as streams of water and ventilation air (Wanat, 1973).

When the parameters of the work environment, where the crew is located, are approximately constant or slightly changing, then it may be called normal conditions. Normal working conditions generally entail a relatively constant relationship between the conditions of the work environment and the location. Emergency conditions, on the other hand, usually entail sudden and significant changes in the conditions of the work environment, including such events as a sudden increase in temperature, air pressure, toxic gases, or a significant change in the shape of the excavation. The intrinsic nature of the mining profession is such that providing completely comfortable conditions is impossible. Therefore, existing safety standards in the mining industry represent a compromise between working comfort and production requirements. It is, however, expected that full safety measures be provided for all of the hazards known to be associated with an ongoing mining operation. Security standards for the conditions of the work environment are determined by mandatory safety regulations. These regulations are defined by:

- desirable work environment parameters, e.g., for the application of fireproof lining of excavations next to the shaft;
- technical procedures for avoiding known hazards, such as the use of directional drilling near water hazards;
- an automatically controlled atmosphere with regard to the allowable concentrations of methane;
- a maximum acceptable concentration (MAC) for dust and gases;
- a maximum acceptable intensity (MAI) for noise (Cichowski, 1999; Sobala & Rosmus, 1996).

Concepts related to the harmfulness of mining activities

Mining hazards are the unintended consequence of mining activities. More specifically, hazards result from a particular cause or series of causes that occur in a specific sequence that is capable of triggering dangerous and/or damaging events. Conditions that are known to lead to major problems are called "absolute hazards." Although these absolute hazards are straightforward and easy to understand, their actual probability of occurrence is probabilistic, so they can only be predicted with a certain margin of error.

Absolute hazard is determined by the parameters of the work environment and by the behavior of the crew. Absolute hazard, caused by a specific sequence of events, is determined by the same factors (Cichowski, 1998; Krzemień, 1992). Al-though separate calculations are sometimes made, for property damage hazards together with accidents risk, and health hazards.

The opposite of hazardous is secure, which in the mining industry usually refers to a state-maintained work environment that is intended to create conditions that are unlikely to be associated with accidents (Cichowski, 1998). "Security" also refers to a state in the work environment that either tends to protect mining machinery and equipment, or the welfare of the crew. The level of security is determined by applicable safety regulations, and is supposed to create conditions lessening the probability of specific types of accidents.

The quantity and type of deviations from a safe condition must be described before a hazard can be quantified. Hazards to equipment and/or the crew are usually identified by discussing security deficits in the work environment. Some of the security deficits are caused by the failure of mining employees to abide by standards addressing health and safety legislation. In other cases, human-caused safety deficits occur in areas that have not been covered by established health and safety regulations.

Due to the difficulty of identifying absolute hazard as described in the literature (Cichowski, 1999; Bobrowski, 1980; Dwiliński, 1985; Leniewicz, 1975), it is proposed that safety hazards be evaluated in relative instead of absolute terms. A relative hazard is defined as a safety deficiency of the work environment that threatens human safety (Cichowski, 1999). Before it represents a clear and present danger to human safety, a relative hazard must progress through three phases: a phase considered without hazard, a phase of contractual hazard, and a phase of full (clear and present) hazard. Accidents are considered impossible under the phase considered to be without hazard; it is assumed to represent a completely safe work environment. The level of safety can be corrected through continuous improvements in a safety management process. The contractual hazard phase describes a state affected by existing security deficits risk factors on the human side, without the harmfulness possibility. The full hazard phase represents a state in the work environment, in which an accident may well occur after the activation of the hazard occurs (Cichowski, 1998; Krzemień, 1992).

In the case of accident hazard, causes of activation are uncontrolled processes occurring in the work environment, or uncontrolled parameters or activities. In case of a health hazard, a necessary hazard activation condition is the set of events, which consists of uncontrollable harmful factors in the work environment to which the crew receives uncontrolled exposure. Then the most common problem is a lack of proper monitoring. Uncontrollable events often arise from a lack of a hazard identification program, but they can also occur despite control, measurement, and observation.

Events theory elements with relation to the work environment

Events occurring in the work environment are assigned two logical values, 1 or 0. The logical value 1 is assigned to the occurring events (true events), while the logical value 0 is assigned to events that do not occur. The description of events in the work environment uses basic logical functions, such as conjunction, alternative, negation, implication and equivalence. In addition, logical laws are used to describe events according to mathematical logic (Pasenkiewicz, 1968).

The working environment can be considered as a set of elementary events. All events occurring in the environment can be divided into static events, signifying states, and kinetic events, signifying changes in these states. The kinetic events are the cause and static events are results of a sequence of conditions (Kotarbiński, 1975). Besides the elementary events are macro- and micro-complex events, with varying degrees of complexity consisting of environmental subsets. Complex events consist of certain number of static and kinetic events occurring simultaneously and/or one after the other. They represent a specific process taking place in the work environment (Pszczółkowski, 1988). In certain circumstances, crew activities can directly or indirectly cause of an activation of a specified hazard (Cichowski, 1999).

The sequence of events determines the principle: every effect is clearly and sufficiently appointed by the general causes and conditions in which it occurs (Bobrowski, 1980; Palec, Przełęcki & Szaniawski, 1957; Leniewicz, 1975).

A sequence of events illustrates causes and effects in the work process. A set of events immediately preceding the change (qualitative and quantitative) presents a sufficient conditional sequence of events. A sufficient condition-specific effect consists of:

- principal cause and conditions (fixed);
- side conditions (random).

Principal conditions occur whenever they are a necessary condition for a result representing a qualitative change (Palec, Przełęcki & Szaniawski, 1957; Dwiliński, 1984; 1985). For example, a flame of the necessary energy and a primary cloud of explosive coal dust are the cause and the main condition which are necessary to initiate a coal dust explosion. Side conditions in a sequence of conditions are random variables that can make the accident more or less likely or affect the size, the course and range of the event. For example, when coal dust explodes, side conditions determining its strength and range are: participation of non--combustible elements (stone dust), the fragmentation of dust, the proportion of volatiles in the mixture, mixing and concentration of dust in the original cloud, and so on.

Phenomena occurring in the work environment can be described by using the chain events model. A model of such an events chain is well illustrated by dominoes blocks, stood on end side by side. Knocking over all of the dominoes requires the toppling of the first block, which knocks over the second domino, and so on, until the last. In order for the dominoes to fall, the toppling of the first domino must appear as a factor initiating the entire sequence of events (Dwiliński, 1984; 1985; Leniewicz, 1975).

Relevant combinations of necessary event sequences in the work environment of the mining plant can be events both in terms of work environment parameters (materials factors) and the human factors (actions and decisions). Mining operations are the cause: the specified work environment parameters, their change, the processes that affect them and finally, the activities and states on the side of the crew, are the effects of their action. For example, the effect of an action might be: crew members present in a particular place at a particular position during operation, use ordered technologies under specified conditions. Uncontrolled event sequences occurring in the workplace, on the side of the work environment parameters and the human factors side, can lead to the initiation of the full hazard, that is to say, to undesired processes immediately preceding the harmfulness. The necessary events chain preceding the accident shows the arrangement of subsequent indirect effects and necessary reasons for remaining in the causal relationship.

These processes, in which events are considered due to their arrangement, can be assigned to an image geometry, called a graph (Karpiński, 1978). A graph is a topological mapping of an events sequence, defining unequivocally the relationships between the individual events. In the graph, nodes represent the necessary conditions of the events sequence, and the branches oriented towards the implication represent indirect results, that can turn into causes in the nodes and/or principal conditions of the event sequence (Cichowski, 1999). Figure 1 shows a simplified graph of an events sequence. In the graph there are three external nodes and one internal node that represent necessary conditions of event sequence. Three branches represent a result *gk*, and essential combinations of a necessary sequence of events, i.e. the cause *ek* and principal condition *es*.

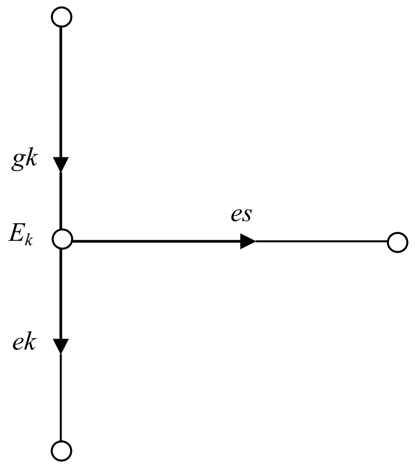

Figure 1. Reduced graph sequence of events (Cichowski, 1999)

Accident and material damage in the events chain at work

As mentioned, the accident hazards affecting human safety are considered along with the risk of material damage accompanying some accidents. Accidents at work *WY* and/or material damage *SM* imply an injury *UR,* and a chain of a necessary sequence of events in the phase of the full hazard. The essential chain of necessary condition elements in the full hazard phase are:

- accident event – *ZW*;
- activation of accident hazard from the side of parameters of work environment and the human factor – AZ^P, AZ^C;
- crew staying within range hazard AZ^P – *ys*;
- actual threshold of hazard from the objects or the dose of harmful factors – RZ_c, RZ_{dwy};
- undesirable change of the lithosphere parameters, the technosphere, atmosphere and other – AZ^L, AZ^T, AZ^A.

The essential ingredients of necessary conditions of initiating the full hazard phase are as follows:

- uncontrolled processes, uncontrolled parameters changes or uncontrolled crew activities;
- activities performed by the crew currently;
- the state of the workspace;
- mining works;
- influence crew on the mining work crew and inspection;
- the movement of mining plant;
- influence management on the mining plant movement (Cichowski, 1999; Szczurowski, 1983).

In order to determine whether a defined event is an important component of the necessary conditions chain, it should be considered whether the events sequence would be possible without it. In accordance with applicable safety regulations (Polska Norma, 2004; Koradecka, 1997), an accident at work is a sudden event caused by external circumstances that occurred in connection with work and led to the injury. Sufficient condition to recognize event as an accident at work is the presence of a macro event, that is a set of events:

$$WY = \{UR \wedge c_1 \wedge c_2 \wedge c_3\} \tag{1}$$

where:
UR – injury;
c_1 – event giving reason the injury, which lasts no longer than a period of one work shift;
c_2 – injury induced an external cause;
c_3 – injury is related to the work (Cichowski, 1999).

In order to be considered an event regarded as an accident at work, there must all four of these essential components of a sufficient condition must be fulfilled. Example of qualifying injuries include: bone fractures, burns, paralysis, lesions to the physiological or psychological functions of the body, and so on. A necessary condition, but not a sufficient one, is the appearance of an injury *UR* to fulfill a set of accident events. The accident event is sudden, caused by an external cause, and represents a dangerous encounter between the crew and objects of work environment (Koradecka, 1997; Krause, 2012). The crew is also exposed to contact with the effects of changes in the work environment parameters such as:

- crumps;
- gas and rock breakouts;
- methane explosions;
- coal dust explosions;
- the sudden intrusion of water or quicksand to the excavations;
- gravitational rock falls;
- vent streams with newly changed, abnormal parameters;
- an atmosphere is not suitable for respiration;
- electrical shock;

- spark within the workplace;
- contact with the products of the explosion of blasting agents (Szczurowski, 1987).

Generally it can be said that a necessary condition of accident event *ZW* is a set of events Y_k:

$$ZW \Rightarrow Y_k \equiv \left\{ \left[AZ^P \wedge ys \right] \vee \left[AZ^C \wedge \left[RZ_c \vee RZ_{dwy} \right] \right] \right\} \quad (2)$$

where:

AZ^P – activation of accident hazard on the part of the work environment parameters;
ys – crew staying within range AZ^P;
AZ^C – activation of accident hazard on the human factor side;
RZ_c – actual threshold of accident hazard from the environment objects, which represent objects dangerous for the crew;
RZ_{dwy} – actual threshold hazard from the dose harmful factor.

Examples of actual thresholds of accident hazard RZ_C are moving machine elements or equipment, and all stiff, angular, hard, sharp, hot, etc. objects in the work environment. The actual threshold accident hazard on the side of harmful factors dose can be achieved by undesirable changes in the vent stream parameters such as pressure, temperature, and presence of toxic or suffocating gases in normal or emergency conditions (Cichowski, 1999).

Occupational disease in the events chain during labor

Occupational diseases are an important undesirable result of mining activities. A sequence analysis of events preceding an occupational disease can be determined by a detailed chain of the necessary conditional events sequence in the phase of the full hazard.

Occupational disease *CH* implies irreversible lesions *NZ*, which implies the full hazard phase $\Pi_{kP}^{CH}\left(Z_k, Y_k\right)$. The phase full hazard implies necessary condition of initiation phase full hazard. Necessary sequence of events immediately preceding the occupational disease looks like:

$$CH \Rightarrow NZ \Rightarrow \left[\Pi_{kP}^{CH} \equiv \right.$$
$$\left. \equiv \left\{ Z_k \equiv \left\{ RZ_{dch} \right\} \Rightarrow Y_k \equiv \left\{ AZ^{CH} \right\} \Rightarrow I_k \equiv \left\{ iq \wedge is \right\} \right\} \right] \quad (3)$$

where:

- essential ingredients of chain necessary conditions in full hazard phase is: actual threshold morbidity RZ_{dch} and disease hazard AZ^{CH} activation;
- essential ingredients of necessary condition initiating full hazard phase are events: uncontrolled concentration or intensity of harmful factor *iq* and uncontrolled exposure of crew to harmful factors, occurring in the workplace *is* (Cichowski, 1999).

Examples of irreversible lesions occurring in the mining industry include: pneumoconiosis, vibration disease, reduced hearing not associated with age, kneecap damage, leukemia, and so on. Irreversible lesions are a necessary precondition for recognition of an occupational disease. Irreversible lesions resulting result from a dose of harmful factors, absorbed by the exposed person and necessary to cause disease. The dose absorbed depends on both the state of hazard from harmful factors and on biological and sociological human factors. These states of hazard are defined as the actual threshold of disease hazard, or the actual threshold of morbidity (Kordecka, 1997; Szczurowski et al., 1987; Krause, 2012). Knowledge about the real threshold of morbidity concerns only isolated harmful factors with properties that accumulate in the body, such as toxic gases, reparable dust, noise, vibration and so on. The actual threshold of morbidity in the case harmful factor resulting from the technology used is poorly understood and difficult to evaluate. However, as an activation of disease hazard, it should be considered to influence the crew by all the possible harmful factors in the work environment, as shown in the relationship:

$$AZ^{ch} \equiv AZ_p^{CH} \vee AZ_h^{CH} \vee AZ_w^{CH} \vee \ldots \vee AZ_i^{CH} \quad (4)$$

where:

AZ_p^{CH} – activation of reparable dust hazard;
AZ_h^{CH} – activation of noise hazard;
AZ_w^{CH} – activation of vibration hazard;
AZ_i^{CH} – activation of other factors harmful hazard, occurring in the work environment.

Sequence of events preceding occupational disease: the example of pneumoconiosis

Pneumoconiosis recognized *CH* precedes irreversible pneumoconiosis changes *NZ* which, in turn, precedes the achievement of actual morbidity threshold by victim – that is to say, absorbed dust, sufficient to initiate irreversible pneumoconiosis changes.

The use of medical prevention may create conditions that discourage the development of the actual morbidity threshold RZ_{dCH}. The actual threshold incidence of pneumoconiosis is preceded by lengthy (often many years), activation of disease hazard AZ^{CH} (Cichowski, 1993; 1995). The activation of disease hazard is preceded by: uncontrollable concentration of dust, *iq,* and uncontrolled exposure of crew, *is*. The chain Π_k^{CH} of eleven necessary conditions preceding pneumoconiosis shows the following relationship:

$$
\begin{aligned}
& CH \Rightarrow NZ \Rightarrow \\
& \Rightarrow \left[\Pi_k^{CH} \equiv \{Z_k \equiv \{RZ_{dch}\} \Rightarrow Y_k \equiv \{AZ^{CH}\} \Rightarrow \right. \\
& \Rightarrow I_k \equiv \{iq \wedge is\} \Rightarrow H_k \equiv \{hq \wedge hs\} \Rightarrow \\
& \Rightarrow G_k \equiv \{gq \wedge gq_z\} \Rightarrow F_k \equiv \{fq\} \Rightarrow \\
& \Rightarrow E_k \equiv \{eq \wedge eq_z \wedge eq_d\} \Rightarrow D_k \equiv \{dq \wedge dq_k\} \Rightarrow \\
& \Rightarrow C_k \equiv \{cq \wedge cq_d\} \Rightarrow B_k \equiv \{bq \wedge bq_k\} \Rightarrow \\
& \left. \Rightarrow A_k \equiv \{aq \wedge aq_w\}\}\right] \Rightarrow aq \wedge bq \wedge cq \wedge dq
\end{aligned}
\qquad (5)
$$

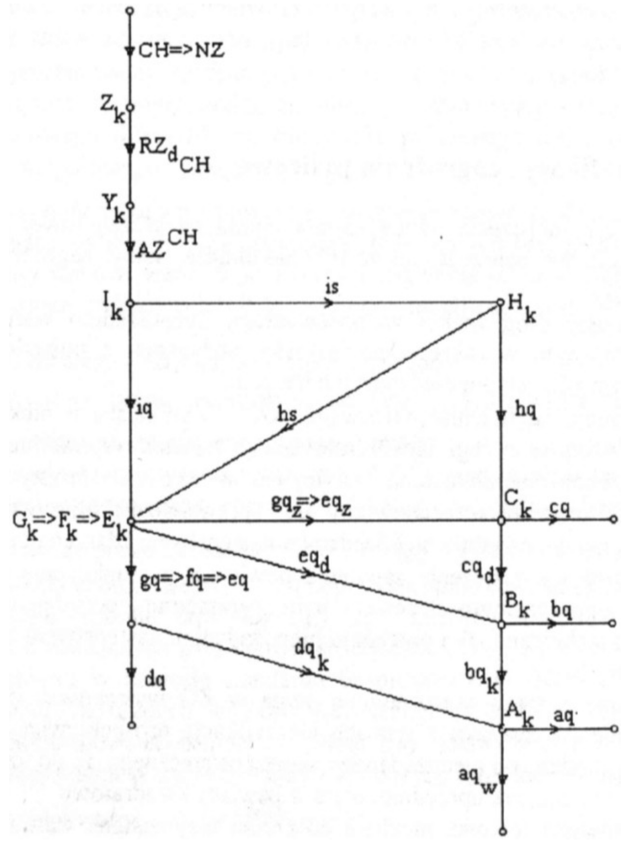

Figure 2. Causality of the pneumoconiosis – graph (Cichowski, 1999)

The graph shown in Figure 2 (representing the above formula) shows an additional causality, pneumoconiosis (branches graph), which consists of:

- 2 indirect causes *NZ* and RZ_{dCH};
- 6 direct causes AZ^{CH}, *iq*, *hq*, *gq*, *fq*, *eq*;
- 4 root causes *dq*, *cq*, *bq*, *aq*;
- 9 main conditions *is*, *hs*, gq_z, *eq*, eq_d, dq_k, cq_d, bq_k, aq_w (Cichowski, 1999).

Identification of the pneumoconiosis hazard is based on a detailed analysis of the undesirable events sequence preceding three states of hazard:

- the actual threshold of morbidity to the crew;
- activation of the pneumoconiosis hazard;
- uncontrolled air dust concentration.

Possible undesirable the events sequence preceding pneumoconiosis in the mining industry, constitutes the essence of the pneumoconiosis hazard, creating exploitation risk.

This risk, described by Cichowski (1999), consists of 17 causes (causes indirect and main conditions) that can be conditioned by 20 possible safety deficits (deviations from the prescribed safety levels on the side the parameters of work environment) and 27 possible deviations on the human side.

Conclusions

Building a security system, which the aim of eliminating harmfulness, as well as the identification of relative hazards, requires the determination of all significant components of the necessary events sequence preceding the results (losses) in the mining plant. To that end, the chain of necessary conditions preceding harmfulness is analyzed. The use of events theory elements to identify hazards very clearly shows the complexity of the harmfulness (loss) causes. This analysis provides a broad overview of the factors (direct and indirect) influence on events such as: accidents, material damage and occupational diseases in the workplace. During the events chain analysis hazards are identified, which are the causes of interim and final effects and the relationships between causes and effects (losses) in the mining industry.

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