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JÓZEF KABIESZ*

PRINCIPLES OF MODELLING ASSOCIATED HAZARDS

PODSTAWY MODELOWANIA ZAGROŻEŃ SKOJARZONYCH

Natural hazards occurring in mines that can interact by altering their states and forms are called "associated" hazards. Thus, traditional methods for assessing and predicting their states may appear unreliable. Therefore, a need arises to find certain of their definitions so that the above-mentioned shortcomings can be eliminated. This aim can be achieved using the conventional and normalised measures of hazard state assessment, by comparing or summing these hazards in an n-dimensional space and by creating linguistic characteristics of the interrelated coincidences. A suitable tool to accomplish this task is the "fuzzy sets" theory. This theory may additionally optimise the choice of sets of preventive measures, take into account their conflicts with the coexisting hazards and indicated a preference for the reduction of the dominant hazard.

Key words: mining industry; associated hazards; modelling

Naturalne zagrożenia górnicze są przyczyną występowania w kopalniach katastrof i innych gwałtownych zdarzeń (tabl. 1) kształtujących stan bezpieczeństwa. Na ich powstanie i przebieg czasami wpływ ma więcej niż jedno z nich (rys. 1). Analiza takich przypadków wskazuje na możliwość wzajemnego oddziaływania niektórych przejawów zagrożeń i skutków stosowanych profilaktyk na zagrożenia współwystępujące (rys. 2). Zjawisko takie nazywane jest zagrożeniami skojarzonymi (Kabiesz 2000). Nie jest to nowy rodzaj zagrożenia, a jedynie nowa, nietypowa forma ich manifestacji. Charakterystyczną cechą takich form zagrożeń są trudności w ocenie i prognozie ich stanów oraz efektywnej prewencji.

Dla oceny stanu zagrożenia bezpieczeństwa pracy w takich warunkach pomocna może być syntetyczna ocena stanu zagrożeń skojarzonych zakładająca, że jest ona funkcją (1), (2) i (3) stanów zagrożeń współwystępujących. Ze względu na fizyczną odmienność większości naturalnych zagrożeń górniczych, dla porównywania (sumowania) wartości ocen ich stanów wykorzystywane może być pojęcie przestrzeni zagrożeń (rys. 3), będącej zbiorem umownych bezwymiarowych wartości (5) odpowiadających stanom zagrożeń współwystępujących. Stosownie do praktycznych potrzeb przestrzeń tę (4) można podzielić na kryterialne przedziały stanu zagrożeń (rys. 4).

* GŁÓWNY INSTYTUT GÓRNICTWA, 40-166 KATOWICE, PLAC GWARKÓW 1

Specyficzne warunki środowiska kopalnianego, szczególnie w podziemnych kopalniach węgla kamiennego, powodują, że związki między zagrożeniami mogą być bardzo różnorodne i przejawiać się z dużym nasileniem, a skutki stosowanych metod profilaktycznych kolizyjne w stosunku do zagrożeń współwystępujących (rys. 5 i 6, zależności (6), (7), (8), i (9)). Jest to problem ściśle związany ze skutecznością i doborem profilaktyki. Szczególnie złożone sytuacje mogą zaistnieć w przypadku występowania tzw. zagrożenia dominującego, uznawanego zwykle, w sensie ryzyka zawodowego, za najbardziej niebezpieczne. W przyjętej konwencji modelu zagrożeń możliwa jest definicja zagrożenia dominującego uwzględniająca pojęcie kąta dominacji zagrożenia (rys. 7) oraz przestrzeni dominacji (rys. 8). Możliwe jest także zdefiniowanie kryteriów doboru profilaktyk.

Ocena i prognoza stanu zagrożeń skojarzonych oraz dobór profilaktyk wymagają znajomości charakterystyk wzajemnych oddziaływań między zagrożeniami oraz wpływu na nie skutków zastosowanych profilaktyk. W praktyce charakterystyki takie z konieczności tworzone są najczęściej w trybie werbalnych ustaleń eksperckich. Konieczność przekształcania tak formułowanych zależności skłania do podjęcia próby ujęcia ich w rygory logiki formalnej. Jest to możliwe w logice rozmytej, w której zagrożenia, charakterystyki oddziaływania między nimi i skutki stosowanych metod profilaktycznych mogą być przedstawiane w postaci modeli podlegających ścisłym regułom matematycznym. Górnicze zagrożenia naturalne można przedstawiać w postaci rozmytej (rys. 10, zależność (15) i (16)), podlegającej przekształceniom (rys. 12) odzwierciedlającym wzajemne koincydencje między nimi i efekty stosowania profilaktyk. Przekształcenia te mogą być realizowane według zbioru reguł wnioskowania lingwistyczno-funkcyjnego (18) lub lingwistycznego (19). Aktywizację każdej z reguł określa współczynnik aktywacji (20) będący wartością funkcji przynależności każdej zmiennej do zbioru rozmytego. Zbiór wynikowy jest sumą iloczynów współczynników aktywacji i przesłanek wnioskowania (21). W praktyce, szczególnie w przypadku występowania większej liczby zagrożeń oraz złożonych oddziaływań między nimi, ocena stanu zagrożeń skojarzonych i dobór najmniej kolizyjnych profilaktyk możliwy jest jedynie z wykorzystaniem numerycznych technik obliczeniowych.

Słowa kluczowe: górnictwo, zagrożenia skojarzone, model

1. Introduction

The safety of mining work, to a large degree, depends on the existence of natural hazards. The continual recording of casualties and disasters gives ample evidence of this and their intensity is proportional to the number and rate of the occurrences of such hazards and to the level at which preventive measures are applied. Modern preventive measures allow the potential consequences of the majority of hazards to be controlled. From an analysis of the origin and course of current mining incidents and catastrophic events, they are mostly seen to result from inadequate observance of the principles of work safety and from the atypical forms of hazard occurrence. The latter cause indicates that traditional understanding of hazards and the classical principles of preventive measures do not always guarantee sufficient effectiveness in combating hazards. It particularly refers to assessment and predictive methods and the choice and principles for selecting and using preventive measures.

The occurrence of atypical mining hazards is usually manifested when a number of different hazards occur simultaneously in the same place. They may then interact creating the so-called phenomenon of "associated hazards" (Kabiesz 2000). Under such circumstances these hazards can incorrectly be described by related hazard-state assessment methods and the effects of the applied methods of preventive measures may influence the coexisting hazards.

2. Consequences of the coexistence of hazards

Natural hazards in mines occur frequently, to the following factors:

- world-wide occurrence of natural circumstances inducing hazards,
- man-made technical actions leading to their appearance.

The mining-related hazards pose a serious problem of a technical, organisational and research nature.

Specific mining conditions are induced by:

- the geo-mechanically-dominant impact of associated rock masses on the environment,
- the limited space of mine workings,
- forced and restricted ventilation,
- the density of technical equipment in mine workings.

These factors cause the occurrence, in a typical underground mine of environmentally-related events which differ from those related to other working environments. The above factors are the basic ones that lead to unexpected and sudden mining disasters. High work-safety standards and the depletion of a simple means for their improvement have prompted the author to undertake non-typical, technical and organisational steps and to examine the more refined relationships associated with the phenomena related with hazards. The interaction between hazards can be classified in the category of phenomena, which has, hitherto, in practice, been neglected and only in exceptional cases has been taken into account.

2.1. The interaction between hazards

The studies and analyses of the interaction between natural mining hazards that have been carried out to date mostly involve hazards showing high physico-chemical similarity. Resulting from the analysis of many catastrophic disaster analyses, there are certain common features, indicating that the catalyst of such an event could mainly be attributed to the easily flammable, or even explosive mixture of methane and air. This mixture becomes the creator of very high temperatures and an air wave blast. Then, the coal dust cloud formation explodes. This process can frequently be repeated until the oxygen and/or volatile dust are depleted. Sometimes, in favourable conditions, flammable material such as coal bursts into flames causing exogenic combustion (Roszkowski et. al. 1997). In conditions of reduced oxygen availability, the coal combustion products may also consist of the following chemical compounds:

- methane gas,
- carbon monoxide,
- hydrogen,

- hydrocarbons,
- hydrogen sulphide.

On contact with the fresh, oxygenated air, these gases may explode. The process may also progress inversely, in that the fire constitutes the source of a methane gas explosion. The sequence of interrelated events may also include other factors, to be discussed later. A special role in mine disasters can be played by geo-mechanical, dynamic events such as mine tremors, rockbursts and roof falls, leading to further catastrophic hazards (Kabiesz, Konopko 1997). Rapid displacements of rocks, machines and mine equipment may initiate the ignition of methane gas and/or coal dust and the associated rock mass failure can lead to the occurrence of methane gas explosion or water hazards. Fig. 1 illustrates a probable sequence of catastrophic consequences of the most frequently occurring natural hazards. This sequence need not necessarily encompass all the hazard stages and it may assume a different forms.

The consequences of co-existing natural mining hazards do not have to be catastrophic in nature. For example, there are recorded cases of intense methane emission without ignition or explosion resulting from mine tremors and rockbursts. Well-known cases of such events from Polish hard coal mines (Matuszewski 1997) are summarised in Table 1.

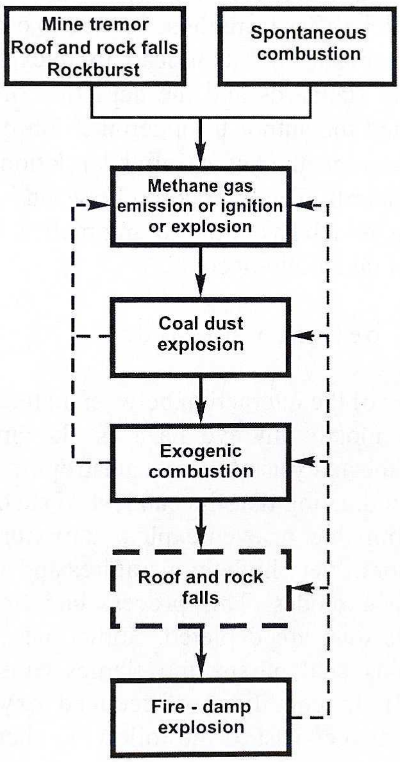

Fig. 1. Schematic of the sequence of the causes and effects of mine disasters

Rys. 1. Schemat przyczynowo-skutkowego następstwa zdarzeń katastrof górniczych

TABLE 1

Coexisting methane gas explosion and rockburst hazards

TABLICA 1

Współwystępowanie zagrożenia tąpaniami i metanowego

Coal mine	Date	Coal seam No.	Type of event
Nowy Wirek	10 June 1969	504	rockburst, increase in methane concentration up to 65%
Nowy Wirek	29 July 1978	510	rockburst, methane emission of 9500 m^3
Nowy Wirek	15 September 1978	510	rockburst, methane emission of 3300 m^3
Nowy Wirek	2 October 1978	510	rockburst, methane emission of 6800 m^3
Wawel	13 August 1979	507	rockburst, increase in methane concentration up to 5%
Halemba	7 March 1991	507	rockburst, increase in methane concentration up to 50%
Halemba	9 December 1993	506	rockburst, methane emission rate of 100 m^3/min
Zabrze- -Bielszowice	12 December 1996	507	rockburst, methane emission of 140 000 m^3
Śląsk	21 May 1999	502	mine tremor, methane emission of 11 050 m^3
Śląsk	25 August 1999	502	mine tremor, methane emission of 170 m^3
Śląsk	6 November 1999	502	mine tremor, methane emission of 630 m^3

Considering the analysis of such events, it may be found that the interactions can occur between the hazards either directly or indirectly when the indirect cause-effect relations model their occurrence states and forms.

We are faced with direct interactions when a characteristic parameter of a given hazard directly influences the state of another hazard. A typical situation can be a coal dust explosion initiated by the methane gas explosion effects (blast air wave, high temperature) or a methane gas explosion initiated by rockburst effects (convergence in mine workings resulting in emission and ignition of methane).

The indirect interactions involve changes in some properties of the work environment, which, whilst not considered to be directly associated with the hazards may influence the parameters modelling the states of other hazards. Such situations may arise from the roof falls and rockbursts when the rock mass failure-related damage to mine workings leads to changes in ventilation conditions. As a result, changes in the state of methane gas explosion risk and fire hazards can occur.

The most frequently occurring cause-effect relations are as follows (see Fig. 2):

- emergence of another so far non-existent or latent hazard,
- changes in the occurrence-rate of another hazard,

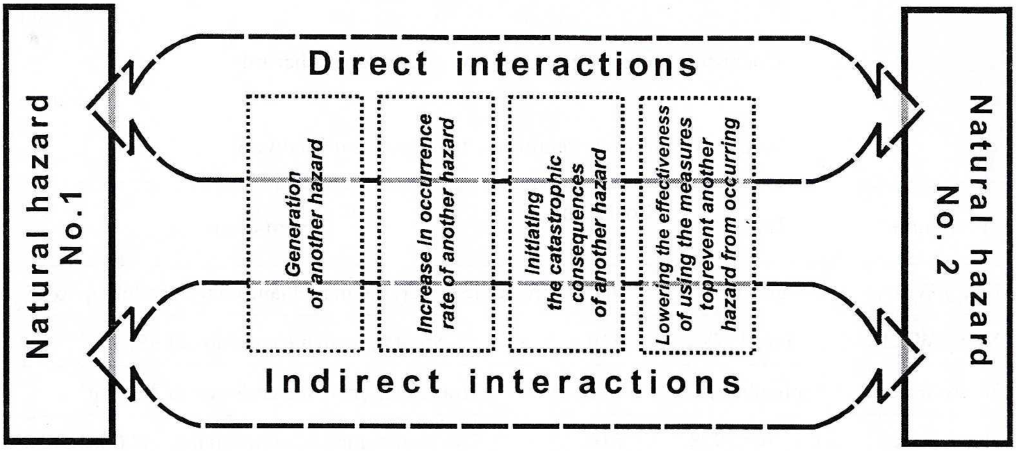

Fig. 2. Interactions between hazards

Rys. 2. Oddziaływania między zagrożeniami

- initiation of catastrophic consequences of another hazard,
- lowering the effectiveness of using measures to prevent another hazard from occurring.

The essence of these events and their systematisation allows us to generally define the associated hazard (Kabiesz 2000) as being those coexisting natural hazards that mutually interact with their initiation, intensity and the occurrence forms.

3. Assessment of the state of associated hazards

The assumption can be made that the state of associated hazards, *SZS*, is a function of the states of coexisting hazards SZ_1, SZ_2, ..., SZ_n defined as:

$$SZS = f(SZ_1, SZ_2, ..., Sz_n) \tag{1}$$

or, in particular, a union or sum of the states of individual coexisting hazards *SZ* defined as:

$$SZS = \cup_i SZ_i \tag{2}$$

Each hazard has its own fixed path of determination.

To this end, various physico-chemical, mechanical and also conventional quantities can be used. Comparing them directly with each other and, particularly, summating them is often impossible. Therefore, it is necessary to create an environment and tools that may perform such operations. Such an environment can only consist of conventional, dimensionless values, the set of which, designed for the assessment of the state of associated hazards will be called the "hazards space". The parameter describing the state of associated hazards is the value of a distance of each point of the space from the origin of the co-ordinate system forming the constitutive hazards. In the Cartesian co-ordinate system, it can be expressed as:

$$SZS = \sqrt{\sum_{i=1}^{i=n} (SZ_i)^2} \tag{3}$$

Fig. 3 illustrates the graphical interpretation of the *SZS* index for a case involving three hazards. The position of point *SZS* uniquely determines the resultant state of hazard, as well as the states of the constitutive hazards. From the mathematical point of view, a similar conceptual procedure for the n dimensional space can be imagined. Performing any logical operations in the hazard-space requires an estimate of each state of hazard to be converted into a conventional quantity contained within the criteria range uniformly made for all hazards. First of all, we assume that the criterion-based values of the state of constitutive hazards are contained in the range:

$$0 \le (SZ_i) \le 100 \tag{4}$$

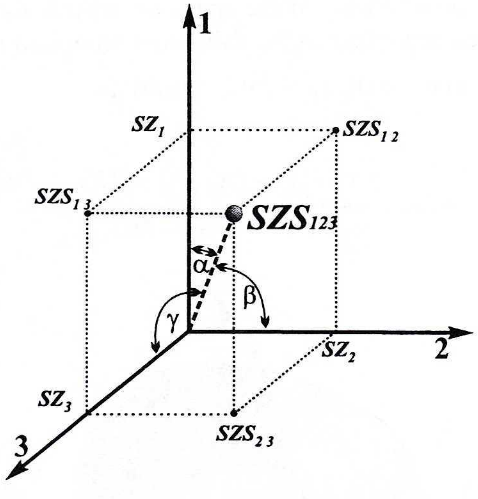

Fig. 3. Model of summating the estimates of the states of associated hazards in the hazard-space

Rys. 3. Model sumowania ocen stanów zagrożeń skojarzonych w przestrzeni zagrożeń

The value of 0 denotes the lack of occurrence of a given hazard, while the value of 100 denotes high hazard risk. Values in excess of 100 correspond to dangerous situations. Next, the boundary conditions for the intermediate criteria states are determined followed by normalisation principles using estimation scales. This procedure can be accomplished by analysing interrelations between the estimates of each hazard state and the criteria for dividing the states into particular degrees, groups, classes or categories. The above considerations have led to the elaboration of five hazard-state criteria ranges bounded by maximum and minimum values of SZ_i. The hazard states can be defined as follows:

1) state a denotes the absence of hazard determined by the index $SZ_i \leq 0$;
2) state b denotes low hazard risk determined by the index in the $0 < SZ_i \leq 25$ range;
3) state c denotes average hazard risk determined by the index in the $25 < SZ_i \leq 50$ range;
4) state d denotes the high hazard risk determined by the index in the $50 < SZ_i \leq 100$ range;
5) state NB denotes dangerous conditions determined by the index $SZ_i > 100$.

The above classification allows the determination of the following criterion-based states of associated hazards (see Fig. 4) with corresponding maximum values of the *SZS* index, calculated for three hazards with a safety factor of 15%:

- hazard state a $SZS_{max} = 0$,
- hazard state b $SZS_{max} = 36.8$,
- hazard state c $SZS_{max} = 73.6$,
- hazard state d $SZS_{max} = 147.2$,
- hazard state NB $SZS_{max} > 147.2$.

A rationalisation of the estimates of the states of hazards for the bilaterally closed intervals can be achieved according to the following empirical relationship:

$$SZ_i = [x_i + (DG_{SZ_i} - DG_i \pm 0.001)] + \tag{5}$$

$$+ (x_i - DG_i)\frac{(GG_{SZ_i} - DG_{SZ_i}) - (GG_i - DG_i)}{GG_i - DG_i}$$

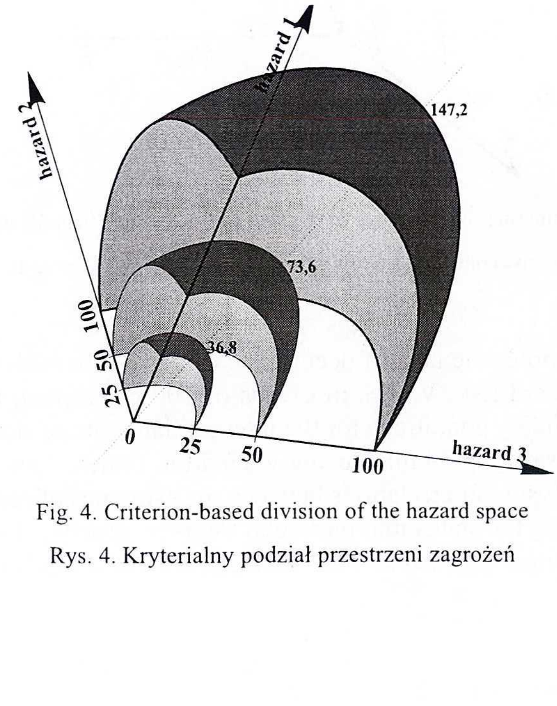

Fig. 4. Criterion-based division of the hazard space

Rys. 4. Kryterialny podział przestrzeni zagrożeń where:

SZ_i — is the conventional estimate of the i^{th} hazard state,

DG_{SZ_i} — is the conventional lower boundary-value of the criteria range of a given degree of the i^{th} hazard,

GG_{SZ_i} — is the conventional upper boundary-value of the criteria range of a given degree of the i^{th} hazard,

DG_i — is the lower boundary-value of the criteria range of a given degree or category of a group of the i^{th} hazard,

GG_i — is the upper boundary-value of the criteria range of a given degree or category of a group of the i^{th} hazard,

X_i — is the estimate of the state of the i^{th} hazard.

The estimates of the states of individual hazards summed over the hazard-space should take into account their interactions. It requires a development of the relevant characteristics which, in practice, are mostly selected by means of subjective, expert analyses.

4. Principles of the selection of preventive measures

The effects of using preventive measures do not always have to be beneficial for each coexisting hazard. Such a statement appears to be surprising as all the preventive measures methodologies have been developed and used to improve work safety. Such a condition really exists in simple and explicit situations when hazards occur individually. This inconsistency disappears, however, in more complex situations when the effects of using preventive measures lead to changes in the properties of rock masses, mine-atmosphere, rock support, etc., influencing the coexisting hazards (see Fig. 5).

It may then so happen (Kabiesz, Konopko 2001) that these effects, while advantageously influencing the state of a given hazard, lead to the other hazard occurrences. They also increase the rate of other hazard occurrences and reduce the feasibility of effective use of other preventive measures. The selection of preventive measures must be based on the assessment of their effectiveness on all hazards occurring at a given site. The direct assessment of the effectiveness of such preventive measures is usually a very difficult and complicated task, sometimes even impossible. In such cases, a differential assessment of the state of hazards prior to and following the utilisation of preventive measures may be applied. Fig. 6 illustrates a conceptual method of assessing the interactional effect of preventive measures by using an assumed, vectorial representation of hazard states.

On vectorially adding, in the hazards space, the states of constitutive hazards $\overrightarrow{SZ_1}$ and $\overrightarrow{SZ_2}$ and the associated hazards $\overrightarrow{SZS_{12}}$ to the preventive measures interaction affects

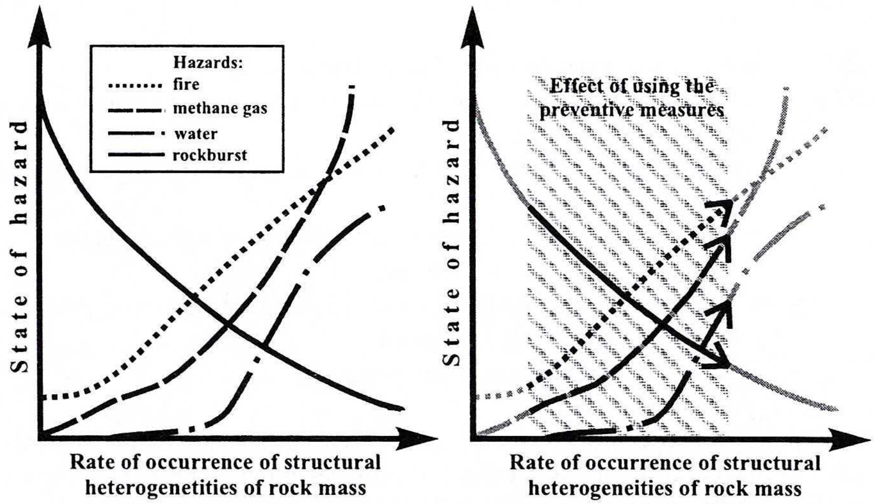

Fig. 5. The impact of preventive measures on the states of coexisting hazards

Rys. 5. Wpływ profilaktyki na stany zagrożeń współwystępujących

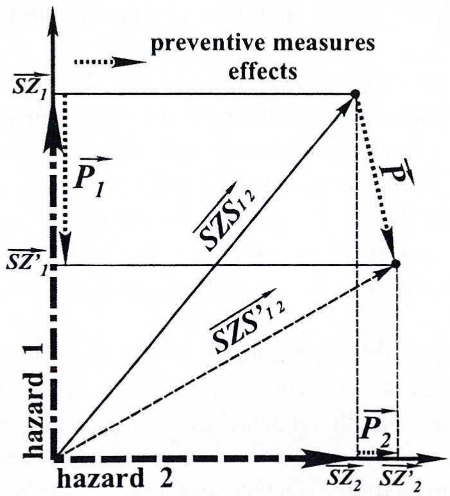

Fig. 6. The interaction effect of preventive measures on the state of associated hazards No. 1 and 2

Rys. 6. Oddziaływanie skutków profilaktyk na stany skojarzonych zagrożeń 1 i 2

vector $\vec{P}$ or its components $\vec{P_1}$ and $\vec{P_2}$.We thereby obtain a new state of constitutive hazards $\vec{SZ'_1}$ and $\vec{SZ'_2}$ and the associated hazards $\vec{SZS'_{12}}$. Its corresponding to the state created following the application of preventive measures (see relations 6, 7 and 8). These relations can be expressed as:

$$\vec{SZ_1} + \vec{P_1} = \vec{SZ'_1} \tag{6}$$

$$\vec{SZ_2} + \vec{P_2} = \vec{SZ'_2} \tag{7}$$

$$\vec{SZS_{12}} + \vec{P} = \vec{SZS'_{12}} \tag{8}$$

where:

$\vec{SZ_1}$, $\vec{SZ_2}$ — are the hazard states prior to the application of preventive measures,

$\vec{SZ'_1}$, $\vec{SZ'_2}$ — are the hazard states following the application of preventive measures,

$\vec{SZS_{12}}$ — is the state of associated hazards prior to the application of preventive measures,

$\vec{SZS'_{12}}$ — is the state of associated hazards following the application of preventive measures,

$\vec{P}, \vec{P_1}, \vec{P_2}$ — are the interaction effects of preventive measures.

The criteria of conflicts of the interaction effects of preventive measures can be defined as:

$$SZ_i - SZ'_i = \pm\Delta SZ_i \tag{9}$$

where:

SZ_i — is the estimate of the i^{th} hazard state prior to the application of preventive measures,

SZ'_i — is the estimate of the i^{th} hazard state following the application of preventive measures,

$\pm\Delta SZ_i$ — is the difference between the estimates of the i^{th} hazard state; the "+" sign denotes the lack of a conflict occurrence, the "–" sign denotes the conflict occurrence.

The interaction effects of preventive measures may constitute a complex phenomenon, particularly, if their number is large and the so-called *dominant hazard* considered to be the most dangerous occurs. Because we usually attach great importance to lowering this hazard state, the rational selection of preventive measures may be jeopardised. It requires that the concept of dominant hazard be defined in the hazard space. The introduction of concepts of an angle of domination and a space of domination could achieve a solution. When it appears that the states of all the given, constitutive hazards are equal part in the resultant state of associated hazards *SZS* and the angles α, β and γ in the hazards space made by each constitutive hazard, with the associated hazards can approximately be equal to 55° (see Fig. 3).

For $SZ_1 = SZ_2 = SZ_3$

$$\alpha = \beta = \gamma \approx 55^\circ \tag{10}$$

If we, for example, assume that the dominant hazard, i.e. the most dangerous one, is hazard No. 1, which can usually be its estimate, then the angle α between hazard No. 1 and the associated hazards *SZS'* may be less than 55°. This implies that the "domination" of hazard No. 1 can be defined by the value of the difference between angles 55° and α expressed as 55° — α (see Fig. 7). The domination space of a dominant hazard is the interior of the cone sector surface of the vertex located in the origin of co-ordinates of the hazard space and has an apex angle equal to the domination angle of a given hazard. The base is bounded by a plane parallel to the plane defined by the remaining two hazards Nos. 2 and 3 and the *SZS'* value (see Fig. 8).

If n hazards are taken into account, the corresponding domination space will be a similar n-dimensional geometric figures and solids. If can be assumed that the application of preventive measures to such conditions would be efficient if a "new" state of associated hazards *SZS''* were acceptable and the volume of the dominant space of a dominant hazard were reduced. The dominant hazard can be the hazard that will be the highest in the working environment. It can be assumed that during the use of preventive measures, some hazards might be allowed to increase if this led to a substantial reduction in the state of dominant hazard.

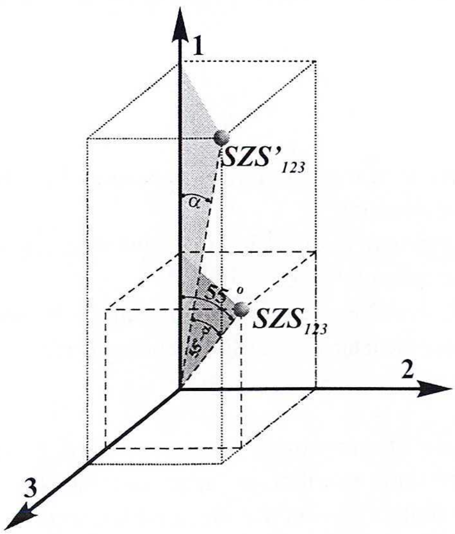

Fig. 7. The domination angle of a dominant hazard in the hazards space

Rys. 7. Kąt dominacji zagrożenia dominującego w przestrzeni zagrożeń

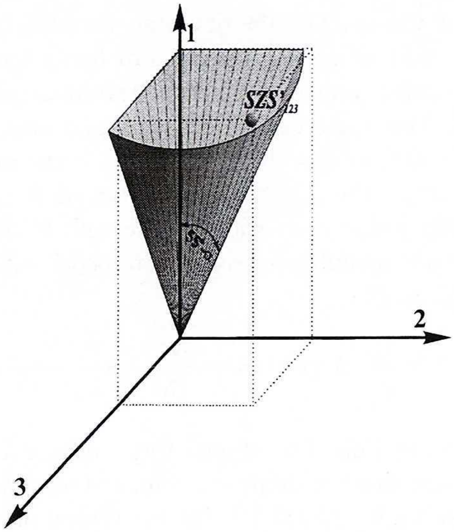

Fig. 8. The domination space of a dominant hazard in the hazards space

Rys. 8. Przestrzeń dominacji zagrożenia dominującego w przestrzeni zagrożeń

5. Hazards interaction characteristics

The assessment of the state of associated hazard requires consideration of their interaction characteristics and the effects of using preventive measures. The traditional methods for assessing and predicting the states of individual hazards do not provide information about this matter and do not take them into account. For practical reasons, experts are busy to determine concrete values for the coefficients (weights) to modifying the assessment parameter values and to make a verbal statement directly correcting these assessments. This procedure can also be burdened the many disadvantages of the officialdom. The characteristics of verbal interaction can be rearranged within the framework of formal logic.

5.1. Fuzzy logic

Man, in his everyday life, can efficiently govern complex systems, as for instance driving a car during heavy traffic, mostly using an inaccurate description of the state of the system. People can subconsciously use rules of approximate reasoning, multivalued logic, etc. (Wanat, Kabiesz 2000). In evaluating the state of an object, numbers can often be replaced with the terms such as much, little, safety, faster, etc.

The domain of such a description of the world is multivalued logic, the first precursors of which date back to the ancient times (Heraklit, Platon). Its systematic principles for the three-value logic was given by Łukasiewicz (Łukasiewicz 1957) in the twenties of the 20th century who introduced the formalised notation and the system of axioms. Multivalued logic was used for the first time thanks to the studies carried out by Lotfi A. Zadeh (Zadeh 1965), where the concepts of fuzzy sets and, in general, fuzzy logic were defined. In recent years, its intense development and wider and wider use have been observed. This logic can objectively take into account and accurately transform human judgements expressed linguistically. It encourages one to attempt to utilise the principles of fuzzy logic in the description of the associated hazards and particularly, in the way in which their state is assessed. In the classic two-value, or binary logic, each value has unambiguously determined limits separating it from the other values. It can be defined as:

$$\underset{x \in X}{\forall} X_A(x) = \begin{cases} 1 & \text{for} \quad x \in A \\ 0 & \text{for} \quad x \notin A \end{cases} \tag{11}$$

which implies that X_A is a function of set A returning universe X to set $\{0,1\}$. This is the two-valued membership function confining the course of reasoning to alternative values either 0 or 1. With fuzzy logic (Zadeh 1965), this limitation was removed by using the continuous or discrete form of membership function α_A that returns universe X anywhere in the interval from 0 to 1, inclusive [0,1] (see Fig. 9a and 9b).

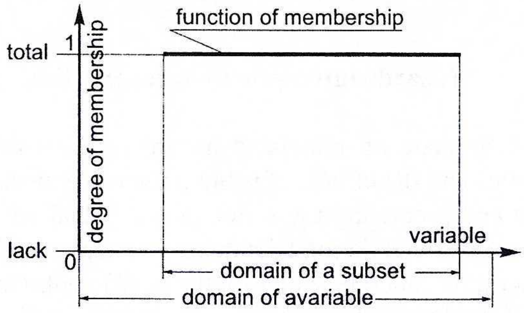

Fig. 9a. Classic set

Rys. 9a. Zbiór klasyczny

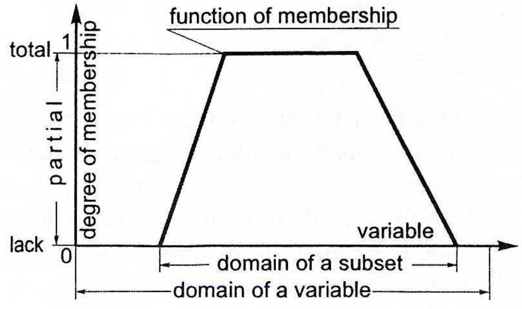

Fig. 9b. Fuzzy sets

Rys. 9b. Zbiór rozmyty

Therefore, the following relations can be written:

$$\alpha_A\colon X \to [0,1] \tag{12}$$

$$\alpha_A(x) \in [0,1] \tag{13}$$

$$A = \{(x, \alpha_A(x))\} \text{ for } x \in X \tag{14}$$

using the fuzzy logic theory as defined above, we may perform mathematical operations and modelling that meet the formal logic technique requirements.

5.2. The fuzzy logic hazard model

The hazards, including natural mining hazards, can scarcely be precisely and objectively defined. In practice, numerically or descriptively defined hazard state values are used producing their characteristics, as for example, in the form of low, average and high hazards. Knowing the type or name of the hazard, its state and characteristics in numerical form or as a linguistic description, we can, in the consolidation process, present it either in the fuzzy logic form (Wanat, Kabiesz 2000) as:

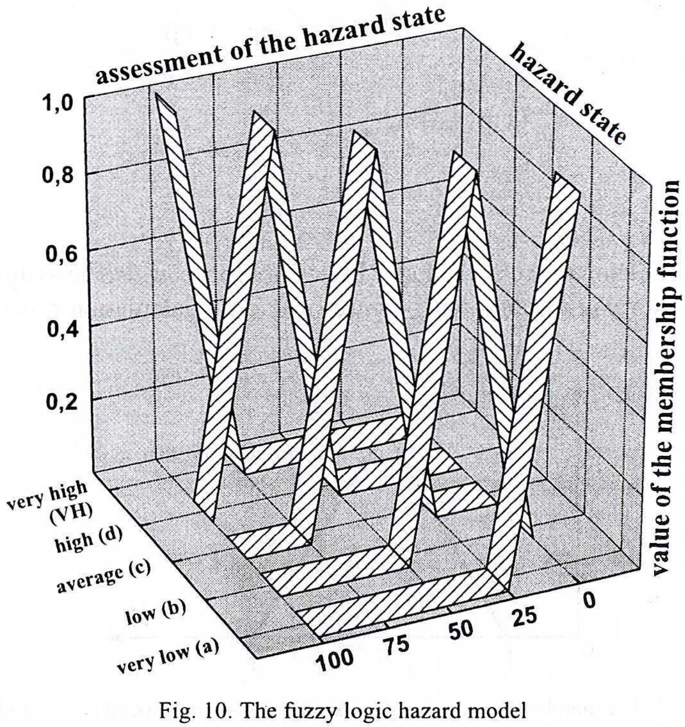

Fig. 10. The fuzzy logic hazard model

Rys. 10. Rozmyta postać pojęcia „zagrożenie"

$$Z=\left(\frac{\alpha_1}{x_1},\frac{\alpha_2}{x_2},\ldots,\frac{\alpha_i}{x_i}\right) \tag{15}$$

where:

Z — is the hazard,

α_i — is the value of the membership function,

x_i — is the estimate of the hazard state,

or in the hierarchical-structure form (see Fig. 10).

The concept of the hazard state hierarchical structure has arisen from work safety classification needs. In practice, we always take an interest in the occurrence rate of a given hazard in relation to the permissible safety level. Therefore, hazard states have been systematised in an increasing order forming a system of classes, degrees, categories, etc. Fig. 10 shows five such classes from "a" to "VH" valid in Poland for some mining hazards. Using the above-defined concepts, we can perform any logic operations, including their conversion into other fuzzy logic concepts representing changes in hazard states.

The shape of the membership function for the criterion-based hazard standards has been assumed to be straight lines forming the arms of an isosceles triangle (Fig. 11) defined by the following relations:

$$\alpha_{x_i}(x,\beta,\gamma,\delta)=\begin{cases}0 & \textit{for} \quad x<\beta\\ \dfrac{x-\beta}{\gamma-\beta} & \textit{for} \quad \beta\le x\le\gamma\\ \dfrac{\delta-x}{\delta-\gamma} & \textit{for} \quad \gamma\ge x\ge\delta\\ 0 & \textit{for} \quad x\ge\delta\end{cases} \tag{16}$$

In the defusification process, the fuzzy logic concepts can also be assigned numerical values mostly by using the following centre-of-gravity calculation procedure:

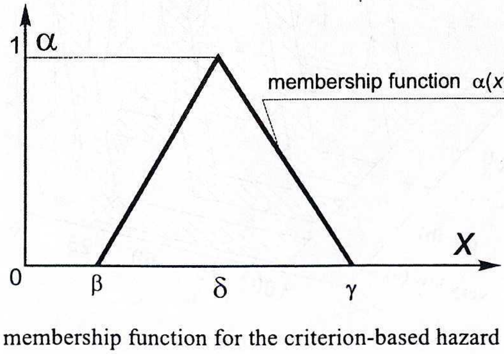

Fig. 11. The membership function for the criterion-based hazard state standard

Rys. 11. Funkcja przynależności kryterialnego wzorca stanu zagrożenia

$$x = \frac{\sum_{i=1}^{i=n} \alpha_{A_i} x_i}{\sum_{i=1}^{i=n} \alpha_{A_i}} \tag{17}$$

5.3. Modelling the characteristics of the interaction between hazards and preventive measures

As a result of using preventive measures and the interaction between hazards, the states of the hazards undergo changes. The characteristics of these changes are fundamental for assessing the state of associated hazards and for selecting the optimal package of preventive measures to combat all the coexisting hazards. According to the fuzzy logic theory, these characteristics can be formed through the fuzzy judgements involving the evaluation of outputs from inputs using the set of fuzzy logic rules. This procedure enables the experts to utilise their knowledge in forming the hazard state conversion modifier.

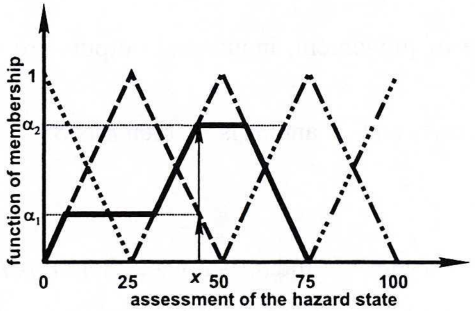

Fig. 12a. The fuzzy logic hazard state estimate model before conversion

Rys. 12a. Rozmyty model oceny stanu zagrożenia przed przekształceniem

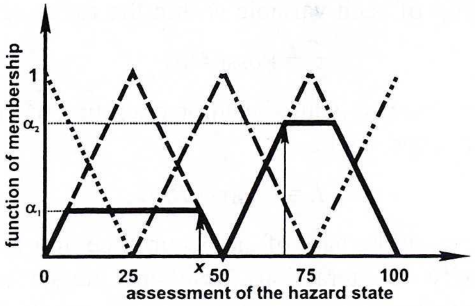

Fig. 12b. The fuzzy logic hazard state estimate model after conversion

Rys. 12b. Rozmyty model oceny stanu zagrożenia po przekształceniu

Any estimate of the hazard state determines the fuzzy logic form of a model of this hazard state (Fig. 12a). On applying the fuzzy logic rules to the conversion modifier, this model can be converted into the result form corresponding to a new hazard state as, for example, that arising from using preventive measures (Fig. 12b).

Judgement on the way in which the conversion is made, can be based on the Takagi-Sugeno or Mamdani models (Takagi, Sugeno 1985; Mamdani 1977). The Takagi-Sugeno judgement is the linguistic-functional type of judgement, where the successors are given as a function of objective knowledge in the form defined as follows:

$$\begin{array}{l} \text{if } a_1 \text{ is } A_1 \text{ and } \dots \text{ and } a_n \text{ is } A_n \text{ then } b_1 = f_1(a) \\ \text{also} \\ \dots\dots\dots \\ \text{also} \\ \text{if } a_1 \text{ is } A_2 \text{ and } \dots \text{ and } a_n \text{ is not } A_m \text{ them } b_2 = f_2(a) \end{array} \tag{18}$$

where:

a_1, a_n, a_m, b are the linguistic variables,

A_1, A_n, A_m, B_1, B_m are the fuzzy subsets.

In the Mamdani type of judgement, inputs and outputs are the linguistic concepts defined as follows:

$$\begin{array}{l} \text{if } a_1 \text{ is } A_1 \text{ and } \dots \text{ and } a_n \text{ is } A_n \text{ then } b \text{ is } B_1 \\ \text{also} \\ \dots\dots\dots \\ \text{also} \\ \text{if } a_1 \text{ is } A_2 \text{ and } \dots \text{ and } a_n \text{ is not } A_m \text{ them } b \text{ is } B_m \end{array} \tag{19}$$

The "is" rule designates the membership of the fuzzy set and "and" symbolises the intersection denoted by $\cap$.

The output of the whole model is the superposition of outputs of individual criteria. The activation of each rule depends on the value of activation factor τ, which is the value of a degree of membership of each variable within the fuzzy set, that is:

$$\tau_i = \text{Poss}(A/B) \tag{20}$$

Set of results E can be obtained using the union operation of the product of activation factors τ_i and premises B expressed as:

$$E = \cup_{j(i)} \tau_i \cdot B_j \tag{21}$$

In practice, particularly, in the case of the occurrence of a large number of hazards and the related complexity of interactions, assessing the state of associated hazards and selecting the least conflicting preventive measures would only be possible if the numerical, computational technique were utilised.

Conclusions

The natural and mining-related hazards occurring in mines can interact, influencing their formation and states and reducing effectiveness of preventive measures. Ample evidence of the real occurrence of such phenomena is the mine disasters and other violent events arising from more than one hazard. The effects of the interaction between hazards can considerably influence the state of work safety, which is sufficient to warrant carrying out relevant studies and descriptions.

The problems considered in the paper give the reasons for drawing the following conclusions and statements:

1. The natural mining hazards interacting between themselves and preventive measures can be defined as associated hazards, which is considered to be a new quality in the problem of the occurrence of mining hazards.
2. Associated hazards may not always be properly described by the current assessment and prediction methods of their states and efficiently combated by the preventive measures.
3. The method of assessing the states of associated hazards taking into consideration the current mine-based systems for combating them is based on the conventional, dimensionless values forming a set called the hazards space. It is proposed to divide this space into the following five hazard state criteria ranges or classes: a, b, c, d and VH.
4. To carry out the summation operation of the states of individual hazards from the hazard space, it is necessary to normalise the values of the states of all the coexisting hazards.
5. In conditions of the associated hazards, there may occur conflicts of the preventive measures application effects, which may create a need to develop the optimization of hazard selection.
6. The criteria of the selection of preventive measures should be as follows:
   - lowering the state of associated hazards to the permissible value,
   - dominant hazard state reduction preference.
7. To assess the state of associated hazards and the effects of preventive measures, a definition of their characteristics is necessary, which, with few exceptions, would only be possible to obtain by way of expert decisions.
8. A suitable tool for describing the hazards and the relating interaction characteristics can be the fuzzy logic set theory, according to which a relationship between the objective, practical experience becomes obtainable.

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REVIEW BY: PROF. DR HAB. INŻ. NIKODEM SZLĄZAK, KRAKÓW

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