# DIVING TECHNOLOGY DESIGN IN A MINE COUNTERMEASURE SYSTEM PART II RELIABILITY

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## ABSTRACT

The article is another paper in an unintended series on designing the technology of diving [1,2,3]. It refers to the elements of the methodology[1] used in the works to develop the technology of using the Mx/O_2-SCR CRABE SCUBA[2] type diving apparatus in the mine countermeasure system as an example [4,5]. The previous article focused on the impact of the NATO Standardization Organization requirements on the purpose of the main process implemented in the system that constitutes the aforementioned diving technology. The present article discusses the reliability of the process implemented in the system.
**Keywords:** diving technology, reliability, mine countermeasure.

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## INTRODUCTION

The analysis of the underlying causes of problem situations, based on the functional properties of the *system* structure, may be carried out with the use of various methods: $FMEA$[3], $FMECA$[4], $PHA$[5], $FHA$[6], $DFM$[7], *success path models*[8], *event trees*[9] $FT$[10] as well as other *discriminant analysis methods* etc. An example of utilising $FMEA$ methods was discussed earlier in a series of articles [2]. *Discriminant analysis methods* form a basis for building artificial intelligence $AI$[11] and are used in quantitative risk assessment.

## RISK AND HAZARD

In everyday language, risk and hazard function as synonyms. Here hazard $Z$ is defined as the integral value of risk $R$: $Z = f(R) = \int_t R\,dt$, where $t$ is the time of exposure to risk $R$. When analysing a problem situation, the risk $R(t)$ and hazard $Z(t)$ functions should be given explicitly, since the general integration operation[12] can only be performed with an accuracy of the offset value of a constant value $a = const$ , which value $(a)$ can be important in the process of risk analysis with the problem situation under consideration.

## ACQUISITION OF DATA FOR ANALYSIS

Quantitative estimation of risk $R$ requires knowledge of the probability of individual events. They are obtained by way of: analysing archival data during the utilisation of the analysed *systems*[13] based on the knowledge collected so far, theoretical calculations[14], information obtained as a result of various studies[15] and testing[16].

There are different opinions on how to use data, depending on its origin. From a practical point of view, the only data to be used is that which very well reflects the *processes* that are based on the structure of the analysed *system*. The data should reflect the broadest possible spectrum of how the *process* implemented based on the analysed *system* structure behaves, in order to ensure proper scenario prediction for the course of events that may occur in the future. When using the available data, it is important to keep in mind that a safety assessment may involve many complex interactions between the variables that characterize the *processes* taking place. The descriptive methods of estimating risk $R$ provide a qualitative assessment of hazards[17], which in many situations is inadequate, as it does not provide an opportunity to compare risks between different *processes* that occur in problem situations under consideration[18]. The use of analytical methods based on statistical methods can lead to a sufficiently consistent, quantitative assessment of risk $R$ and, on that basis, the predicted hazard, although sometimes the use of probabilistic methods and data can also lead to significant discrepancies in risk assessment $R$ for predicted events. A situation like that can occur when there are spurious interactions/correlations[19] in place between the *processes* under consideration.

In order to reliably assess the probability of a phenomenon, a relatively large population is needed, as basing statistical inference on a small sample can be subject to significant errors of the first[20] and second kind[21], which can lead to completely unauthorized conclusions [6].

Data for hazard analysis is often provided in a selected reference time section[22]. Such statistics can vary significantly, depending on the selected time period[23].

## RELIABILITY

Risk analysis[24] $R$ is an element of security management which ensures the orderly and consistent operation of the system in terms of its continued suitability to ensure trouble-free execution of *processes* that the *system* developers are interested in. Risk analysis $R$ is linked to the *reliability model* of the structure of the analysed *system*.

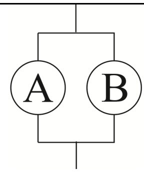
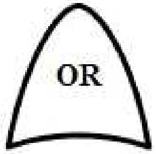
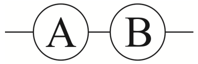
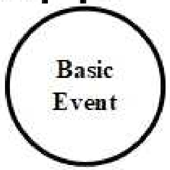
In the *reliability model* the existing real interactions[25] are replaced with a *model* that reproduces the reliability of this *structure*, which often differs from the physical structure of the system by the interactions that occur. For example, if in a lighting *system* with a structure that consists of two light points, whose mutual physical interaction is that they are connected in parallel, it is required that both of them shine[26], the structure of this *system* has a serial reliability structure.

## MODEL

Various reliability models can be assumed, but *event trees* are the ones which are most commonly used. The method based on *event trees* involves the notation of deterministic relations between cause and effect using *Boolean* algebra. In risk analysis for the *systems,* one encounters applications of this method which show the relationships presented in Table 1.

Tab. 1

Basic operators used in the construction of event trees and Markov chains [27].

| Type of operation | Action | Structure | Symbols for the event tree | Relations of the set theory[28] | Boolean operators | Engineering symbols |
|---|---|---|---|---|---|---|
| Substitution *OR* (or) | must act A or B or simultaneously A and B† |   |   | ∪ | ∨ | + |
| Cut *AND* (and) | must act A and B |   |   | ∩ | ∧ | . or · |
| Contradiction | contradiction of action | |  | ~ | ¬ | ⬚ |
| Output/ input | continuing the tree structure elsewhere | |   | | | |
| Event | A occurred | |   | | | |

Tab. 2

Principles of Boolean algebra.

| | Relations in the set theory | Engineering relations | Right |
|---|---|---|---|
| 1a | $A \cap B = B \cap A$ | $A \cdot B = B \cdot A$ | commutative |
| 1b | $A \cup B = B \cup A$ | $A + B = B + A$ | |
| 2a | $(A \cap B) \cap C = A \cap (B \cap C)$ | $(A \cdot B) \cdot C = A \cdot (B \cdot C)$ | associative |
| 2b | $(A \cup B) \cup C = A \cup (B \cup C)$ | $(A + B) + C = A + (B + C)$ | |
| 3a | $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$ | $A \cdot (B + C) = (A \cdot B) + (A \cdot C)$ | distributive |
| 3b | $A \cup B)(A \cup C)$ | $A + (B \cdot C) = (A + B) \cdot (A + C)$ | |
| 4a | $A \cap A = A$ | $A \cdot A = A$ | idempotence |
| 4b | $A \cup A = A$ | $A + A = A$ | |
| 5a | $A \cap (A \cup B) = A$ | $A \cdot (A + B) = A$ | absorption |
| 5b | $A \cup (A \cap B) = A$ | $A + A \cdot B = A$ | |
| 6a | $\bar{A} \cap A = \emptyset$ | $\bar{A} \cdot A = \emptyset$ | complement |
| 6b | $\bar{A} \cup A = \Omega$ | $\bar{A} + A = \Omega = 1$ | |
| 7 | $\sim(\sim A) = A$ | $\bar{\bar{A}} = A$ | double negation |
| 8a | $\sim(A \cap B) = \sim A \cup \sim B$ | $\overline{A \cap B} = \bar{A} \cup \bar{B}$ | De Morgan's |
| 8b | $\sim(A \cup B) = \sim A \cap \sim B$ | $\overline{A \cup B} = \bar{A} \cap \bar{B}$ | |
| 9a | $\emptyset \cap A = \emptyset$ | $\emptyset \cdot A = \emptyset$ | operations on empty sets and the whole space |
| 9b | $\emptyset \cup A = A$ | $\emptyset + A = A$ | |
| 9c | $\Omega \cap A = A$ | $\Omega \cdot A = A$ | |
| 9d | $\Omega \cup A = \Omega$ | $\Omega + A = \Omega$ | |
| 9e | $\sim\emptyset = \Omega$ | $\bar{\emptyset} = \Omega$ | |
| 9f | $\sim\Omega = \emptyset$ | $\bar{\Omega} = \emptyset$ | |
| 10a | $A \cup (\sim A \cap B) = A \cup B$ | $A + \bar{A} \cdot B = A + B$ | simplifying operations |
| 10b | $\sim A \cap (A \cup \sim B) = \sim A \cap \sim B = \sim(A \cup B)$ | $\bar{A} \cdot A + \bar{B} = \bar{A} \cdot \bar{B} = \overline{A + B}$ | |

where: $X$ –denotes the result of event $X$, $X.Y$ –denotes the result of event $X$ and $Y$, $X + Y$ –denotes the result of event $X$ or $Y$, $\bar{X}$ –denotes the result of event opposite to event $X$, $\Omega$; $1$ –denotes a certain event, $\emptyset$ –denotes an impossible event

The analyses that use *event trees* are implemented in two ways. *The hazard tree* is analysed using the 'top-down' deduction method to look for the underlying causes of the problem situation. This approach is often used in engineering to analyse the risk of operational reliability $R$ for the designed *systems.*

*The cause tree* is analysed in the bottom-up approach, and shows the impact of various events on the safeguarding of the possibility of uninterrupted *process* execution by the *system*. This approach can be used for risk analysis $R$ of designed systems, although it is more commonly used for risk analysis $R$ during the operation of systems.

## RELATIONS

Table 2 collects the principles of *Boolean* set algebra. Fig. 1 schematically shows the probability of a conditional event $P(A|B)$, which can be noted in the form of an equation: $P(A|B) = \frac{P(A\cap B)}{P(B)}$, hence in general for event $A \cap B$, which runs sequentially —(A)–(B)—, denoted in Tab. 1 as a gate $AND$, can be noted as:

$$P(A \cap B) = P(A|B) \cdot P(B)$$

where: $P(A)$ –denotes the probability of event $A$, $P(A \cap B)$ –denotes the probability of event $A$ and $B$, $P(A|B)$ –denotes the probability of event $B$ occurring under the condition of a prior occurring of event $A$.

For independent events $P(A|B) \equiv P(A)$, hence the relation (1) can be rewritten to a simpler form – Tab. 3:

$$\forall_{P(A|B)\equiv P(A)} \quad P(A \cap B) = P(A) \cdot P(B)$$

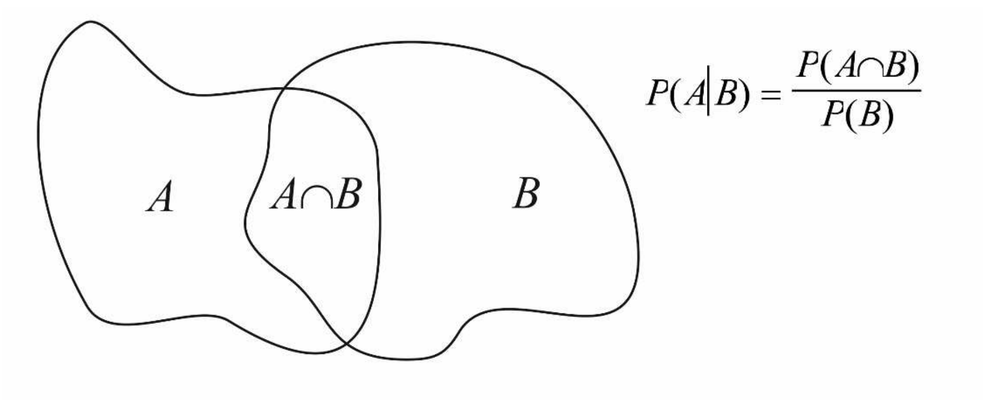
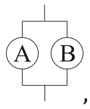



Fig. 1 Interpretation of relations between sets of events.

Tab. 3

Rules for calculating event probabilities for operations AND and OR.

| Operator | Probability |
|---|---|
| for dependent events $A \cap B \neq \emptyset$ | |
| AND | $P(A \cap B) = P(A) \cdot P(B|A) = P(B) \cdot P(A|B)$ |
| OR | $P(A \cup B) = P(A) + P(B) - P(A \cap B)$ |
| for independent events $A \cap B = \emptyset$ | |
| AND | $P(A \cap B) = P(A) \cdot P(B)$ |
| OR | $P(A \cup B) = P(A) + P(B)$<br>$P(A \cup B) = 1 - P(\bar{A}) \cdot P(\bar{B})$ |

Based on Fig. 1, for alternative events , denoted in Table 1 as gate $OR$, we can note:

$$P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

where: $P(A)$ –denotes the probability of event $A$, $P(A \cup B)$ –denotes the probability of event $A$ or $B$, $P(A \cap B)$ –denotes the probability of event $A$ and $B$.

Using relation (3), for independent alternative events, equation (4) can be rewritten to – Tab. 3:

$$P(A \cup B) = P(A) + P(B) - P(A) \cdot P(B)$$

Using the fact that $P(A) = 1 - P(\bar{A})$ the following product can be calculated: $P(A) \cdot P(B) = [1 - P(\bar{A})] \cdot [1 - P(\bar{B})] = 1 - P(\bar{B}) - P(\bar{A}) + P(\bar{A}) \cdot P(\bar{B}) = P(B) - P(\bar{A}) + P(\bar{A}) \cdot P(\bar{B})$. Inserting this solution into relation (**5**), we can obtain: $P(A \cup B) = P(A) + P(B) - P(B) + P(\bar{A}) - P(\bar{A}) \cdot P(\bar{B}) = P(A) + P(\bar{A}) - P(\bar{A}) \cdot P(\bar{B})$. Since $P(A) + P(\bar{A}) = P(A \cup \bar{A}) = P(\Omega) = 1$, the relation (5) can be noted in alternative form:

$$P(A \cup B) = 1 - P(\bar{A}) \cdot P(\bar{B})$$

where: $P(\bar{A})$ –denotes the opposite probability to event $A$.

According to relation (3), for the product of three sequential independent events $A \cap B \cap C$, the probability $P(A \cap B \cap C)$ will be: $P(A \cap B \cap C) = P(A) \cdot P(B \cap C) = P(A) \cdot P(B) \cdot P(C)$. Thus, in general, we can note that for $i$ sequential independent events, the probability of their occurrence will be:

$$P(\cap_i A_i) = \prod_i P(A_i)$$

where: $\cap_i A_i$ –denotes the product composed of $i$ events $A_i$.

For the sum of three alternative independent events $A \cup B \cup C$, their probability $P(A \cup B \cup C)$ will be: $P(A \cup B \cup C) = 1 - P(\bar{A}) \cdot P(\overline{B \cup C}) = 1 - P(\bar{A}) \cdot P(\bar{A} \cap \bar{B})$. Hence, according to (6) we can note: $P(A \cup B \cup C) = 1 - P(\bar{A}) \cdot P(\bar{B}) \cdot P(\bar{C})$. In general, for $i$ alternative independent events, the similarity of their occurrence can be noted as[29]:

$$P(\cup_i A_i) = 1 - \prod_i P(\bar{A}_i)$$

where: $\cup_i A_i$ –denotes the sum composed of $i$ events $A_i$,

## DUAL STRUCTURE

For a system consisting of two elements that can only be in two states: *fit and unfit*, it can be shown that the possible structures[30] are: *parallel and serial* [7].

*The analytical model of the reliability structure* can be an algebraic expression that explicitly defines the state of the system $X$ based on the state of its components: $X(x_1..x_i) \mid X; x_i \in \{1,0\}$. The suitability paths for the *system* structure can be divided into substructures, called *cuts*, for which, with all its elements unfit, the *system* will be unfit. The cuts of the fitness structure, which correspond to the paths of the *dual structure*, are defined by the formula [7,8].

$$X_D(x_1..x_i) \stackrel{\text{def}}{=} 1 - X(1 - x_1..1 - x_i) \mid X_D; X; x_i \in \{1,0\} \land (X_D)_D \equiv X$$

where: $X_D$ –state of the system with a dual structure, $X$ –state of the system under consideration, $x_i$ –state of the element $i$for the system structure under consideration.

The peak event $T$in the fault tree structure $FT$[31] indicates a *system* failure. From a reliability standpoint, it is more interesting to prevent *system* failure. To replace the top event in the fault tree with the non-occurrence of a peak event[32] $\bar{T}$, then in the original fault tree the complements of all events need to be inserted, and gates $OR$ should be replaced with gates $AND$ and vice versa [8]. Such a tree has the so-called dual structure in relation to the original fault tree.

For independent events, *dual structure* for the parallel configuration is the serial configuration and vice versa, because according to (3), (5) and (9) [7].

$$X_D(A \cup B = A + B - A \cdot B) \stackrel{\text{def}}{=} 1 - (1 - A) - (1 - B) + (1 - A) \cdot (1 - B) = A \cdot B = X(A \cap B)$$

## CUTS

According to the definition, the set of minimum cuts is the smallest combination[33] of major events, sufficient for a peak event $T$ to occur. In this combination, all the unfit events must occur for a peak event $T$ to occur[34]. Each fault tree $FT$ will consist of a finite number of minimum cut sets that are unique to the peak event $T$under consideration. If there are single-component sets of minimum cuts, they represent single unfit events[35] that will bring about a peak event $T$. Two-component sets of minimum cuts, represent dual unfit events that together will bring about a peak event $T$. In the case of $n$ –component minimum cut, all $n$ components in the cut must occur for a peak event $T$ to be brought about. According to Boolean algebra of sets, expressions for the minimum set of cuts $M$ for a peak event $T$, can be noted as: $T = \sum M_i$, where each minimum cut $M_i$ is a combination of events $X$: $M_i = \prod X_j$. The laws of distribution[36] and absorption[37] are most often used to simplify the structure during the analyses based on event trees. An example of an event tree structure is shown in Fig. 2 [8]. (8)

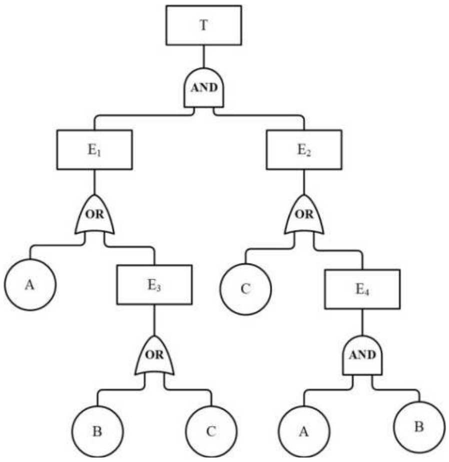



Fig. 2 Example event tree structure [8].

The dual structure to the one that has been received will be:

$$\bar{T} = \overline{A \cdot B + C} = \overline{A \cdot B} \cdot \bar{C}$$
$$\bar{T} = (\bar{A} + \bar{B}) \cdot \bar{C}$$
$$\bar{T} = \bar{A} \cdot \bar{C} + \bar{B} \cdot \bar{C}$$

Hence, there will be no unfitness in the structure shown in Fig. 2 if events $A$ and $C$, or $B$ and $C$ do not occur simultaneously.

## RELIABILITY

From the binomial structure model of system $R(x_1 .. x_i) \mid X: x_i \in \{1, 0\}$, we can proceed to a probabilistic structure: $R(P_1 .. P_i) \mid P_i \in [1, 0]$, where

$$\forall_{X:x_i \in \{0;1\}} \begin{cases} P(x_i = 1) = p_i \\ P(x_i = 0) = 1 - p_i \end{cases} \mid \forall_{i \in \mathbb{N}}\ p_i \in [0, 1]$$

where: $P$ –probability, $p_i$ –value $i$ –of this probability $P$, $X$ –random variable, $x_i$ –realization of $i$ for random variable $X$ .

The probability $R_i$ is called the *unreliability of element* $i$. Unreliability $R$ is equal to the expected value $EX$ for a random variable $X$: $EX = P(X: 1 \leftarrow x) \cdot 1 + P(X: 0 \leftarrow x) \cdot 0 = p$.

The probabilistic model of the *process* running in the *system* makes it possible not only to track the *fitness of the system* when part of its structure fails, but also to estimate the probability of the correct course of the *process*. If we were to mark time $\tau$ of the correct operation of the *process* as the realization of random variable $T$, then the undisturbed course of the *process* will last $t = 0$ to $t = \tau$, hence the *unreliability of the process* can be noted as $R(T: t \leq \tau)$.

For a series structure, the system will go from a state of fitness to a state of unfitness if even one of the components fails: $\tau = \min\{\tau_1 .. \tau_i\}$, where $\tau_1 .. \tau_i$ denote the realization of random variables $T_1 .. T_i$, and time $\tau$, which is the realization of random variable $T$, denotes the time segment from $t = 0$ to $t = \tau$ for the uninterrupted execution of the *process.* However, time $t$ may be shorter than time $\tau$, as the *system* may be shut down before the time $\tau$ is up or stopped due to an external failure that prevents the *system* from continuing to operate. For independent events, *unreliability* $R$ can be noted with the equation: $R \equiv P(t_i \leq \tau_i) = P(t \leq \tau_1 .. t \leq \tau_i)$. For independent random variables $T_i$: $\forall_{i \neq j}\ T_i \notin T_j$ is $R = P(t \leq \tau_1) \cdot\cdot P(t \leq \tau_i)$, the following can be noted:

$$\forall_{T_i \notin T_j \mid i \neq j}\ R = \prod_i p_i \ \Big|\ p_i = P(T_i: t \leq \tau_i)$$

where: $T_i$ –random variable, $R$ –unreliability, $t$ –time, $\tau$ –defect-free work time.

A parallel structure remains in a state of fitness when at least one of the elements is in a state of fitness, hence the following can be noted: $1 - R = P(t > \tau) = P(t > \tau_1 .. t > \tau_i)$. For independent events, *reliability* $1 - R$ can be noted with an equation:$\forall_{i \neq j} T_i \notin T_j \ \rightarrow\ 1 - R = P(t > \tau_1) \cdot\cdot P(t > \tau_i)$, which can ultimately be noted as:

$$\forall_{T_i \notin T_j \mid i \neq j}\ 1 - R = 1 - \prod_i (1 - p_i) \ \Big|\ p_i = P(T_i: t \leq \tau_i) \qquad (11)$$

Equations (12) and (13) are analogous to the previously derived (7) and (8).

The manner of estimating the suitability of the *system* to sustain[38] the *processes* that are taking place in it, estimating the probability of failure in the elements of its structure or collecting such data based on the fault-free time during the operation of the *system*, is the basis for analysing hazards and their causes.

## CAUSE TREE

A simple example of how causes of hazard are analysed would be to estimate the probability $p_T$ of losing air supply to a *system* component with a structure consisting of a diving helmet equipped with a breathing apparatus powered from a wired compressor *subsystem*.

Based on more than a 10 –year long observation of the incidence of various events occurring during the operation of the diving *system*, the probabilities of damage to: the diving helmet supply line $p_B$, diving helmet $p_C$, reducer $p_D$ and compressor $p_A$ were estimated [9].

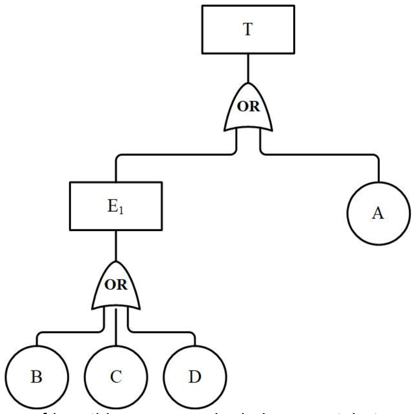



Fig. 3. Cause analysis of the hazards that make up the loss of breathing gas supply during a certain type of diving [9] where: T: Loss of air supply $p_T \cong$ $\cong 2.078 \cdot 10^{-4}$; $E_1$: Damage to a diver's equipment $p_{E_1} \cong 1.678 \cdot 10^{-4}$; A: Damage to the compressor $p_A \cong 4.000 \cdot 10^{-5}$; B: Damage to the umbilical cable $p_B \cong 7.718 \cdot 10^{-5}$; C: Damage to the helmet $p_C \cong 6.538 \cdot 10^{-5}$; D: Damage to the diving regulator $p_D \cong 2.526 \cdot 10^{-5}$.

The selected events can be entered in the structure of the fault tree $FT$, which is shown in Fig. 3.

The probability for independent events $P(E_1)$, related to the possibility of helmet dysfunction[39] will be: $P(E_1) = P(B \cup C \cup D)$. According to Fig. 3 and relation (8), it can be estimated at:

$$P(E_1) = 1 - \{[1 - P(B)] \cdot [1 - P(C)] \cdot [1 - P(D)]\} =$$
$$= 1 - [(1 - 7.718 \cdot 10^{-5}) \cdot (1 - 6.538 \cdot 10^{-5}) \cdot (1 - 2.526 \cdot 10^{-5}) =$$
$$\cong 1.678 \cdot 10^{-4}$$

The probability of air supply loss as unreliability $R$ can be noted as: $R \equiv P(T) = P(A \cup E_1) = P(A \cup B \cup C \cup D)$, which according to fig. 3 and relation (**8**) may be estimated at:

$$R \equiv P(T) = 1 - \{[1 - P(E_1)] \cdot [1 - P(A)]\} =$$
$$= 1 - [(1 - 1.678 \cdot 10^{-5}) \cdot (1 - 1.4000 \cdot 10^{-5}) =$$
$$\cong 2.078 \cdot 10^{-4}$$

Thus, the probability of air supply loss $P(T)$, representing a risk of unreliable $R$ dysfunction of the *system* under consideration, will be about $R \cong 2.078 \cdot 10^{-4}$, for the analysed type of diving.

## HAZARD TREE

An example analysis of the causes of unreliability risk $R$, by way of *hazard tree* analysis, is shown on the example of supplying a diver with air from a *system* consisting of a compressor, a backup compressor and tanks located on the diver's lowering[40] platform.

Based on many years of observations it was determined that for surface-supplied diving conducted in the above-defined *system*, the probability of losing the supply of breathing gas $p_T$ was the same as in thepreviously discussed example [9]. An analysis of the actions taken by divers to switch to supply from cylinders located on the lowering platform $E_2$ and taken by the staff to change from the primary compressor to the backup one $E_1$, has shown that these actions were taken just as often for the defined *system*. Thus, the relative frequency $\nu$ for these cases was: $\nu_{E_1} = \nu_{E_2} = 0.5$. Thus, based on the frequency definition of probability, it can be assumed that: $p_{E_1} = p_{E_2} = 0.5$ – fig. 4.

Based on more than a 10 –year observation of the frequency of various events occurring during the operation of various diving *systems*, we know that the probability of compressor dysfunction $p_1$ is approximately $p_1 \cong 4.000 \cdot 10^{-5}$.

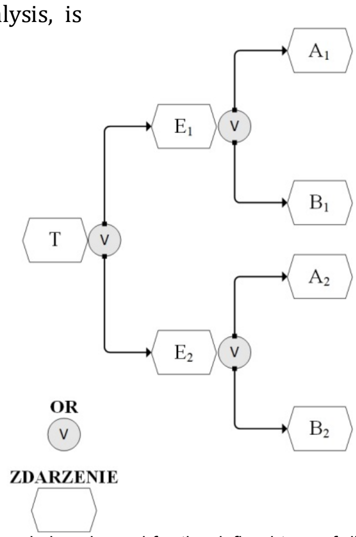



Fig. 4 The top-down analysis of the causes of breathing air supply loss hazard for the defined type of diving [9], where: T: Loss of air supply $p_T \cong 2.078 \cdot 10^{-4}$; $E_1$: Switching to backup compressor $p_{E_1} = 0.5$; $E_2$: Switching to backup power $p_{E_2} = 0.5$; $A_1$: Diving accident $p_{A_1} \cong 0.3871$; $A_2$: Diving accident $p_{A_2} \cong 0.3871$; $B_1$: Emergency abortion of dive $p_{B_1} \cong 0.6129$; $B_2$: Emergency abortion of dive $p_{B_2} \cong 0.6129$.

On the same basis, the probability $p_1$ of system malfunction following the switch to bell cylinders was also estimated at the same level: $p_2 \cong 4.000 \cdot 10^{-5}$. The probabilities of compressor $p_1$ and gas tank $p_2$ dysfunction referred to a potentially dangerous situation $B_1$ and $B_2$, involving the diver's need to switch to emergency power from the escape respirator, which caused the dive to be interrupted, but without the occurrence of a diving accident.

The probability of a diving accident $p_3$ following a backup compressor malfunction $E_1$, and $p_4$ following a gas tank malfunction $E_2$ was estimated to be at the same level as the probability of a demand regulator failure[41], $p_3 = p_4 \cong 2.526 \cdot 10^{-5}$.

It should be noted that the presented estimates of probability, for the occurrence of a dysfunction in backup compressor $B_1$, dysfunction in diving bell gas tanks $B_2$, the occurrence of a diving accident following a switch to backup compressor supply[42] $A_1|E_1$, and the occurrence of a diving accident after switching to bell tank supply[43] $A_2,|E_2$, were estimated from observations for all observed *systems*, not just the one defined above. Since these events could refer to the occurrence of many other potential events, they should be normalized[44] to the situation shown in Fig. 4.

Normalized to the unity of probability, correct operation of the escape respirator after failure of power supply from the backup compressor, as well as from the set of cylinders located in the bell $p_{B_1} + p_{B_2} = 1$, can be calculated based on known probabilities: $p_{B_1} = p_{B_2} = \frac{p_1}{p_1+p_3} = \frac{p_2}{p_2+p_4} \cong 0.6129$ and for $p_{A_1}$ and $p_{A_2}$ as a complement: $p_{A_1} = p_{A_2} = 1 - 0.6129 \cong 0.3871$.

The probability estimation of a diving accident hazard after the loss of breathing gas $T$ supply can be presented with the calculation of events: $R \triangleq P(T) \cdot P[(E_1 \cap A_1) \cup (E_2 \cap A_2)]$ [9]. Hence: $R = p_T \cdot (p_{E_1} \cdot p_{A_1} + p_{E_2} \cdot p_{A_2}) \cong 2.078 \cdot 10^{-4} \cdot 2 \cdot 0.5 \cdot 0.3871 \cong 8.044 \cdot 10^{-5}$.

An example analysis of the causes of unreliability risk $R$, by way of *hazard tree* analysis, shown in fig. 4, most often occurs when there are gaps in probability values for individual events. In such case some events are estimated in approximation or at the same level, as otherwise it would be impossible to make estimates.

## MILITARY DIVES

The process of estimating the hazard $R$ for diving technology has been presented based on the example of analysing a potentially dangerous situation related to the occurrence of decompression illness $DCI$[45]. The data has been taken from a study of diving technology using a $Mx/O_2 - SCR\ CRABE\ SCUBA$ diving apparatus.

Using a cause tree, a similar scheme can be suggested to estimate the occurrence of a potentially dangerous situation associated with using a $Mx/O_2 - SCC\ CRABE\ SCUBA$ type diving apparatus during a dive. It has been assumed that a potentially dangerous situation is associated with:

- $E_1$: exposure to a central form of $CNSyn$ oxygen poisoning,
- $E_2$: hyperbaric exposure associated with the possibility of decompression sickness $DCS$ symptoms,
- $E_3$: exposure to risks associated with loss of diving apparatus supply

The average risk $p_{E_1}$ associated with the possibility of a central form of oxygen poisoning ($CNSyn$) has been set here at 5.5%: $p_{E_1} = 5.50 \cdot 10^{-2}$.

Based on the conducted study, the average risk $p_{E_2}$ associated with the possibility of decompression sickness $DCS$ both for $Tx$ and $Nx$ divings was estimated at $P(DCS;\ \alpha_0 \cong 5\%;\ \alpha_1 \cong 20\%) \in [1.58;\ 2.95]\%$: $p_{E_2} = 2.95 \cdot 10^{-2}$. This has been assumed because, for interval estimation, the solution, with assumed critical significance $\alpha_k \lesssim 0.05$ and critical power of inference $\beta_k \lesssim 0.8$ due to the coverage interval $\hat{R} \in (\rho_l;\ \rho_r)$for the estimated true value of the risk $\hat{R}$ of spontaneous occurrence of $DCS$ symptoms for $N = 101$ experimental dives, $n = 0$ cases of $DCI$, can be calculated numerically from the system of equations [6].

$$\forall_{i \in \{0;1\}}\ P(H_{1-i}|H_i) \equiv \alpha_i \begin{cases} 1 - \sum_{x=0}^{N} \left[ \frac{N!}{x! \cdot (N-x)} \cdot \rho_l^x \cdot (1-\rho_l)^{N-x} \right] = \beta_k \\ \sum_{x=0}^{N} \left[ \frac{N!}{x! \cdot (N-x)} \cdot \rho_r^x \cdot (1-\rho_r)^{N-x} \right] = \alpha_k \end{cases}$$

where: $H_0$ –null hypothesis; $H_1$ –alternative hypothesis; $N$ –number of dives; $n$ –number of $DCS$ cases; $\rho_l$ –left limit of hazard $R$ of $DCS$ occurrence; $\rho_r$ –right limit of hazard $R$ of $DCS$ occurrence; $\alpha_k$ –critical value of $\alpha_0$ significance; $\beta_k$ –critical value of $\beta = 1 - \alpha_1$inference power; $\alpha_0$ –error of $I -$ type;$\alpha_1 -$ error of $II -$ type.

The estimated scope of values for the hazard $\hat{R}$ of $DCS$ symptom occurrence should be in the range: $\hat{R} \in [0.0158;\ 0.0292]$ with the value of the $I -$ type error of $\alpha_0 \cong 5\%$, consisting in the rejection of the true $H_0$, and $\alpha_1 \cong 0{,}2$ probability of the $II -$ type error, consisting in the acceptance of a false null hypothesis $H_0$.

Tab. 4

Results of interval estimation for the validation results of the decompression *system* by the Polish Naval Academy $AMW$ approach, for: $N = 101$; $n(DCS) = 0$; $\beta = 0.8\%$ .

| | Significance $\alpha_0$ [%] | | |
|---|---|---|---|
| | 10 | 5 | 1 |
| Probability of $\rho$ symptom occurrence $DCS$ [%] | $\rho_l \cong 1.58$ $\rho_r \cong 2.25$ | $\rho_l \cong 1.58$ $\rho_r \cong 2.92$ | $\rho_l \cong 1.58$ $\rho_r \cong 4.46$ |

So far, only one case of oxygen loss in a diving apparatus has occurred in several hundred dives. This was not synonymous with the loss of breathing gas supply from the integral set of the apparatus, but it has been assumed here that the maximum practical frequency of losing breathing gas $\nu$ was $\nu = 1/300$, hence the probability of losing breathing gas will be $p_{E_3} = 3.33 \cdot 10^{-3}$.

The above data enables us to estimate the probability of a potentially dangerous situation $R$: $R \triangleq P(E_1 \cup E_2 \cup E_3)$. Thus, for independent events, according to the equation (**6**), the probability of a potentially dangerous situation $R$ can be noted as: $R = 1 - P(\overline{E_1}) \cdot P(\overline{E_2}) \cdot P(\overline{E_3})$ and then $R = 1 - (1 - p_{E_1}) \cdot (1 - p_{E_2}) \cdot (1 - p_{E_3})$. By entering the data and performing calculations, the following result may be obtained: $R = 1 - [(1 - 5.5 \cdot 10^{-2}) \cdot (1 - 2.95 \cdot 10^{-2}) \cdot (1 - 3.33 \cdot 10^{-3}) \cong 8.59 \cdot 10^{-2} \triangleq 8.59\%$.

The calculated hazard $R$ of a potentially dangerous situation occurring during a dive with the use of $Mx/O_2 - SCR\ CRABE\,SCUBA$ diving apparatus is relatively high and has been estimated here at about 8.6%. The risks associated with the incidence of decompression sickness $DCS$ and the central form of oxygen poisoning ($CNSyn$) are always present. However, it is possible to choose a lower level of risk of a central form of oxygen poisoning ($CNSyn$). If the risk of a central form of oxygen poisoning ($CNSyn$) is reduced to $p_{E_1} \sim 1.00 \cdot 10^{-2}$, the risk of a potentially dangerous situation $R$ is halved.

The risks associated with the possibility of decompression sickness $DCS$ hazard can only be minimized by determining them accurately, by conducting a long series of experimental dives, as long as they are less than those already determined. As stated above, if the risk of a central form of oxygen poisoning ($CNSyn$) is reduced to $p_{E_1} \sim 1.00 \cdot 10^{-2}$, the risk of a potentially dangerous situation $R$ is halved. While minimizing the risk associated with the possibility of decompression sickness $DCS$ to the same level $p_{E_2} \sim 1.00 \cdot 10^{-2}$, the risk of a potentially dangerous situation $R$ will fall to the level of $R \cong 2.3\%$.

It is also possible to minimize the risks associated with supply loss. However, if the possibility of supply loss drops 100 times to the level of $p_{E_3} \sim 3.33 \cdot 10^{-5}$, the risk of a potentially dangerous situation $R$ will decrease slightly by $\Delta R \cong 0.3\%$, to the level of $R \cong 0.0829 \triangleq 8.29\%$.

As can be seen from the above estimates, military diving carries one of the biggest hazards $R$ of an incidence of a potentially dangerous situation of all military tasks performed in peacetime.

## TACTICAL ANALYSIS

The causes and hazards of the tactical use of divers can be analysed with the use of event trees. For example, event trees can be used to estimate the impact of using divers in $MCM$[46] or risk analysis of anticipated operational scenarios, both for diving and entire tactical situations. However, broader analyses should be computer-assisted. The calculation of large reliability structures is tedious and their analysis without computer support may lead to a number of mistakes, as even analysis of small systems can be quite complicated – Fig. 5.

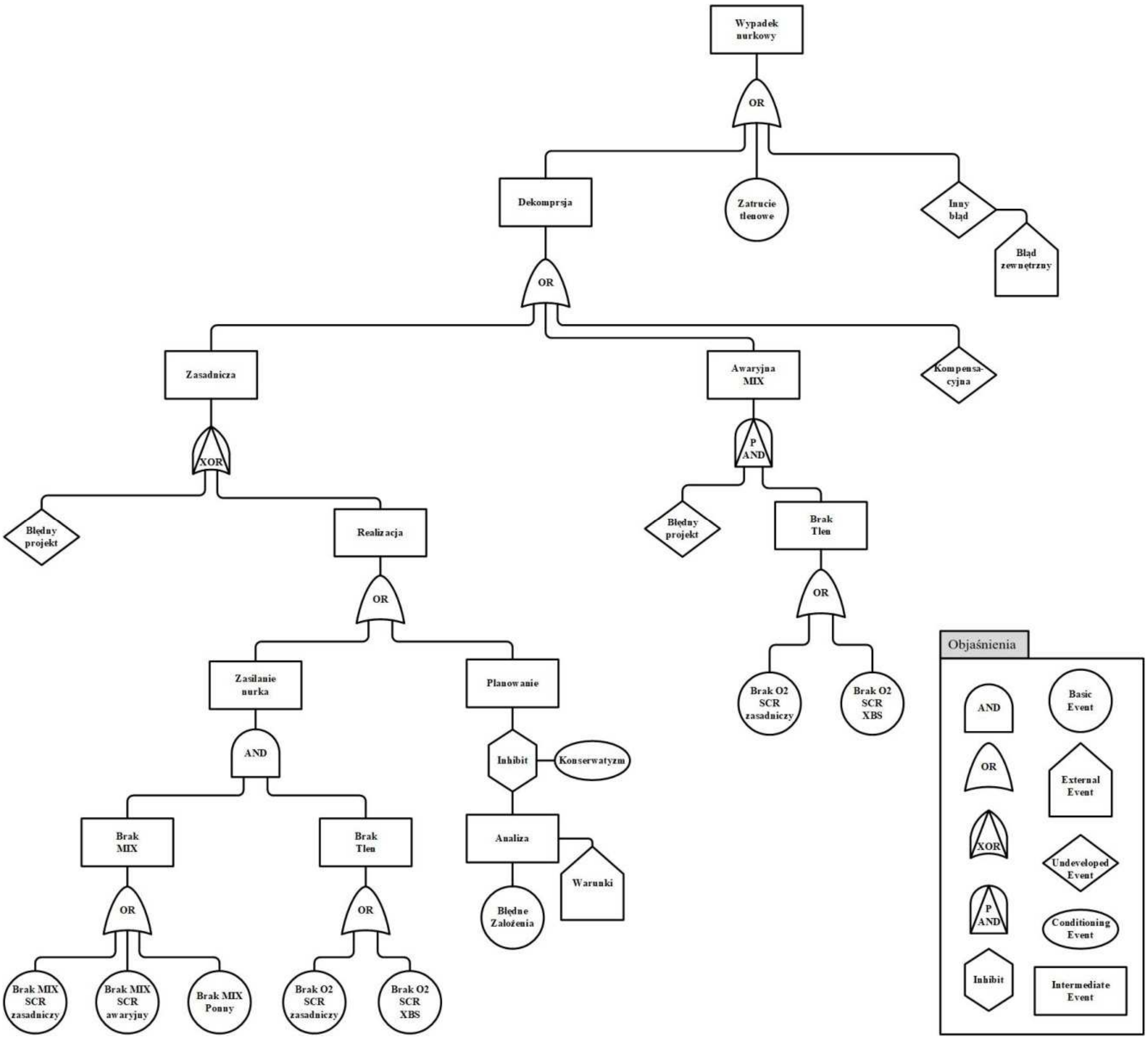



Fig. 5. Fault tree proposal $FT$ for an example analysis of a potentially dangerous situation related to the incidence of decompression illness $DCI$ using a $Mx/O_2 - SCR\ CRABE\ SCUBA$ diving apparatus.

The search for the causes of problem situations during the execution of a combat task by a method of deduction may be carried out with the use of top-down *hazard trees*.

The analysis of the impact of various events on the effectiveness of the tactical use of divers $MCM$ can be carried out with the use of top-down *cause tree* analysis.

The use of quantitative statistical methods, such as *discriminant analysis*, provides the opportunity to plan combat operations taking into account the probability of success for all sub-operations, such as $MCM$. Such an approach provides an opportunity to apply the *systems theory* to strategic planning of combat operations. Combat operations scenarios make up the main *process* in the *system*, which is structured to ensure that it runs smoothly. The context for this *system* is, first and foremost, the recognized actions of the enemy and the tactics of own troops[47]. The main *process* has a number of sub-processes for specific operations, such as $MCM$. Such approach allows us to determine the impact of individual *sub-processes* on the main *process* and indicates what the minimum required *system* structure[48] for the *process* is.

The use of *discriminant analysis* methods provides an opportunity to quantitatively estimate the success of the implementation of the *process* that is described in the combat operation scenario.

## CONCLUSION

According to modern tactical strategy, the soldier is increasingly more often eliminated from the battlefield. This is now evident in military aviation, where the role of unmanned aerial vehicles ($UCAV$)[49] has grown significantly. This is particularly evident in battlefield reconnaissance and launching precision attacks. The scale of $UCAV$ unmanned technology deployments in aviation appears to be significantly reducing the role of satellite reconnaissance[50].

## CONCLUSIONS

The *system* tactical context[51] is the basis for specifying requirements for the elements of the *system* structure and the *subsystems*, providing a basis for researching its properties, e.g.: reliability, vapourability, redundancy, etc.

When carrying out project tasks, one must remember that diving is only a component of the *system* for the implementation of *processes* within a larger *system*, e.g. mine countermeasure ($MCM$). In its essence, diving is merely a means of moving forces to perform combat tasks that are part of their objectives.

The national tasks that are assigned to the $CDT$[52] groups should focus on fixed position dives as the primary scenario based on national $MCM$ needs. Other scenarios became less relevant after the amphibious forces were disbanded in 1993.

It should be remembered that in peacetime, of all military specialties, it is military diving that carries one of the highest hazards that a potentially dangerous situation takes place, as shown in the above estimates.

## CONCLUSION

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[1] a collection of methods
[2] Mx refers to the breathing mixture, which for this diving apparatus can be either nitrox Nx or trimix Tx
[3] Failure Mode and Effect Alalysis
[4] Failure Mode Effect and Criticality Alalysis
[5] Preliminary Hazard Analysis
[6] Fault Hazard Analysis
[7] Double Failure Matrix
[8] Success Path Models
[9] classification trees
[10] Fault Tree
[11] Artificial Intelligence
[12] indefinite integral
[13] historical data
[14] e.g. computer simulations
[15] e.g. modelling studies
[16] e.g destructive testing
[17] semiquantitative at most
[18] does not provide the opportunity for quantitative comparison and thus selecting the safest solution in the decision-making proces
[19] spurious correlations occur much more often than would be generally thought, especially if discrete (discontinuous) data are collected over a short period of time, just as a good correlation between the population of storks and newborns was found in the classically discussed example of observations in 1930-1936 conducted in Oldenburg.
[20] rejecting the null hypothesis when it is true
[21] accepting the null hypothesis when it is false
[22] e.g. the number of equipment failures per year, equipment downtime per year, etc.
[23] e.g. for different months of the same year, analogous months in different years, etc.
[24] the theoretical basis of risk analysis comes from survival analysis
[25] interactions between elements of the structure of the analysed system
[26] for example, for light points that illuminate a relatively long corridor that ends with stairs
[27] Markov processes are sequences of events in which the probability of each event depends only on the outcome of the previous one
[28] algebras of sets

[29] the use of the calculus of probability for inverse events gives a noticeable computational gain because for three alternative independent events the calculus would have to look as follows: $P(A\cup B\cup C)=P(A)+P(B\cup C)-P[A\cap(B\cup C)]=P(A)+P(B)+P(C)-P(B)\cdot P(C)-P(A)\cdot P(B\cup C)=P(A)+P(B)+P(C)-P(B)\cdot P(C)-P(A)\cdot[P(B)+P(C)-P(B)\cdot P(C)]=P(A)+P(B)+P(C)-P(B)\cdot P(C)-P(A)\cdot P(B)-P(A)\cdot P(C)+P(A)\cdot P(B)\cdot P(C)$
instead of: $P(A\cup B\cup C)=1-P(1-A)\cdot P(1-B)\cdot P(1-C)=1-P(\bar{A})\cdot P(\bar{B})\cdot P(\bar{C})$
[30] as shown earlier, the structure used for the analysis of reliability should not be equated with its physical connection structure
[31] Fault Tree
[32] complement
[33] intersection in the sense of algebra of sets: $A\cap B$
[34] if one of the unfit events in the set of events does not occur, the peak event T will not occur either
[35] faults
[36] 3a and 3b in Tab.2
[37] 5a and 5b in Tab.2
[38] based on its structure
[39] unreliability
[40] without the ability to breathe from the atmosphere of a dry or wet bell
[41] it was assumed that the probability of dysfunction of the escape respirator is at the same level as in the previous ex-ample for the dysfunction of the demand regulator
[42] it has been assumed that events $A_1$ and $E_1$ are independent
[43] it has been assumed that events $A_2$ and $E_2$ are independent
[44] normalization involves adjusting probabilities in such a way that the probability for a certain event equals unity
[45] a broad term Decompression Illness is used here because in addition to Decompression Sickness DCS, the risk of Central Nervous Syndrome CNSyn – a form of oxygen poisoning, is also considered
[46] in mine countermeasure
[47] according to Clausewitz theory, war is only a continuation of politics by other means, hence the context of the system that supports combat operations also includes political conditions and many other factors, such as the law of war (international humanitarian law)
[48] hence the necessary system redundancy needed to ensure uninterrupted execution of the core process can be assessed
[49] Unmanned Combat Air Vehicle,
[50] satellite reconnaissance requires extensive and expensive investments and, as shown in the recent Russian experience, it is very easy to shoot down a satellite, which, in view of the relatively cheap UCAV technology and the fact that they make a difficult target to shoot down, is the rationale for their increased use
[51] it is not just about military tactics
[52] Clearance Diving Tea