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Calculation of the Significance of Hazard Causative Factors

O. M. Serebrovsky

Institute of Mathematical Machines and Systems of the Ukrainian National Academy of Sciences, 42, Acad. Glushkov Prospect, Kiev 03680, Ukraine.

ABSTRACT-*The paper is devoted to the actual problem of the estimation of hazard casual factors significance. Indices characterizing the significance of hazard casual factors in the occurrence of elementary undesirable events at potential hazard facility are proposed as well as indices of significance factors in accident occurrence. Algorithms for such calculation are described. Proposed indices are not alternative to probabilistic safety assessment indices but afford additional opportunity for analysis. Required precedent conditions for the significance indices calculation are described: knowledge base about factors and their impact on basic events occurrence made by the Method of Expert Evaluative Scales; formalized description of relations between basic events and an accident in the disjunctive-normal form; description of the situation when the situational significance of casual factors has to be calculated. The proposed indices can be used during the analysis of hazard casual factors. The algorithms proposed for the calculation of significance indices orient for developers of situational emergency centers, automated systems for hazard analytic at potential hazard facilities, particularly analytic systems of business projects when hazard technology is used.*

ABBREVIATIONS- *BE: Basic Events;; ETA: Event Tree Analysis; FM: Failure Models; FTA: Fault Tree Analysis; KB: Knowledge Base; MEES: Method of Expert Evaluative Scales; PHF: Potentially Hazardous Facilities; PSA: Probabilistic Safety Assessment; IF: Influence function; AHP: Analytic Hierarchy Process; MPC: Matrix of Paired Comparisons.*

KEYWORDS-*failure models; expert knowledge; hazard factor significance; situation impact; probability assessment, accident prevention, potential hazard facility, method of expert evaluative scales*

1. INTRODUCTION

Accident prevention at potentially hazardous facilities (PHF) is an urgent problem of hazard safety. PHF includes nuclear power plants, plants for chemically hazardous substances, stores for fire-hazardous and explosive objects and substances as well as their separate units. PHF is the complicated system where the structural elements are clearly identified (for example, nuclear power consisted of reactor, steam generator, turbine, circulating pumps etc). Events that can happen at system elements are named Basic Events (BE). BE includes: equipment failures, staff errors, and environmental phenomena. In certain combinations, BE may lead to a system failure (accident).

The procedure for determining the most important elements of PHF and BE is one of the main procedures in preventing accident technology. In general, the notion "significance" characterizes the role of a subject in the specific object occurrence probability. In [1,2] quantitative significance indices are proposed for cases when the subjects are BE and the object is a system failure (accident). Traditional significance indices are given below.

$$B^r = P_S^r(1) - P_S^r(0) \tag{1}$$

where B^r - significance (by Birnbaum) [1] of the event a_r in system (S) failure;

$P_S^r(1)$, $P_S^r(0)$ - the probability of system failure at conditions $P(a_r)=1, P(a_r)=0$, respectively.

$$FV^r = [P_S^r(N) - P_S^r(0)] / P_S^r(N) \tag{2}$$

where FV^r - significance (by Fussell-Vesely) [2] of the event a_r in system S failure;

$P_S^r(N)$ - probability of system failure when the event a_r takes normal value.

At the probabilistic safety assessment (PSA) other significance indices are also used [3] such as: Risk

Increase Ratio (RIR); Risk Reduction Ratio (RRR); Risk Increase Interval (RII); Risk Reduction Interval (RRI). These indices are effective means for:

- analysis of hazardous complex system projects;
- development of optimal reservation strategy;
- risk analysis of real PHF and weak link detection in their structure;
- establishing of regimes and maintenance checkup priority of the PHF elements;
- planning and organizing activities preventing component failure.

However, this set of indices does not characterize the causative hazard factors. Meanwhile, the analysis of causes of the hazard is one of the necessary conditions for the development of effective and timely decisions aimed at PHF preventing accidents. The simplest method to determine the significance of the causal factors is the method of expert evaluations. There are two possibilities for expert actions: to establish "direct" expert evaluations of significance factors according to their experience, or to apply the "hybrid" technology.

In this case, the "hybrid" technology consists of the following steps:

- expert performs paired comparison of factors on the basis of their importance in accident occurrence (in accordance with the rules of the analytic hierarchy process -AHP) [4], the result is a matrix of paired comparisons (MPC);
- automatically calculation of the Eigen MPC values, the result is the vector $(C_1, C_2, \dots C_M)$;
- automatically calculation of causal factors significance according to the expression:

$$V_j = C_j : \sum_{i=1}^{M} C_j \qquad (3)$$

where V_J - the factor significance, M - number of factors.

Such significance indices can be satisfactory only for simple objects. Therefore, the problem of calculating the causal factors significance for complex objects remains relevant. The cases when it is necessary to take into account the relationship between factors, BE, accidents and their probabilities are of particular interest.

Objective: To develop the significance indices of casual hazard factor and the algorithms for their calculation for cases when:

- a factor influences the BE;
- a factor influences the system failures (accidents).

The significance indices must consider: statistics of BE, the conditions taking place at PHF (nominal or situational).

Situational condition is the condition when causal risk factor values are determined by specific current situation at PHF. Nominal condition is the condition when causal risk factor values are determined by design rules and standards.

With this objective, the following tasks are formulated:

- develop a logical basis for the calculation of hazard causative factors significance;
- develop a formal representation and algorithms for the calculation of following indices:
  - hazard causative factors significance in the BE occurrence (statistical, nominal, situational);
  - hazard causative factors significance in the accident occurrence (nominal, situational).

2. METHODOLOGY (Logical basis for calculation of hazard causative factors significance)

In this section we describe two components: a component that provides a calculation of factor significance in BE occurrence and the component providing calculation of the factor significance in the PHF accidents occurrence.

2.1 Logical Basis For Calculations of Factors Significance in be Occurrence

The Method of Expert Evaluative Scales (MEES) [5,6] is the means by which the cumulative impact of independent causal risk factors on the BE probability occurrence can be estimated. MEES includes the rule for the Knowledge Base (KB) construction and the rule for the BE probabilities calculation.

The content of KB created by MEES means includes:

2.1.1 Formalized Description of the Factors that Influence Be Occurrence

On the basis of expert assessments a set of causative factors is formed in which the factors influence the BE occurrence independently. A set of factors includes aspects: the quality of PHF elements manufacturing; the level of maintenance; the operation rate; the level of environmental aggressiveness etc. For each factor $X_J\left(j=\overline{(1,M)}\right)$ the possible values $(x_{j,1}; x_{j,2}; \dots; x_{j,L_j})$ are preliminarily defined. These values are ordered according to the degree of factor influence on BE probability, and the first value $(x_{j,1})$ is considered to be the norm factor $(x_{j,1}^N)$.The latter value (x_{j,L_j}) is considered to be critical $\left(x_j^{KP}\right)$.

2.1.2 *Formalized Description of Situations Possible at PHF*

Situation at the system is represented as a set of causal hazard factor values $X_j(j=\overline{1,M})$. The situation "C" is given if one specific value is determined for each factor $X_J\left(j=\left(\overline{1,M}\right)\right)$:

$$"C": X_1 = x^c_{1,i_1}; X_2 = x^c_{2,l_2},..., X_k = x^c_{M,l_M} \quad (4)$$

A simplified example of situation description:

Let us suppose: expert analysis has shown that the situation at the system is determined by factors: humidity (X_1), vibration (X_2), ambient temperature (X_3), mode of equipment usage (X_4), technological discipline at service (X_5), the quality of power supply (X_6), equipment remaining life (X_7). In addition, possible factor values are set as: normal (N), satisfactory (S), anxiety (A), and hazard (H). Then, the total number of possible situations at the system is equal to 4^7. Most safe situation is described by the vector (N, N, N, N, N, N, N), and the most hazardous – by (H, H, H, H, H, H, H,).

Vector (S, N, N, S, A, S, A) defines the situation when

$$X_1 = S;\ X_2 = N;\ X_3 = N;\ X_4 = S;\ X_5 = A;$$
$$X_6 = S;\ \ X_7 = A.$$

2.1.3 *Formalized Description of Separate Impacts of Individual Factors on the Probability of Be Occurrence*

The impact of factors on the BE probability is described by the influence functions (IF). IF of BE factor is a correspondence between the possible values of the factor and the conditional probability of BE occurrence when all other factors take on normal values.

To create IF of factor X_j on the BE a_r it is necessary to set for each possible factor value x_{j,l_j} the corresponding value of BE a_r occurrence probability when all other factors take on the normal values. The sources of IF are: the statistics; the results of tests processed by the failure model [7]; expert evaluations. An approach to the construction of IF based on a combination of the above sources, and the analytic hierarchy process (AHP) is presented in [8]. Thus, for each pair

$\lfloor X_j \,\&\, a_r \rfloor,\ j=\overline{1,m};\ \ r=\overline{1,R}$ the L_j tuples are formed:

$$\left(r, j, x_{j,l_j}, f^r_j\left(x_{j,l_j}\right)\right) \quad (5)$$

when R - the number of BE;

M - the number of factors impacting the BE;

L_j - the number of possible values of the factor X_j;

x_{j,l_j} - one of the possible values X_j;

$f^r_j\left(x_{j,l_j}\right)$- value of the influence function of X_j factor on the a_r when $X_j = x_{j,l_j}$.

2.1.4 *The Rule for the be Probabilities Calculation that Occur Under Cumulative Effect of Hazard Factors*

KB described above creates a prerequisite to carry out the assessment of BE probabilities arising under the simultaneous impact of hazard causative factors. The cumulation rule can be represented by the following expression [9]:

$$P(a) = 1 - \prod_{j=1}^{M}\left[1 - f^a_j\left(x^C_j\right)\right] \quad (6)$$

where $P(a)$ - the probability of the BE "a", when $X_j = x^C_j\ (j=\overline{1,M})$;

x^C_j - value of factor $X_j(j=\overline{1,M})$ when the situation is monitored;

$f^a_j(x^C_j)$ - IF value of the factor X_j on the BE "a", when $X_j = x^C_j$.

Expression (6) is the "convolution" of separate influence functions of the independent hazard causal factors. Thus, MEES allows calculating the BE current value probability based on observations of situations on PHF. The resulting probabilities of the BE can be used for the calculation of risk according to traditional PSA methods.

2.2 Logical Basis for Calculation of Hazard Causative Factors Significance In PHF Accident

The Probabilistic Safety Assessment (PSA) [3,10,11] is the logical basis for the solution of this problem. One of the central PSA tasks is the probability estimation of technological accidents and emergencies. Cause-and-effect relations between the events are formalized by logical-and-probabilistic modeling techniques: "Fault Tree Analysis" (FTA) and "Event Tree Analysis" (ETA) [10,11]. As a result, accident is formalized as a disjunctive normal form (DNF) where BE are logical variables:

$$S = G(\{a_r\}\ (r = \overline{1,R})) \tag{7}$$

where C –accident at PHF;

G – logical function in the form of DNF;

$\{a_r\}\ (i = \overline{1,R})$ - BE at elements of PHF.

DNF allows representing the probability of the accident S in the form of an analytic function whose arguments are the probability of BE.

After replacing logical variables by their probabilities and logical operations - by corresponding arithmetic operations, the probability of hazard occurrence can be evaluated by means of analytic functions where BE probabilities are the arguments:

$$P(S) = Q[P(a_1), P(a_2), \ldots, P(a_R)] \tag{8}$$

where $P(a_r)\ \ (r = \overline{1,R})$ - probabilities of BE.

3. RESULTS: SIGNIFICANCE INDICES OF HAZARD CAUSATIVE FACTORS

Definition. Significance indices of hazard causative factor in the event (accident) occurrence is the parameter characterizing the variation of probability occurrence of the event (accident) when this factor changes its state from normal to critical and all other factors are normal.

3.1 Significance Indices of Hazard Causative Factors in the Be Occurrence

3.1.1 The Statistical Significance

$$Z_u^a(X) = F^a(x^{KP}) - F^a(x^N) \tag{9}$$

where $Z_u^a(X)$- the statistical significance of hazard causative factors in the event $"a"$ occurrence;

$F^a(x^{KP}),\ F^a(x^N)$ - the frequency of occurrence of an event when the factor takes critical or normal values, respectively.

The condition for calculating the statistical significance of the factor is the availability of statistical data about the frequency of an event occurrence at different factor values.

3.1.2 Nominal Significance Of Factor In The Be Occurrence

Definition. Nominal significance of X factor is a significance calculated under the condition when all other factors take their normal values.

$$Z_N^a(X) = f_X^a(x^{KP}) - f_X^a(x^N) \tag{10}$$

where $Z_N^a(X)$ is nominal significance of X factor in the BE $"a"$ occurrence;

$f_X^a(x^{KP})$, $f_X^a(x^N)$ is the IF of X factor in the BE $"a"$ occurrence when X factor takes critical or normal values, respectively.

3.1.3 Situational Significance of Factor X_K In The Be $"a"$ Occurrence

Definition. Situational significance of X_K factor is the significance calculated when all other factors are equal to that at the moment of monitored situation. The description of the situation is the result of PHF monitoring.

$$Z_C^{a_r}(X_K) = P_C^{KP}(a_r) - P_C^N(a_r) \tag{11}$$

where $Z_C^{a_r}(X_K)$ is situational significance of X_K factor in the BE $"a"$ occurrence,

$$P_C^{KP}(a_r) = 1 - \prod_{j \in \{(1,M)\setminus K\}} [1 - f_j^r(x_j^C)] \times [1 - f_K^r(x_K^{KP})] \tag{12}$$

$$P_C^N(a_r) = 1 - \prod_{j \in \{(1,M)\setminus K\}} [1 - f_j^r(x_j^C)] \times [1 - f_K^r(x_K^N)] \tag{13}$$

M - the number of factors that describe the situation;

x_j^C - situational value of the factor; $X_j\ j \in \{(\overline{1,M}) \setminus K\}$;

$f_j^r(x_j^C)$ - value of IF factor $X_j\ j \in \{(\overline{1,M}) \setminus K\}$ when $X_J = x_j^C$;

$f_K^r(x_K^{KP})$, $f_K^r(x_K^N)$ - the influence function of X_K factor in the BE $(r = \overline{1,R})\ "a_r"$ occurrence under normal and critical values, respectively.

Note. The necessary condition for the calculation of nominal and situational significances of hazard casual factors is a prior creation of KB factors and IF.

3.2 Indices that Characterize the Significance of Hazard Causative Factors in Accident Occurrence

The prior operation for the calculation of these indices is:

- creation of accident model in disjunctive-normal form (DNF) where the variables are BE a_r $\left(i=\overline{1,R}\right)$(according to (7));
- formation of accident probability function (according to (8));
- description of PHF situation when the calculation of significance is performed.

3.2.1 Situational Significance Of Factor X_K In Accident Occurrence

The procedure is consisted of following steps:

- the probability of every BE a_r $\left(r=\overline{1,R}\right)$ is calculated (according to (12) and (13)) under two conditions when factor X_K takes critical and normal values , results are $P_C^{KP}(a_r)$, $P_C^N(a_r)$ $(r=\overline{1,R})$;
- the probability of an accident is calculated under critical and normal values of factor X_K, for this purpose the function $Q(\{P(a_r)\}$ $(r=\overline{1,R})$ is used (according to (8)) where values $P_C^{KP}(a_r)$ and $P_C^N(a_r)$ are substituted by that calculated at the previous step

$$P_C^{KP}(S)=Q[\{P_C^{KP}(a_r),\ r=\overline{1,R}\}] \quad (14)$$

$$P_C^N(S)=Q[\{P_C^N(a_r)\ ,r=\overline{1,R}\}]; \quad (15)$$

- calculation of X_K factor situational significance in accident occurrence.

$$Z_C^S(X_K)=P_C^{KP}(S)-P_C^N(S) \quad (16)$$

3.2..2 Nominal Significance Of Factor X_K In Accident Occurrence

The procedure described above allows calculating the nominal significance of factors when instead of situational values of factors in expressions (12) and (13) the nominal factor values are substituted.

$$Z_N^S(X_K)=P_N^{KP}(S)-P_N^N(S) \quad (17)$$

where $P_N^{KP}(S)=Q[\{P_N^{KP}(a_r),\ r=\overline{1,R}\}]$ (18)

$$P_N^N(S)=Q[\{P_N^N(a_r)\ ,r=\overline{1,R}\}] \quad (19)$$

$$P_N^{KP}(a_r)=1-\prod_{j\in \underline{J}}(1-\beta_J^r)\times(1-f_K^r(x_K^{KP})) \quad (20)$$

where $\underline{J}=\left\{\left(\overline{1,M}\right)\setminus K\right\}$; $\beta=f_j^r\left(x_j^N\right)$

$$P_N^N(a_r)=1-\prod_{j\in\{(\overline{1,M})\}}[1-f_j^r(x_j^N)] \quad (21)$$

x_j^N - normal value of factor X_j $j\in\left\{\left(\overline{1,M}\right)\right\}$;

$f_j^r\left(x_j^N\right)$ - value of FI factor X_j $j\in\left\{\left(\overline{1,M}\right)\right\}$ when $X_J=x_j^N$.

4. CONCLUSION

<u>Novelty.</u> Indices characterizing the significance of hazard casual factors in the occurrence of elementary undesirable events at potential hazard facility are proposed as well as indices of significance factors in accident occurrence. Algorithms for such calculation are described.

<u>The role of indices characterizing the significance of hazard casual factors in traditional Probabilistic Safety Assessment.</u> Proposed indices are not alternative to PSA indices but afford additional opportunity for analysis. At the first stage of the analysis the traditional indices are used for the estimation of most undesirable events influencing accident occurrence. After that the proposed indices are used for the estimation of main causes of undesirable events revealed at the first stage.

<u>Required precedent conditions for the significance indices calculation.</u>

1. Knowledge base about factors and their impact on basic events occurrence made by the Method of Expert Evaluative Scales must be created. The complexity of such knowledge base creating can be drastically reduced if imposing restrictions on the PHF types and accident species eventual at this PHF. As a result the amount of base events and the number of influencing factors will be decreased and the problem of creating such a highly specialized knowledge base will be completely soluble in acceptable term and at minimal cost.
2. Formalized description of relations between basic events and an accident in the disjunctive-normal form. Similar formalized descriptions are created by highly tailored experts using traditional PSA automated complexes. Good example is PSA of atomic stations. It is possible to adopt this technology buying appropriate program systems.
3. Description of the situation when situational significance of casual factors has to be calculated. Description is fulfilled using the Method of Expert Evaluative Scales.

Practical importance

The proposed indices can be used during the analysis of hazard casual factors:

- by PHF designing, particularly for optimal reservation of systems at PHF;
- by PHF operation in normal conditions, (current situation assessment, weak point detection, planning and organization of routine maintenance).
- In the time of emergency situations at PHF when real threat of accident appears (decision support to prevent accident).

The proposed algorithms for the calculation of significance indices orient for developers of situational emergency centers, automated systems for hazard analytic at PHF, particularly analytic systems of business projects when hazard technology is used.

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