Expert system for aggregate industrial safety assessment at enterprises based on knowledge technologies

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Abstract. The work presents the knowledge base of the expert system of the aggregate assessment of the level of industrial safety at a hazardous production facility, based on the use of the logico-axiological approach. The fundamental hypothesis: the reduction in production safety is due to the presence of "NE-factors": poor implementation of organizational measures, improper working conditions, inadequate personal protective equipment and so on. Failure to take measures to provide protection against industrial accidents leads to a reduction in the level of industrial safety. According to the approach used, the influence of "NOT-factors" on the level of "non-safety" of production is formalized by products of the type: (SIC)A ->(SIC)B.

1. Introduction

In accordance with Federal Law No. 116 “On industrial safety of hazardous production facilities” [1], industrial safety (IS) of hazardous production facilities (HPFs) including railway facilities shall mean the state of safety of individual and public vital interests against accidents at hazardous production facilities and post-accident consequences of the above accidents.

Despite that there are a number of works on quantifying the industrial safety level at industrial facilities this problem remains unsolved [2].

The IS level assessment is mostly performed using the probabilistic statistical methods based on the calculation of the following performance characteristics [3–8]:

• accident rate at HPF ignoring both the accident type and its consequences, which cannot reflect adequately the actual picture because the number of accidents is 100–200 per year while the total number of supervised HPFs is 110,000;
• rate of fatal injuries at HPF, which is a classical approach in the risk theory evaluating the probability of a causal chain resulting in an accident; still, probability is a rather strict concept that needs a statistical justification to be used, which is not always possible in unique or new industries;
• industrial specialization of an enterprise (ratio of the number of injured workers to the product output), e.g. accident rate with respect to the pipeline length in main pipelines; the disadvantage of this approach is a narrow specialization and inefficiency for the activity assessment at small enterprises with a zero injury incident rate;
• damaging consequences of accidents and incidents; the disadvantage is that some damage parameters are impossible or infeasible to determine;
• indicators of supervisory and control measures such as a number of inspections, violations, disciplinary penalties imposed on officials for allowing violations, and measures focused on increasing the industrial safety level; time of reaction to registered violations; and staff qualification; in [9], the
proposed accident and incident classifier and the HPF IS assessment technique for gas distribution and gas consumption systems based on factor analysis of the safety state considering weights of the relevant factors (number of registered IS requirement violations, accidents, incidents, and injury cases); the disadvantage is the subjectiveness of the assessment and its significant dependence on the thoroughness of IS measures.

It is known that industrial emergencies such as injuries and accidents result from the combined action of multiple background conditions. The classical approach in the risk theory is focused on the probability assessment of this or that causal chain considering the damage done by an event. From this viewpoint, the risk event assessment at an enterprise is the probability assessment of factors that cause risk. Unfortunately, the concept of probability is a rather strict concept that needs a statistical justification to be used, which is not always possible in unique industries. A commonly used concept is subjective probability though such assessments are mostly nominal, which actually makes the probability approach similar to other methods that employ the expert assessment technique [10–13].

A promising approach to the integrated IS assessment of organizational and technical systems characterized by uncertainty, which are hard to represent by statistical models, is based on an expert system based on the logical-axiological quality assessment [12]. This method provides the IS assessment of an industrial system based on fuzzy inference using a production knowledge model. A knowledge base is developed as a result of the system analysis of the causal complex providing accident-free operation and occupational safety of an enterprise. Inference is based on the concepts of efficiency (value) and degree of actualization of factors and classes of factors that affect IS of a system.

The present article is concerned with a technique based on the logical-axiological assessment methodology proposed in [14, 15].

2. Stages of Aggregate IS Assessment Technique

The proposed technique is based on the idea that the normal operation of any complex system, including an accident-free operation system of an enterprise and an occupational safety (OS) system, requires the joint operation of all its subsystems composing it, and the damaged state of one subsystem leads to the damaged state of the whole system. This concept can be formalized by a set of fuzzy causal relationships (productions) of the following type: “If Not-A then Not-B”, where B is the assessed component (a system or any of its subsystems) and A is one of its direct subcomponents (functional elements or subsystems). The states of each component are represented by numbers in the interval [0,1]. Here, 1 denotes the normal operation of a component and 0 denotes its loss. In fact, it is the declaration of the fuzzy truth of the propositions “Component A functions normally” and “Component B functions normally”. The fuzziness also formalizes the degree of influence of the damage of component A on component B that contains it, which is expressed by a number in the interval [0,1], i.e., it is the declaration of the truth of the causal relationship “Damage in the operation of A causes the damage in the operation of B”. Truth of this relationship is called value of A for B.

A system providing accident-free operation and occupational safety at an enterprise is described by the corresponding system of productions (an example of such a system is given below). The assessment is represented as a direct fuzzy attached inference from a knowledge base (KB) consisting of such productions and its implementation is based on the expert system technology (knowledge technology). The starting facts are state assessments of the initial functional elements of an industrial safety system and the result is the aggregate state assessment of the whole system [10–12].

The stages of the aggregate IS assessment technique are as follows:

1. System analysis of causes and factors relevant for the occurrence of an emergencies such as industrial injuries, occupational diseases, or accidents. Determination of the major factors and causes.
2. Formation of causal chains, their division into classes of factors. Determination of Not-factors leading to NOT safety of each class: damage to health of workers and accidents.
3. Determination of measures (factors) providing workplace safety and accident-free operation of the technological process.
4. Formulation of the main factors of each class in productions of the following form:
5. Development of survey questionnaires for auditors, who assess the truths (degrees of actualization) of the initial factors at an object of study, and experts, who assess the values (degrees of influence) of the main factor for a class of factors and a class of factors for the industrial safety (IS) level. The assessments are assigned on a scale [0, 1] or, which is more convenient from the viewpoint of computation, on an integer scale 0–100.

6. Survey for auditors and experts.

7. Development of algorithms and software for an expert system (ES) with a database for storing classes of factors, main factors of classes, productions, and expert and auditor survey results.

8. Check of competence and consistency of experts and auditors in ES. Development of aggregate assessments of NOT safety of an enterprise and computing the IS level.

3. Knowledge Base Design

According to the technical literature, factors and causes that affect the industrial injury incident rate can be the following: organizational, sanitary and hygienic, technical, and psychophysiological [16].

Another system of background conditions for the occurrence of an accident and injury hazardous situation is shown in Table 1 [17, 18].

One can see that, in both cases, the initiation and development of an unfavorable situation is caused by “NOT-factors”: imperfections, incomplete/low-quality implementation of appropriate measures, poor staff training, lack of appropriate working conditions, etc., which are naturally formalized in the proposed approach. Let us note that the concept of value makes it possible to consider the relevance of each factor for a certain subsystem, and the whole approach considers that some factors can be regarded as key factors, which can devalue the whole system.

In Fig. 1, the causal relationship between the workplace damage to workers (occupational diseases and industrial injuries) and the industrial safety is represented as a tree of classes of factors providing IS and OS [11, 12].

The whole causal chain is formed and divided into classes as follows.

*NOT safety of organizational class* is determined by the following Not-factors:

- low quality or lack of professional training;
- lack of a work project and instructions on OS;
- violation of technological process organization;
- violation of work and rest schedule, etc.
### Table 1. Factors of accident and injury incident rate at industrial enterprises

| Group                        | Factors of accident and injury incident rate                                                                 | %    | In group |
|------------------------------|------------------------------------------------------------------------------------------------------------|------|----------|
| Technologies of work performance                                                                                              | Inconvenience of technology of preparation and performance of work                                         | 3.8  |          |
|                              | Inconvenience of repair and maintenance                                                                     | 2    |          |
|                              | Complexity of algorithm of actions of a human                                                               | 1.2  |          |
|                              | Necessity of entering a potentially dangerous area                                                          | 0.8  |          |
|                              | Poor emergency skills of staff                                                                             | 12.7 |          |
| Workers (humans)             | Inability to estimate the information about the process state                                               | 12.3 | 50.1     |
|                              | Poor theoretical knowledge of the processes                                                                 | 7.3  |          |
|                              | Technological indiscipline                                                                                   | 8    |          |
|                              | Lack of self-control under conditions of stress                                                              | 5.6  |          |
|                              | Other disadvantages of workers                                                                              | 4.2  |          |
|                              | Discomfort of environment in terms of physico-chemical parameters                                           | 2.8  |          |
|                              | Low quality of information model of environment state                                                        | 4.8  | 16.6     |
|                              | Possibility of dangerous impacts on humans and machines                                                     | 9    |          |
|                              | Low quality of workplace structures                                                                          | 6    |          |
|                              | Ignorance of working capacity of humans                                                                      | 1.5  |          |
|                              | High energy consumption of energy source                                                                     | 0.7  | 18.1     |
|                              | Possibility of dangerous failures                                                                           | 8    |          |
|                              | Other factors of equipment (machines)                                                                        | 1.9  |          |
| Others                       | Other factors                                                                                               | 7.4  | 7.4      |
| Total                        |                                                                                                            | 100  | 100      |

![Industrial safety model](image)

**Figure 1.** Conceptual model of an industrial safety system
The deficiency in these types of measures leads to “Not-safety” of organizational class. The deficiency in measures leading to “Not-safety” of the other classes is demonstrated in Table 2. The knowledge base (KB) is the following system of assessed factor and productions. Causes of health damage to workers are insufficient workplace safety measures.

**Table 2. NOT-factors of NOT safety classes**

| Class                      | NOT-factors of NOT safety classes |
|----------------------------|-----------------------------------|
| Technical                  | insecurity and accident hazard of equipment, devices, collective and personal protective equipment (PPE) |
|                            | non-mechanized and non-automated technological processes |
|                            | non-ergonomic workplaces |
|                            | design imperfection of equipment |
|                            | lack or malfunction of enclosing, protecting, blocking, signaling, and other devices |
|                            | imperfection of technological process |
|                            | non-adherence to preventive repair schedule |
|                            | lack of adequate PPE, etc. |
|                            | unfavorable industrial microclimate parameters |
|                            | low-quality lighting |
| Dangerous and harmful      | increased noise and vibration |
| industrial factors (DIF and HIF) | monotonous working conditions |
|                            | high concentration of harmful substances |
|                            | aerosols of predominantly fibrogenic action in air of work area |
| Cognitive                  | electric and electrostatic fields |
|                            | stressful and intense work process |
|                            | electromagnetic, radioactive radiation, etc. |
|                            | lack of knowledge and understanding by staff of their role in technological chain |
|                            | lack of knowledge by staff of technical production regulations |
|                            | lack of knowledge by staff of regulatory legal acts on OS and IS |
| Psychophysical              | slow reaction |
|                            | low stress resistance |
|                            | indiscipline, irresponsibility |
|                            | mismatch between psychological features of a worker to conditions of performed work, etc. |
|                            | poor professional qualification |
| Staff-related              | short experience of work in harmful working conditions |
|                            | inappropriateness of a worker at occupied position, etc. |
|                            | lack of warning posters |
| Informational              | lack of safety signs |
|                            | lack of surface marking |
|                            | lack of barrier for dangerous areas, etc. |

The given-below measures of the organizational class of factors provide workplace safety (WS) and IS.
**Organizational class of factors:**
- industrial and occupational safety requirements are met;
- staff training and instruction is timely and of high quality;
- there is a work project and instructions on occupational safety;
- satisfactory organization of workplaces;
- work and rest schedule is adhered to.

In Table 3, measures of the other classes of factors providing WS and IS are listed. Statements about the state of classes of factors that determine WS and IS (intermediate aggregating facts) are as follows:
- organizational measures are provided;
- technical conditions are appropriate;
- DIF and HIF are appropriate;
- psychophysiological state of workers is appropriate;
- professional qualification of workers is appropriate;
- workers have the necessary knowledge on occupational and industrial safety;
- hazard information signs are available.

The final aggregate inference is as follows: industrial safety and occupational safety at an enterprise is provided and a system for protection of workers from DIF, HIF, and injuries is appropriate.

Using the above facts, they are formulated as corresponding productions.

A production is a structure of the following form: If A → B; in the studied case, NOT-a → NOT-b: NOT appropriateness of the main factor causes NOT appropriateness of the corresponding class of factors.

Some example productions on the main factors of the organizational class are given below:
- NOT(true that)-“staff training and instruction are timely and of high quality” → Not(true that)-“organizational measures are provided”;
- NOT-“there is a work project and instructions on occupational safety” → Not-“organizational measures are provided”;
- NOT-“workplaces are organized satisfactorily” → Not-“organizational measures are provided”;
- NOT-“technological process is adhered to” → Not-“organizational measures are provided”;
- NOT-“labor discipline level is high” → Not-“organizational measures are provided”;
- NOT-“work and rest schedule is adhered to” → Not-“organizational measures are provided”;  
- NOT-“there are appropriately used PPE” → Not-“organizational measures are provided”.

For the other groups of factors, productions are formulated similarly. In addition, aggregating productions are needed:
- NOT-“organizational measures are provided” → Not-“industrial and occupational safety is provided”;
- NOT-“technical conditions are appropriate” → Not-“industrial and occupational safety is provided”;
- NOT-“DIF and HIF are appropriate” → Not-“industrial and occupational safety is provided”;
- NOT-“psychophysiological state of workers is appropriate” → Not-“industrial and occupational safety is provided”;
- NOT-“professional qualification of workers is appropriate” → Not-“industrial and occupational safety is provided”;
- NOT-“workers have the necessary knowledge on occupational and industrial safety” → Not-“industrial and occupational safety is provided”;
- NOT-“hazard information signs are available” → Not-“industrial and occupational safety is provided”.

Other productions for the main factors of the other classes are formulated similarly.
Table 3. Measures of a class of factors providing WS and IS

| Class                     | Measures of the class |
|---------------------------|-----------------------|
| **Technical**             | equipment and devices are functioning properly |
|                           | there are means of mechanization and automation |
|                           | no design imperfection of equipment |
|                           | there are properly functioning enclosing, protecting, blocking, and other devices |
|                           | technological process of necessary degree of perfection |
|                           | adherence to preventive repair schedule |
|                           | workplace ergonomics is satisfactory |
|                           | technological process is adhered to |
|                           | appropriately used, are available and appropriately used |
|                           | technical state of equipment is satisfactory |
| **Dangerous and harmful industrial factors (DIF and HIF)** | favorable industrial microclimate parameters |
|                           | high-quality lighting meeting the standards |
|                           | noise and vibration are appropriate |
|                           | no monotonous working conditions |
|                           | concentration of harmful substances is appropriate |
|                           | stressfulness and intensity of the work process are appropriate |
|                           | strength of electric and electromagnetic fields is appropriate |
|                           | no harmful radiation |
| **Cognitive**             | knowledge and understanding by staff of their role in the technological chain |
|                           | knowledge by staff of technical production regulations |
|                           | knowledge by staff regulatory legal acts on occupational and industrial safety |
|                           | knowledge of rules and skills for using PPE |
|                           | knowledge by staff of rules of conduct in emergency situations |
|                           | knowledge and understanding by staff of causes and consequences of accidents, etc. |
| **Psychophysiological**   | fatigability of workers is appropriate |
|                           | attention is appropriate |
|                           | psychological features of workers correspond to conditions or performed work |
|                           | reaction rate is appropriate |
|                           | stress resistance is appropriate |
|                           | discipline and the responsible attitude of staff to performed duties |
| **Staff-related**         | professional qualification of workers is appropriate |
|                           | sufficient experience of work in harmful working conditions |
|                           | appropriateness of a worker at the occupied position, etc. |
| **Informational**         | there are warning posters |
|                           | there are safety signs |
|                           | there is surface marking |
|                           | there is barrier for dangerous areas, etc. |

4. Inference: Aggregate Computation

Truths of the initial facts is assessed on a scale [0,1] or, which is more convenient from the viewpoint of computation, on an integer scale of 0÷100. Truths of intermediate facts (here, they are aggregating facts) are assessed in accordance with the modus ponens rule considering computed truth of the conclusion based on truths of propositions:

\[
\neg A, \neg A \rightarrow \neg B \vdash \neg B; \| \neg B \| = \| \neg A \| \| \neg A \rightarrow \neg B \|. \]

Here, the \( \vdash \) symbol separates propositions from the conclusion; after a colon, the computed truth of the conclusion; \( \| \neg A \| \) is the truth of the negation of the fact A, \( \| \neg A \rightarrow \neg B \| \) is the truth of the implication “If Not-..., then Not-...” (value of A for B).
The aggregation is performed using the rule of evidence integration, which, considering the probability nature of events, should be taken in the form:

\[ ||-B|| = ||-B||1 + ||-B||2 - ||-B||1 ||-B||2; \]
\[ ||-B||1 \text{ and } ||-B||2 \text{ are the truths of the negation of B computed through different inference chains.} \]

The resulting aggregate industrial safety level is as follows: \( ||B|| = 1 - ||-B||. \)

Risk (already not “probable” but certain “fuzzy” risk) can be computed as the product of the final aggregate system assessment by the damage caused by the corresponding event.

Let us consider the formulation of an inference in the following example.

Let there be a fact \( A_1 \) = “organizational measures are provided”. The auditor’s assessment of the degree of influence of organizational class of factors on occupational safety is “good” (0.8).

\( A_2 \) = “technical conditions are appropriate”, the auditor’s assessment of the degree of influence of technical class of factors on occupational safety is “excellent” (0.9).

\( B \) = “industrial and occupational safety are provided”. According to the expert assessments, value of \( A_1 \) for \( B \) = 0.4; value of \( A_2 \) for \( B \) = 0.5.

Inference step 1: \( \neg A_1, \neg A_1 \rightarrow \neg B \Rightarrow \neg B: ||\neg B|| = 0.2 \cdot 0.4 = 0.08. \)

Inference step 2: \( \neg A_2, \neg A_2 \rightarrow \neg B \Rightarrow \neg B: ||\neg B|| = 0.1 \cdot 0.5 = 0.05. \)

Inference step 3: Resulting degree of certainty that the event will occur

\[ \neg B: ||\neg B|| = 0.08 + 0.05 - 0.08 \cdot 0.05 = 0.126. \]

Thus, the deficiency in providing all the industrial safety measures is 12.6 %.

Inference step 4: “industrial and occupational safety are provided, the system of protection of workers from workplace damage” = 1 – 0.126 = 0.876 ≈ 0.9 “excellent”.

![Figure 2. The results of testing the basic factors of the technical class](image)

Hence, the logical-axiological assessment technique provides the aggregate state assessment of the system for providing safety and prevention of injuries at enterprises. The technique is implemented based on the ES technology and relies on Not-factors as causes of a risk situation leading to workplace damage and decrease in the IS level.

The results of testing on real data from objects of the East-Siberian railway are presented in Fig. 2. It can be seen that the level of PB is 0.49, the probability of emergencies is 0.52. The aggregated technical grade safety assessment does not exceed 79 %, although the expert value of this class of factors
for industrial safety is the highest (0.68) compared to the values of other classes. Derivatives of histograms of values of basic factors and their execution within the technical class show that the basic conditions such as the availability of adequate protective equipment (95.5 % with a value of 0.90), equipment reliability and reliability, and adaptation (91.8 % with a value of 0.83); compliance with the terms of scheduled maintenance (95.0 % with a value of 0.70). Hence, in front of the decision maker, it is necessary to state the problem of the primary solution of problems in these particular directions, to develop plans of measures for industrial safety of these types.

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