Risk management of emergence of dangerous events on the basis of three-planimetric model of reliability of technological systems

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Abstract. The reliability of machine-building industry technological systems is determined by the risks of hazardous events: failures of technological equipment, production items, executors of specified technological processes. The paper proposes the use of the G. Heinrich pyramid, built on the basis of the risks of technological system failures, which include primary failure, secondary failure, initiated failures, multiple failure, necessary to determine the significance of the influence of failure risks on the possibility of dangerous events. This is necessary for the organization of safe working conditions for workers through risk management of hazardous events based on a three-planimetric model for managing the reliability of technological systems. The authors have developed a three-planimetric model for managing the reliability of technological systems. The incident management process takes place on the first contour. According to the analysis of the statistics of incidents, the failure factors are managed on the second contour of the model. The third contour is process functionality management. The contours use the “Analytics” database, updating it and the database of possible options for technical solutions with the subsequent adjustment of operating conditions or methods for managing failure risks. Based on the obtained statistical information databases, solutions are being developed to manage the indicated risks of dangerous failures of technological systems. The control contour is closed in the cycle of technological system functioning and its risk management. Automation of the management process can be achieved through the use of resources of a machine-building organization and the development of an information management system for a unified technical condition monitoring system (UTCMS) based on the use of the three-planimetric control system.

The priority of any developed country’s policy at present is to preserve the health and ensure the quality of the labour activity of people. At the same time, according to Russian Federal Service for Labour and Employment in 2017, over 25 thousand people received injuries of various degrees of severity, including fatal injuries, as a result of industrial accidents in Russia. The machine-building industry, as a type of economic activity, occupies one of the leading positions in the number of dangerous events leading to the risk of injury in production [1, 2].

Achieving safe labour conditions and reducing injuries can become possible by managing the reliability of the technological systems of production facilities. Failures in equipment operation can cause traumatic situations that refer to production risks [3]. Labour protection management should be based on identifying the risks of hazardous events that are inextricably linked to the risk of failure. To
reduce the level of injuries, it is necessary to identify hazards and associated risks, and then, based on
detailed planning of working operations and at the expense of an effective management system, to
reduce the risks of hazardous events at work sites [4]. At present, managing the risk of hazardous events
is an urgent task. In the engineering industry, more and more solutions are based on particular attention
to predictable risks, for example, in the process of designing and testing equipment, maintaining and
managing various changes. Risk assessment, in its turn, is based on failure rates [1, 5-7].

In this paper, we developed a three-planimetric model for managing the reliability of technological
systems in the engineering industry, designed to manage the risks of hazardous events and ensure safe
labour conditions.

The pyramid of the American scientist G. Heinrich can be used in safety management in the
engineering industry, including managing the risks of dangerous events. They can be associated
with failures (malfunction) in the engineering industry. Therefore, R risk is a consequence of the
failure appearance in the technological process (table 1) [8].

| $R$ value | Risk level          |
|-----------|---------------------|
| 0-4       | Unlikely            |
| 5-19      | Not dangerous       |
| 20-39     | Possible            |
| 40-59     | Dangerous enough    |
| 60-80     | Dangerous           |
| 80-94     | Very dangerous      |
| 95-100    | Inevitably          |

Risk is a set of $R_I$ risks of hazardous incidents in the event of various malfunctions during the
process that can lead to dangerous accidents of varying severity and it is proposed to take this into
account using the weighting factor of the consequences of failure during $m_I$ technological process:

$$R=1-m_I\cdot R_I,$$

$I$ number of possible dangerous events can be determined on the basis of data about the number of
failures of the technological process in the organization. $m_I$ coefficient is also determined by the
statistics of failures or by the results of expert assessment as the share of the worst case outcome,
that is, the situation with a fatal case (table 2).

| $m_I$ level | Level of damage                                      |
|-------------|------------------------------------------------------|
| 0-4         | Insignificant: failure, entailing additional costs, but not violating the process |
| 5-19        | Small: failure, not significantly affecting the process |
| 20-39       | Tangible: failure, significantly affecting the process |
| 40-59       | Major: failure leading to process shutdown or costly repair |
| 60-80       | Emergency                                           |
| 80-94       | Accident                                            |
| 95-100      | Accident with death                                 |

Using the mechanism for constructing the pyramid of G. Heinrich, we shall consider the process
of managing the risks of dangerous events due to technological system failures (figure 2). The risks
of technological system failures can be divided into four levels, which include:

- primary failure in technological systems arising in the form of the need to perform repair work
to return the non-working element to a good condition;
- secondary failure in technological systems caused by the impact of previous or current excess
presses on the elements, in which an inoperative condition occurs, but the element itself is not
the cause of failure;
initiated failures in technological systems occurring when workers perform erroneous commands, which can be a possible source of failures, provided that their actions lead to the failure of elements;

in case of multiple failure, several elements fail for the same reason [9].

**Figure 1.** Distribution of failure risks in technological systems in the pyramid of G. Heinrich.

Let us consider the significance of the influence of failure risks on the risk of dangerous events in accordance with the distribution of failure risks in the pyramid of G. Heinrich.

It is proposed to select as the managed level, the level of influencing failures from the following four:

- primary failure of the technological system (with $R_{aggregate}$ risk),
- secondary failure ($I_m$ malfunction) of the technological system (with $R_I$ risk),
- initiated failure (with $R_{IJ}$ risk),
- multiple failure both in operation and maintenance.

G. Heinrich pyramid can be supplemented with a correlation analysis. For example, during the correlation between the qualification of the machine operator and the number of failures: the employee of the sixth category has no defect, the fifth – defect of about 10%, the fourth - 20%, the third - 30%, the second - 50%, the calculated Pearson coefficient $r$ is -0.46 [7].

According to the methodology of G. Heinrich pyramid, the onset of failures of $I$ technological systems (equipment) at the machine operator with the risk of $R_I$ may be due to a number of dangerous events. For example, equipment wear is the result of overheating during operation: $R_I = 1 - R_{Ik}$, \(2\)

where $R_{Ik}$ is the $I$ failure risk due to $k$ factor.

Each hazardous event does not necessarily lead to $I$ failure. Therefore, in accordance with the FMEA, as well as the risk management standards, the influence index is calculated using the formula:

$R_{Ik} = K_{Ik} \cdot Q_{Ik}$, \(3\)

where $Q_{Ik}$ is the risk of dangerous effects; $K_{Ik}$ is coefficient of failure risk influence on the risk of emergency, $K_{Ik} \in [0, 100]$ (table 3).
Table 3. Impact of failure risk on the risk of dangerous events $K_{Ik}$.

| $K_{Ik}$ value | Significance |
|----------------|--------------|
| 1–29           | Minor (weak): the incident does not directly lead to failure of the process |
| 30–49          | Moderate |
| 50–69          | Significant (noticeable) |
| 70–89          | High |
| 90–100         | Critical (very high): failure almost always leads to a non-operational state |

The proportion of the influence of $k$ failures on $I$ risk of a hazardous event is determined by the correlation coefficient between them:

$$K_{Ik} = 100 \cdot r,$$  \( (4) \)

where $r$ is the correlation coefficient in accordance with Regulation 1.05.515.4 “Methods and tools for improvements. Correlation analysis. Scatter Chart”.

The share of the influence of failures $K_{ik}$ is determined by the formula:

$$K_{ik} = \frac{100 \cdot K_o}{K_C}.$$  \( (5) \)

Example: if a failure to influence the risk of a hazardous event is considered a multiple failure due to an operation error, and a dangerous event is a temporary non-working state that does not require repair to return this element to a working state, then

$$K_{ik} = \frac{100 \cdot 10}{1000} = 1 \text{ (weak influence)}$$  \( (6) \)

Another example: if erroneous commands (initiated by the failure) are considered the failure, and a dangerous event is considered to be traumatic, then

$$K_{ik} = \frac{100 \cdot 1}{2} = 50 \text{ (significant influence)}$$  \( (7) \)

Example: if equipment depreciation is considered a failure (primary failure) and the non-operating state of an element is caused by a dangerous event, and it is necessary to carry out repair work to return the element to a working state, then:

$$K_{ik} = \frac{100 \cdot 1}{1} = 100 \text{ (critical influence)}$$  \( (8) \)

The proportion of influence with a lack of statistical data can be determined using expert estimates, for example, the Delphi method. This method should be used based on the logic of the pyramid of G. Heinrich and thus determine the value of $K_{Ik}$ or correlate the effect of failure with one of the five ranges: minor (weak), moderate, significant (noticeable), high and critical (very high). For each range, the mean values of $-15, 40, 60, 80, 95$, respectively, are determined.

In the event of a refusal $N$ times during the period under consideration, the influence coefficient (the proportion of the failure effect on the risk of a dangerous event) should be calculated using the formula:

$$K_{Ik} = 1 - (1 - K_{ik})^N.$$  \( (9) \)

Let us suppose the value of the share of the influence of failure is 0.01, and the value of the expected number of manifestations of failure for the period under consideration is 150, then:

$$K = 1 - (1 - 0.01)^{150} = 0.77.$$  \( (10) \)

The risk of $Q_{ik}$ hazardous event is calculated as the probability of an event occurring, manifestations of failure, categories of which are determined by analogy with previously used ones (table 3).
The probability of the occurrence of an event affecting failure is determined by the value of the event intensity integral $f(t)$ for the selected period $T$ from time $t_1$ to $t_2$ ($\Delta T = t_2 - t_1$):

$$Q_{Ik} = \int f(t) \, dt.$$  
(11)

Taking the intensity of the manifestation of failures as uniform, for the period $\Delta T$ there will be $N$ cases. Therefore, the probability of failure for the time period $\Delta T$:

$$\lambda = \frac{N}{\Delta T};$$  
(12)

$$Q_{Ik} = \int \lambda \cdot \exp (-\lambda \cdot t) \, dt.$$  
(13)

The probability of occurrence of $Q_{Ik}$ parameter with parametric failures will be equal to 1, since they do not have the character of a dangerous event.

**Figure 2.** Three-planimetric model for managing the reliability of technological systems and reducing the risk of dangerous events.

To enable further automation of the risk assessment processes described above and subsequent adjustment of actions, the authors of the paper have developed a three-planimetric model for managing the reliability of technological systems based on risk management of hazardous events in the engineering industry (figure 2).

The incident management process takes place on the first contour - statistics for the G. Heinrich pyramid accumulates: the set of incidents $I$, their intensity, the impact on the $K_{Ik}$ failure.

According to the analysis of the statistics of incidents, the failure factors are managed - the second contour of the model. In determining the failure factor as “insufficiently investigated” (the minimum degree of investigation), it is subjected to additional study. If the factor is defined as known, the main task is to minimize the effects of the factor. At the same time, the calculation of $R_{Ik}$, $R_I$ and $R$ risks is
necessary. The Analytics database is being formed. In addition, the effect of failures on $m_i$ level of damage is determined or clarified.

The third contour is the management of the process functionality. This and the previous contours use the “Analytics” database together, updating it and the database of possible options for technical solutions with the subsequent adjustment of operating conditions or methods for managing failure risks. Based on the obtained statistical information databases, solutions are being developed to manage the indicated risks of dangerous failures of technological systems. The control contour is closed in the cycle of functioning of the technological system and its risk management. Automation of the management process can be achieved through the use of resources of a machine-building organization and the development of an information management system for a unified technical condition monitoring system (UTCMS) based on the use of a three-planimetric control system.

Thus, the work reflected the use of the methods of constructing the pyramid of G. Heinrich in the field of risk distribution of failures of technological systems of the engineering industry. This distribution allows to identify the impact of risk of failure on the risk of dangerous events. Based on the construction of a three-planimetric model for managing the reliability of technological systems, it is possible to organize effective management of both the risks of failures and the risks of dangerous events. Developing a risk management program for the occurrence of hazardous events based on a three-planimetric model for managing the reliability of technological systems will ensure the most efficient organization of safe labour conditions for workers.

References
[1] Serdyuk V S et al 2018 J. Phys.: Conf. Ser. 1050 012077
[2] Porru S, Calza S and Arici C 2017 Prevention of occupational injuries: Evidence for effective good practices in foundries Journal of Safety Research 60 53-69
[3] Rebello S, Yu H and Ma L 2019 An integrated approach for real-time hazard mitigation in complex industrial processes Reliability Engineering & System Safety
[4] Lind S 2008 Types and sources of fatal and severe non-fatal accidents in industrial maintenance International Journal of Industrial Ergonomics 38 927-33
[5] Pittiglio P, Bragatto P and Site C D 2014 Updated failure rates and risk management in process industries Energy Procedia 45 1364-71
[6] Papazoglou I A, Aneziris O N, Bellamy L J, Ale B J M and Oh J 2017 Multi-hazard multi-person quantitative occupational risk model and risk management Reliability Engineering & System Safety 167 310-26
[7] Selvik J T and Signoret J-P 2017 How to interpret safety critical failures in risk and reliability assessments Reliability Engineering & System Safety 161 61-8
[8] Tishanin A G, Lapidus V A and Usoltsev A N 2011 Security Management Method Based on Heinrich Pyramid Quality Management Methods 11 4–9
[9] Lakin I K, Abolmasov A A and Melnikov V A 2013 Model for managing risks of failure of locomotives World of Transport 4 130-6