

METHODOLOGICAL FOUNDATIONS FOR DEVELOPING ACCIDENT SCENARIOS AND ASSESSING EMERGENCY PREPAREDNESS INDICATORS IN INDUSTRIAL ENTERPRISES

Aliev Abu Bakr

Occupational Health and Safety Inspector Foreign Enterprise “ANADOLU INSAAT” LLC
abubakraliyev1997@gmail.com

Narziev Shovkiddin

Professor at the Department of Engineering and Design, Renaissance University
sh_narziyev@renessans-edu.uz

Abstract:

This article develops a conceptual and methodological approach to assessing industrial enterprises' preparedness for technological emergencies based on accident scenarios, time dynamics, and the technical and organizational reliability of protective systems. The study aims to evaluate both the availability of protective measures and their capacity to perform required functions before critical time limits are reached. Accident progression is examined as a complex process involving an initiating event, hazard development, detection, warning, decision-making, protective system activation, and evacuation. The analytical model integrates total protective response time, critical time, the time margin coefficient, and the effectiveness and reliability of protective functions. Overall preparedness is assessed using risk weights reflecting scenario probabilities and consequence severity. Theoretical analysis indicates that a high integrated preparedness score does not guarantee effective protection when time margins are insufficient. Human-related delays in decision-making and evacuation are examined, and high, limited, and insufficient preparedness levels are characterized. Automation, evacuation route optimization, protective system redundancy, and diagnostics are identified as improvement priorities. The proposed approach may provide a methodological basis for conducting safety audits, developing emergency response plans, and designing protective systems.

Keywords: Industrial enterprise, technological emergency, accident scenario, preparedness level, critical time, time margin coefficient, protective function, human factor, risk-based assessment.

Introduction

The increasing complexity of industrial processes and the growing use of high-energy equipment and hazardous substances are increasing the likelihood of technological accidents. Under these conditions, establishing a preparedness system aimed at the timely identification and analysis of hazards and the mitigation of their consequences is a priority for industrial safety [1].

Analytical and scenario-based methods within the frameworks of ISO 31000, IEC 31010, ISO 22320, and ISO 45001 are widely used in hazard and risk assessment [2]. Hazard evaluation approaches provide an important methodological foundation for identifying sources of hazards at industrial facilities and determining potential accident progression pathways [3]. Safety instrumented systems designed in accordance with IEC 61508 and IEC 61511 play an important role in ensuring the timely and reliable performance of safety functions in automated systems [4].

Guidelines issued by international organizations such as the ILO and UNDRR also emphasize the analysis of interactions between time-related and human factors in preventing major industrial accidents and improving emergency preparedness [5]. These principles are fully consistent with the main provisions of the Seveso III Directive [6].

An analysis of existing methodological and practical approaches shows that enterprise preparedness is often assessed in terms of the presence of certain attributes, with the assessment limited to the availability of safety equipment or the level of personnel training [7]. In an actual accident, however, each protective function—detection, notification, decision-making, automatic protection, and evacuation—must be performed within a strict critical time limit [8].

A conceptual and methodological model was developed to assess emergency preparedness in industrial enterprises by jointly analyzing the execution time and reliability of protective actions through the overall integrated indicator (K_{overall}), the time margin coefficient (K_{margin}), and risk-based scenario weights (v_j) [9].

Materials and Methods

The study employed an analytical sequence based on the step-by-step development of accident scenarios and the assessment of the relationships among time parameters.

Definition of accident scenarios and time parameters. An accident scenario (S_j) is represented as a set comprising an initiating event (E_0) and the successive stages in the development of a hazardous factor (E_i):

$$S_j = \{E_0, E_1, E_2, \dots, E_m\}$$

The time interval before a hazardous factor has a critical impact on human life, technological systems, or the environment is termed the critical time (t_{crit}). The total protective response time (t_{prot}), intended to mitigate accident consequences, is the sum of the time spent at the following stages:

$$t_{\text{prot}} = t_{\text{det}} + t_{\text{warn}} + t_{\text{dec}} + t_{\text{act}} + t_{\text{evac}}$$

where:

- t_{det} is the time required to detect signs of an accident;
- t_{warn} is the time required for notification and warning;
- t_{dec} is the time required to assess the situation and make decisions;
- t_{act} is the time required to activate technical and engineering protection systems;
- t_{evac} is the time required to evacuate personnel and the public to a safe area.

Time margin and the preparedness condition. The primary and necessary condition for accident preparedness is that the protective response time must not exceed the critical time:

$$t_{\text{prot}} \leq t_{\text{crit}} \quad \text{or} \quad \Delta t_{\text{margin}} = t_{\text{crit}} - t_{\text{prot}} \geq 0$$

To express the effect of the time margin on facility safety in relative terms, the time margin coefficient (K_{margin}) is introduced:

$$K_{\text{margin},j} = \frac{t_{\text{crit},j} - t_{\text{prot},j}}{t_{\text{crit},j}} = 1 - \frac{t_{\text{prot},j}}{t_{\text{crit},j}}$$

Integration of time effectiveness and reliability. The time effectiveness ($K_{t,i}$) of an individual protective function i and its technical and organizational reliability (P_i) are combined to determine the function-specific preparedness indicator (K_i):

$$K_{t,i} = \min\left(1; \frac{t_{\text{crit},i}}{t_{\text{actual},i}}\right) \Rightarrow K_i = K_{t,i} \cdot P_i$$

The integrated preparedness indicator ($K_{\text{prep},j}$) for a given scenario S_j is calculated using the weighting coefficients (w_i) assigned to individual functions:

$$K_{\text{prep},j} = \sum_i w_i K_{i,j}, \quad \text{where} \quad \sum_i w_i = 1$$

Determination of the risk-based overall preparedness indicator. The overall integrated preparedness (K_{overall}) of an enterprise across multiple scenarios is calculated using risk weights (v_j), which depend on the probability and consequence severity of each scenario:

$$K_{\text{overall}} = \sum_j v_j K_{\text{prep},j}, \quad \text{where} \quad v_j = \frac{R_j}{\sum_k R_k} \quad \text{and} \quad \sum_j v_j = 1$$

Results and Discussion

The results of the analytical assessment demonstrate that emergency preparedness in industrial enterprises cannot be adequately characterized by the availability or nominal reliability of protective systems alone. The proposed methodological approach shows that the effectiveness of emergency protection depends on the interaction between the reliability of protective functions, the time required to execute these functions, and the critical time available before the hazardous factor reaches a dangerous level. This finding directly addresses the main research objective of developing an assessment framework that considers not only whether protective measures exist, but also whether they can perform their required functions within the available time.

1. Relationship between preparedness, response time, and critical time
One of the most important findings is that a high integrated preparedness indicator does not necessarily correspond to effective emergency protection. A facility may possess reliable detection, warning, automatic protection, and evacuation systems while still remaining vulnerable if the total protective response time approaches or exceeds the critical time of the accident scenario.

The proposed model therefore provides a more comprehensive interpretation of preparedness by introducing the time margin coefficient. The time margin represents the available temporal reserve between the completion of protective actions and the moment when the hazardous factor reaches a critical level. When this margin is sufficiently large, the system has a certain tolerance to delays and unexpected variations in human or technical performance. In contrast, when the margin approaches zero, even a relatively small delay in decision-making, system activation, or evacuation may substantially increase the probability of severe consequences.

This result is particularly important for rapidly developing industrial accidents. In such scenarios, the traditional assessment approach based primarily on the presence of safety equipment may overestimate the actual level of preparedness. The proposed approach demonstrates that preparedness should be interpreted dynamically: a protective system is effective only when it can complete the necessary sequence of actions before the critical time is reached.

Thus, the results support the research objective of integrating time dynamics into emergency preparedness assessment. The model shifts the assessment from a predominantly static question—whether protective measures are available—to a dynamic question: whether the complete chain of protective actions can be successfully executed within the available time.

2. Importance of the sequence of protective functions

The analysis also indicates that emergency response should be considered as a sequential process consisting of accident detection, notification and warning, situation assessment and decision-making, activation of technical protection, and evacuation. A delay at any individual stage increases the total protective response time and consequently reduces the available time margin.

This finding has an important methodological implication. The preparedness of an enterprise should not be assessed solely through an aggregated indicator without identifying the individual functions that contribute to the final result. Two enterprises may have similar overall preparedness scores while having significantly different vulnerabilities. For example, one enterprise may have highly reliable technical protection but relatively slow evacuation, whereas another may have efficient evacuation but insufficiently rapid detection or warning.

Consequently, the function-specific preparedness indicators proposed in the study make it possible to identify critical elements within the emergency response chain. This provides a basis for targeted improvement rather than applying identical safety measures to all components of the system.

3. Influence of human factors on emergency preparedness

The results highlight the particular importance of human factors in decision-making and evacuation. Unlike fully automated technical functions, these stages can be strongly influenced by stress, panic, incomplete information, uncertainty, and individual behavioral characteristics. The manuscript therefore identifies decision-making time and evacuation time as important sources of variability in the total response time.

This interpretation is consistent with previous research on emergency evacuation behavior. Gwynne et al. [13] emphasized the importance of modelling human behavior when assessing emergency movement and evacuation. Similarly, Ronchi et al. [14] demonstrated that human and behavioral factors need to be incorporated into emergency evacuation analysis rather than treating evacuation as a purely mechanical movement process. The present study extends this perspective by explicitly connecting human-related delays with the time margin of the industrial accident scenario.

The practical implication is that personnel training should not be evaluated only by whether employees have received formal instruction. More important is whether personnel can perform the required actions quickly and correctly under realistic emergency conditions. Repeated drills can reduce hesitation and improve familiarity with warning signals, evacuation routes, communication procedures, and emergency decision-making. The effectiveness of such training is particularly important in scenarios where the time margin is limited.

4. Comparison with existing risk-based and safety-management approaches

The proposed methodology is consistent with the general principles of risk-based safety management reflected in ISO 31000 and IEC 31010, which emphasize systematic identification, analysis, and evaluation of risks. It also corresponds to emergency-management principles reflected in ISO 22320 and occupational safety management principles reflected in ISO 45001.

However, the contribution of the present approach is the explicit integration of temporal performance into the preparedness indicator. Conventional risk assessment generally focuses on the probability and consequences of hazardous events, whereas the proposed model additionally considers whether protective functions can be completed before the available critical time is exhausted.

The approach is also complementary to the functional-safety principles of IEC 61508 and IEC

61511. These standards emphasize the reliable performance of safety-related systems, while the proposed model considers how such reliable systems contribute to the overall emergency response sequence. Therefore, technical reliability alone is not treated as sufficient; its practical value depends on timely activation and successful completion of the required protective function.

The approach is likewise consistent with the principles emphasized by the ILO, UNDRR, and the Seveso III framework concerning prevention of major industrial accidents, emergency preparedness, and consideration of human and organizational factors.

5. High, limited, and insufficient preparedness

The analytical results allow three conceptual preparedness conditions to be distinguished.

High preparedness is achieved when the integrated preparedness indicator is high and an adequate time margin is maintained across relevant accident scenarios. In this condition, the system possesses not only reliable protective functions but also sufficient temporal reserve to tolerate minor deviations in human or technical performance.

Limited or critical preparedness occurs when the integrated indicator appears satisfactory but the time margin becomes very small in rapidly developing scenarios. This condition represents a significant vulnerability because apparently minor delays may lead to failure of the protective sequence. Consequently, a satisfactory integrated score should not automatically be interpreted as evidence of a safe condition.

Insufficient preparedness occurs when the total protective response time exceeds the critical time. In this situation, the protective system is unable to complete the required actions quickly enough to prevent or substantially limit the consequences of the accident. These three levels provide a more informative interpretation of preparedness than a single numerical score.

6. Risk-based weighting of accident scenarios

Another important methodological result is the use of risk-based scenario weights based on the probability and consequence severity of individual accident scenarios. This is significant because not all scenarios contribute equally to the overall safety profile of an enterprise.

A low-probability scenario with extremely severe consequences may require a different level of preparedness than a relatively frequent scenario with limited consequences. By incorporating scenario weights, the proposed approach allows the overall enterprise preparedness indicator to reflect the risk structure of the facility rather than treating all accident scenarios as equally important.

This approach strengthens the connection between emergency preparedness assessment and risk management. It also provides a rational basis for prioritizing investments in protective systems, training, automation, and evacuation infrastructure.

7. Theoretical implications

The theoretical contribution of the study lies in treating emergency preparedness as a dynamic and multidimensional property rather than a static collection of available safety measures. The proposed model integrates three fundamental dimensions: time effectiveness, technical and organizational reliability, and risk significance of accident scenarios.

This perspective expands conventional preparedness assessment by demonstrating that reliability and availability are insufficient if protective actions cannot be completed within the critical time. The concept of the time margin coefficient provides an additional analytical dimension through which the resilience of emergency response can be evaluated.

The model also provides a conceptual link between technical safety engineering and human-factor analysis. By incorporating decision-making and evacuation times into the same response-time framework as technical protection, the methodology provides a unified basis for analyzing interactions between technological and human components of emergency response.

8. Practical implications for industrial enterprises

The findings have several practical implications for industrial safety management. First, enterprises should identify accident scenarios with particularly short critical times and evaluate whether existing protective functions can be completed before those limits are reached.

Second, automation should be prioritized where human-dependent response times represent a significant part of the total protective response time. Automatic emergency shutdown and automatic warning systems can reduce delays associated with manual intervention. The manuscript similarly identifies automation as a priority for reducing human-dependent response times.

Third, evacuation routes should be assessed not only for their physical availability but also for their actual evacuation time under realistic conditions. Route optimization, improved signage, organizational procedures, and repeated evacuation exercises can contribute to reducing evacuation time.

Fourth, the reliability of critical protective functions should be strengthened through redundancy, diagnostics, regular testing, and maintenance. These measures are particularly important for functions whose failure would significantly reduce the available time margin.

Finally, the methodology can support safety audits and emergency response planning by identifying which protective functions represent the greatest contribution to overall response time and which accident scenarios have the most critical temporal constraints.

9. Overall interpretation of the findings

Taken together, the results indicate that emergency preparedness should be understood as the ability of an industrial enterprise to perform the complete sequence of necessary protective actions reliably and within the available critical time. The principal advantage of the proposed approach is therefore not simply the calculation of an integrated preparedness indicator, but the identification of situations in which a satisfactory indicator may conceal a critical lack of temporal reserve.

The findings support the central research proposition that effective emergency preparedness requires simultaneous consideration of protective-system reliability, response-time dynamics, human factors, and risk-based scenario significance. The approach therefore provides a methodological basis for moving from static compliance-oriented assessment toward a more dynamic, scenario-based evaluation of actual emergency response capability [15].

At the same time, the results should be interpreted as a conceptual and analytical framework rather than as empirical validation of a specific industrial facility. Further research should apply the model to real industrial enterprises using measured response times, historical accident data, evacuation experiments, reliability data, and scenario-specific probabilities. Such empirical validation would allow the proposed preparedness levels and weighting parameters to be calibrated and would provide a stronger basis for quantitative comparison between industrial facilities.

Conclusion

A new conceptual and methodological approach was developed to assess emergency preparedness in industrial enterprises by integrating time dynamics, time margins, and system reliability.

The inclusion of the time margin coefficient (K_{margin}) and risk-based scenario weights (v_j) in the model addresses the methodological limitations of drawing conclusions solely from the overall preparedness indicator.

The theoretical analysis showed that efforts to improve preparedness should focus primarily on reducing time losses caused by human factors in scenarios with limited time margins and on maximizing the automation of technical systems.

This methodological model can serve as a general analytical framework for conducting safety

audits at industrial enterprises, developing emergency response plans (PASA/PASO), and designing safety systems.

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