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ON THE SIGNIFICANCE OF MATHEMATICAL METHODS FOR ASSESING THE RISK OF MAJOR INDUSTRIAL ACCIDENTS

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The present paper presents the importance of applying mathematical methods for assessing the risk of major industrial accidents. The definitions of risk and hazard are presented. The risk assessment methods have been discussed. The regulatory framework for the use of the methods has been reviewed. The specific stages of the quantitative risk assessment have been presented.

1. Introduction. In the modern functioning of the society there is a growing need to guarantee that the risks to the population, economy and the environment, posed by the functioning of industrial plants with potential to generate major accidents, are subject of adequate assessment and management. At the same time, the efficient and optimal distribution of the limited resources has to be guaranteed in the process of risk assessment and management. Considering these circumstances, the risk assessment of industrial accidents occurring with dangerous substances becomes even more urgent. This undoubtedly also has an impact on the activities of the emergency response services in Bulgaria.

The main objective of the present paper is to present the models used for risk assessment of potentially hazardous industrial sites.

2. Definitions of risk and hazard. The review of specialized and regulatory sources on risk assessment in potentially hazardous industrial sites shows that a number of terms are in circulation. The ill-founded use of some of those terms leads to incorrect understanding due to the fact that “risk”, “threat”, “hazard” are frequently used in everyday life. This leads to the need for a preliminary review of the aspect in which those terms are defined and interpreted by different communities before proceeding with discussing the risk assessment.

The Seveso III Directive [1] includes definitions of hazard and risk:

“Hazard” is defined as “the intrinsic property of a dangerous substance or physical situation, with a potential for creating damage to human health or the environment”.

“Risk” is defined as “likelihood of a specific effect occurring within a specified period or in specified circumstances”.

In accordance with the definition put forward, risk should be perceived as a complex function of hazards related to a specific system, the likelihood of a danger to generate an undesired event, the consequences of this event and the vulnerability of the sites exposed to hazard. Risk as it is interpreted by the general public, as well as the acceptability of certain risks, seams to depend on a number of aspects such as control, fear, knowledge and trust.

Hazard and risk should be differentiated. A review of several dictionaries has indicated that hazard is often described as a "risk source", while risk is described as "a likelihood for occurrence of undesired consequences". Therefore, hazard exists only as a source. Risk, on the other hand, includes "the likelihood" in which this source could be transformed into real damage. Applying adequate influence may reduce the risk. In relation to this, risk depends not only on the hazard, but also on the measures for protection which are taken against this hazard [4]. An appropriate measure of influencing the magnitude of the risk is the availability of fire safety units and protection of the population in potentially hazardous industrial sites which, through trained personnel and specialized equipment, can influence the initial moment of the accident.

3. Methods of risk assessment. The review of specialized literature sources on risk assessment indicates that as of the present moment more than 120 methods are applied globally [10]. The research shows that there can be distinguished 84 essential methods which differ in their approach, properties and applicability [11].

Every industrial sector has its own definition of risk relating to its own specificity. Each sector though, takes into account the two quantitative elements – the likelihood of undesired events occurring and the size of their consequences.

The main industrial sectors with importance to the risk for the public and the environment are as follows: chemical, waste treatment, nuclear energy, etc.

In order to adequately manage the risk, i.e. to maintain its numeric value within normal reference limits, it needs to be adequately assessed. The assessment includes the precise formulation of the undesired event and also finding ways of quantitative assessment of the likelihood both for occurrence of this event at specific circumstances and for the severity of the consequences thereof.

In mathematical terms, risk is perceived as the product of the likelihood/frequency of a particular event occurring and the size of the consequences thereof. It is also correct to present it as the ratio between the source of real hazard and the safety measures taken about it. This can be achieved by doing the following:

– identifying the risk source;
– taking safety measures;
– identifying the measures providing the greatest protection;
– identifying the size by which the risk magnitude could be reduced by implementing a particular safety measure.

Solving this task is a major part of risk management. Ensuring safety in industrial establishments with dangerous substances is based on a set of safety principles defined at every stage of their existence.

In order to prove the adopted safety principles, the risk of accidents occurring in industrial establishments with dangerous substances needs to be mandatory assessed by deterministic and probabilistic methods.

The deterministic methods include:

– validation of the conformity of the limits and the operation conditions with the design assumptions for normal operation;
– definition of the set initial events, including those characteristic of the site which need to be taken into consideration in the design basis;

- analysis of the borderline scenarios as a result of the specific initial events;
- analysis of the consequences and verification that the acceptability criteria have been met, etc.

The probabilistic methods complement the deterministic ones with regards to the so called "residual risk", i.e. risk which continues to exist although all technical and organizational measures have been taken. The probabilistic approach provides the opportunity to better assess the main factors contributing to this risk. The probabilistic risk analysis is an analytical method, which through modelling, systematically searches for the answers to the following questions:

- What kind of event could happen? (identification of accident scenarios);
- What would the consequences of a particular event be? (identification of their size);
- What is the likelihood/how often could this happen? (assessment of the likelihood /frequency of event occurring and consequences thereof).

The probabilistic risk analysis needs to:

- systematically analyse the conformity of the general safety of the establishment with the main safety criteria;
- demonstrate the safety of the design project in which every set initial event has a proportionate effect on the overall risk;
- prove that minor deviations in the operation parameters which could lead to negative changes in the technological processes have been prevented;
- assess the frequency of failures in the hazardous technological area and of large releases in the environment;
- assess the frequency and consequences of the site-characteristic external events;
- classify structures and equipment needed for design improvements or modification to the operational instructions leading to reduction in the frequency of major accidents or to limiting the consequences thereof;
- assess the accident response instructions.

For this purpose the probabilistic risk analysis has to include:

- all operational modes of the technological process with dangerous substances and all set initial conditions and hazards (including in-house fires and floods, extreme climatic conditions and seismic effects);
- all possible significant dependencies leading to common cause failures;
- analysis of the uncertainty and of the sensitivity of results;
- realistic modelling of the unfolding of events with loss of content with reporting the actions of the operational personnel in accordance with the operational and accident response instructions;
- analysis of the human errors with reporting the factors that could affect the behaviour of the operational personnel in all operational states and emergency conditions.

The advantages of the probabilistic risk analysis as a method of risk analysis of accidents in establishments with dangerous substances include the following:

- systematic approach and possibility of reporting at different level of details presentation;
- integration of diverse information;
- possibility of reporting various and numerous interactions;
- quantitative assessment of the state of details of the equipment design;

– quantitative assessment as an argument in the decision-making process;
– possibility to analyse the sensitivity of the results;
– possibility for integrated and principle-based approach in the assessment of sources of uncertainty [5].

4. Regulatory argument. In accordance with article 103 of the Environment Protection Act [2] and Annex 3 establishments with significant quantities of dangerous substances are classified as “lower-tier establishments” and “upper-tier establishments”. Construction of such establishments is preceded by issuance of permits [2], for the purpose of which a safety report has to be prepared with regards to upper-tier establishments.

In accordance with Annex 4 of the Ordinance on prevention of major accidents with dangerous substances and mitigation of their consequences [9], the safety report has to contain the following mandatory information:

I. Report on the policy for prevention of major accidents.

II. Detailed description of the following:

1. The surrounding environment in the area of the establishment;

2. Facilities, processes and activities in the establishment;

3. Identified hazards and risk assessment of accidents in the establishment/facility and the relevant preventive measures;

4. Protection measures and tools for limiting the consequences of major accidents, including those of the available fire safety and protection of the population.

III. Information about the organization in place for adhering to the fire-safety and emergency rules and regulations.

IV. Information about the natural persons and/or legal entities participating in the elaboration of the safety report with their address, telephone, fax and email.

In accordance with the Guidance on the preparation of a Safety Report [3], for the preparation of the safety report, different methods of analysis and risk assessment may be used, and the bigger the possible damages are, the more detailed and more precise the analysis and the risk assessment method should be. The risk analysis and risk assessment should include at least the implementation of the following tasks:

– identification of dangerous substances, materials and sections (modules) of the examined site relevant to the safety;
– identification of hazard sources;
– assessment of the consequences of the potential major accidents;
– determination and assessment of the adequacy of the preventive, control and risk mitigating measures, including those of the available fire safety and protection of the population.

The safety report needs to show that the operator has identified the hazard of major accidents occurring and he has assessed the risks related to the facilities and the other activities in the establishment. The safety report needs to present the results from the analysis of hazards and from the risk assessment performed by the operator, and their scope should be proportionate to the risk. In general, the safety report needs to document the identification of the hazard sources, the relative likelihood of major accidents occurring and their consequences.

There are several approaches to the hazard analysis and risk assessment (qualitative or quantitative), each of them, if consistently applied, can provide reliable information about the level of safety. The choice of specific technique can be done only based on the site or the specific risks. In both cases the effort put should be proportionate to the size of possible damages. The quantitatively expressed arguments may be a suitable instrument for limiting the scope of the safety report showing that either a very small likelihood of a particular undesired event occurring exists, or that a particular consequence is relatively insignificant. The quantitatively expressed arguments in the context of risk assessment do not necessarily mean risk quantification in the form of expected mortality. The social or ecological damages may be reviewed. The quantification of consequences and/or the frequency of events in some cases may be sufficient grounds for judgement.

Recommended steps:

Step A.

Focused on the identification and analysis of sections which have a potential for generating major accidents; at the same time though, sufficient attention is paid to the safety in the remaining sections too. Thus, sections with significant potential for generating major accidents due to the dangerous substances processed or used in them are identified as sections of relevance to safety.

Step B.

The aim is to identify those hazard sources which may cause a major accident in the sections of relevance to safety. Also, the conditions in which a major accident can occur, and the consequences of this accident, need to be identified.

Step C.

The aim is to assess the envisaged preventive, control and mitigating measures. The risk assessment can be used to determine the likelihood of major accidents occurring and to show that all adequate measures for protection of the population, property and the environment have been taken. In this respect, a connection can be established between - on the one hand, the type and quantity of staff and equipment of the fire safety units and the protection of the population in potentially dangerous industrial sites as a measure of impact and on the other – the magnitude of the risk.

Based on the described circumstances, the paper is focused on the method of quantitative risk assessment for major accidents with dangerous substances as regulatory valid and globally established.

As it has been found, the probabilistic methods used for the quantitative risk assessment are based on the probabilistic safety analysis, the analysis of the frequency (the likelihood) of a particular event occurring and the comparison with the regulatory accepted (recommended) value of the latter.

5. Specific stages of quantitative risk assessment. The quantitative risk assessment is based on three adopted documents which outline the standards for:

- Methods for determining and processing probabilities – CPR 12E [7];
- Methods for the calculation of physical effects resulting from releases of hazardous materials (liquids and gases) – CPR 14E [8];
- Methods for Determining of Possible Damage to People and Objects Resulting from Releases of Hazardous Materials – CPR 16E [6].

Main stages of quantitative risk assessment:

I. Selection of installations

This includes the installations with most significant contribution to risk formation. Substances which due to the condition in which they exist do not generate hazard for major accidents to occur can be excluded from the analysis and the risk assessment, in accordance with [1]. Sufficient grounds for exclusion of a particular substance are the fulfilment of at least one of the following criteria:

- the chemical substances are in stolid state and in normal and untypical conditions cannot cause a major accident;
- the chemical substances are packaged and stored in such a manner that in case of maximum possible release at any circumstances no risk of major accident can be generated;
- the chemical substances are in such quantities and at such distances from other dangerous substances which neither can generate any risk of major accident on their own, nor can generate a major accident in combination with the other chemical substances;
- the chemical substances classified as dangerous by virtue of the general classification of Annex I, part 2 to [1], which include dangerous substances, which however cannot generate risk of major accident, therefore, the general classification does not apply to them in this specific case.

II. Identification of events with "loss of content", which need to be included in the quantitative risk assessment of establishments

The complete system of events with "loss of content" (LoC) includes:

- general LoC (all causes for failures that do not require explanation, such as for instance: corrosion; construction errors; welding defects; blockages at air-vents of tanks)
- LoC resulting from external influence (mostly caused by means of transport)
- LoC at loading and unloading (covers the movement of materials from the means of transport to the installations and the other way round)
- specific LoC (reactions which have gone out of control and domino effects).

The quantitative risk assessment has to include LoC which contribute to the individual risk formation and/or the public risk. The conditions to include them in the risk assessment are the following:

- the frequency of a particular event occurring to be $\geq$10-8;
- to exist a likelihood of 0.01 for causing death outside the territory of the establishment or the transportation route.

III. Emission and scattering modelling

The following models for emission and scattering modelling have been described:

- leakage and dispersion;
- puddle evaporation;
- vapour cloud explosion;
- heat flows from fires;
- containers destruction;
- vapour cloud scattering;
- jets and torches;
- dense gas scattering;
- passive scattering.

IV. Exposition and injuries modelling

The following indicators are used in the assessment of human injuries:

P_E – likelihood for an individual person to die;

F_E– relative share of casualties showing the part of population that will die at a specific location from a specific exposition.

The part of population that will die is split into two subparts – the first subpart of the population that will die outside the buildings ($F_{E\ out}$) and the second one that will die in the buildings ($F_{E\ in}$). Probabilistic functions are used to calculate the likelihood of toxic and thermal effect on the people.

6. Measures for influencing the risk magnitude. The risk magnitude already identified needs to be compared with a predetermined recommended limit value. Two scenarios stem from this:

– The risk magnitude identified using the presented method does not exceed the preliminary established recommended limit value. In this case it can be concluded that the risk is acceptable and no additional mitigating measures are necessary;
– The risk magnitude identified using the presented method reaches and/or exceeds the preliminary established recommended limit value. In this case it can be concluded that measures for influencing the risk magnitude need to be taken.

A number of approaches for influencing the risk magnitude are known, such as:

– raising the level of organizational regime safety measures in the establishment;
– inclusion in the design process of higher technology safety measures;
– creation of emergency response structures comprised of personnel and equipment for early accident response, including those of the available fire safety and protection of the population structures.

7. Conclusions. This paper outlines only the key points regarding the importance of mathematical methods for assessing the risk of major industrial accidents. The methods have been tested, tested and validated at world level. They should be applied both by the operators of hazardous production facilities and by the expert control bodies in this field.

REFERENCES

[1] Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC.

[2] Environment Protection Act, promulgated, SG, issue 91 of 25.09.2002, amend. and suppl., issue 76 of 19.09.2017.

[3] Guidance on the preparation of a Safety Report, Ministry of Environment and Water.

[4] C. Kirchsteiger. (ed.) Risk Assessment and Management in the Context of the Seveso II Directive. Industrial Safety Series, vol. **6**, 1998, Elsevier, 537 pp.

[5] E. Kirtchev. Probabilistic Safety Analysis – Modern Approach to Risk Management. *First Nuclear*, Periodical of Kozloduy Nuclear Power Plant, issue IV, 2007, 2–6.

[6] Methods for determining of possible damage to people and objects resulting from releases of hazardous materials – CPR 16E, 1992.

[7] Methods for determining and processing probabilities – CPR 12E, 1997.

[8] Methods for the calculation of physical effects resulting from releases of hazardous materials (liquids and gases) – CPR 14E, 2005.

[9] Ordinance on prevention of major accidents with dangerous substances and mitigation of their consequences. Adopted by Decree of the Council of Ministers No. 2 of 11.01.2016, promulgated, SG, issue 5 of 19.01.2016, effective from 19.01.2016.
[10] L. Vladimirov. Comparative analysis of the risk assessment methods of potentially hazardous sites and activities. *Scientific papers of Ruse University*, **48**, series 1.2 (2009), 132–136.
[11] L. Vladimirov. Systematisation of Methods of Risk Analysis. Part I Category, class, subject and topic of risk analysis. International Scientific Conference "Unitech 07", Gabrovo, Technical University, II289–II295. Part II. Area, scope, applied economic activity and rank of risk analysis, page II296–II301.
[12] Guideline for quantitative risk assessment – CPR 18E, 2005.

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ОТНОСНО ЗНАЧИМОСТТА НА МАТЕМАТИЧЕСКИТЕ МЕТОДИ ЗА ОЦЕНЯВАНЕ НА РИСКА ОТ ГОЛЕМИ ПРОМИШЛЕНИ АВАРИИ

Свилена С. Арабаджиева, Стефан И. Първанов

Настоящата работа представя значимостта на прилагането на математическите методи за оценяване на риска от големи промишлени аварии. Представени са определения на риск и опасност. Коментирани са методите за оценка на риска. Разгледан е нормативният регламент за използване на методите. Посочени са конкретните етапи при количествената оценка на риска.