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Approaches, Methods and Techniques for Risk Assessment of Major Industrial Accidents with Dominoeffects occurrence in European Union and Slovak Republic

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In 2015 most of the EU member states implemented the new requirements of the SEVESO III Directive to their legal environment. There were changes in the area of classifying the hazardous substances, critical infrastructure protection and civil protection. From the point of view of the industrial accidents prevention the domino effects and methodologies for identifying and assessing them are the main challenges for the Slovak Republic. This article presents the currently used methodologies of the company assessment with the potential of the domino effects escalation. The particular methodology for the Slovak Republic that took into account its need, advantages and also shortages of already used methods was created in 2015. It is not exactly defined which procedures are to be used for identifying and assessing the domino effects therefore every member country defined its own methodology. Procedure presented in article fulfilled its intended objectives and thus created the required predispositions for the application of the methodological procedures for Slovak companies. Thus, it has provided step-by-step procedure the competent persons in the Seveso companies and their operators, the competent state administration, as well as neighbouring enterprises with the potential to cause a domino effect with the necessary tool for the implementation of this identification.

Keywords: major accidents; methodology; domino effect; Seveso establishment; risk assessment

1. Introduction

When a major industrial accident occurs in installations covered by European Directive 2018/15/EU (Seveso III), there is a probability of a specific phenomenon called the "domino effect". European Directive 2012/18/EU itself defines this phenomenon as "The risk of a major accident or its consequences could be exacerbated because of the geographical location and proximity of lower-tier and upper-tier establishments or groups of establishments and their stocks of dangerous substances (Directive 2012/18/EU of the EP and of the Council)". The reference Dutch BEVI Manual defines this phenomenon more specifically directly from a technical point of view as "An effect whereby a loss of integrity (release of a substance into the atmosphere) in one installation leads to a loss of integrity in other installations due to the consequences" [1].

The database eMars registers the accidents that happened in the European Union (EU) member countries. The basic classification of the indicator: major industrial accidents, near-misses and other events. The database eMars also registers the accident categories with special circumstances: contractors, domino, Natech and transboundary. During 2010 – 2019 the following amounts of the events occurred in the EU - 27 contractors, 11 domino effects, 11 Natech and 2 transboundary (Figure 1).

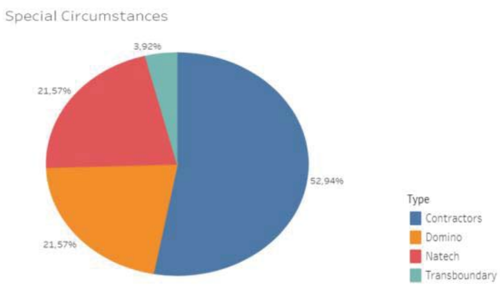

Fig. 1. Special circumstances involving domino effect

The risk connected with the establishments with the potential to cause the domino effect is part of the assessment in the framework of the company safety documentation in the EU. The origins of the domino effect are summarized in the table 1. It is clear that the domino accidents occurred more frequently in the fixed installation than in transportation ones.

Table 1 Origin of domino accidents [5]

Source	Transportation initiated (%)	Fixed installation (%)
Ronza et al.(2003)	41	59
Darbra et al. (2010)	32	68
Abdolhamidzadeh et al.(2011)	20	80
Chen et al. (2012)	24.5	75.5
Hemmatian et al. (2014)	24.4	75.6

We can say that the mechanical failure is the main cause of the domino effect followed by a human error and external events. The design, installation and maintenance of the machines should decrease the domino effects. The human factor has a very important influence on the domino accidents. Therefore, the training of operators, both in maintenance and plant operation, should be significantly improved particularly in the developing countries. The application of suitable methods for risk assessment is still under way and they are specified according to the purpose and location of the application [15-21]. Every EU country uses a certain approach for identifying the domino effect in dependence on the quality level of their users and the need to fulfil the legal requirements. An industrial site contains different installations under pressure, including tanks that store flammable liquids. The risk of explosion and fire characterized by the possibility of an accident at an industrial site is likely to lead to damage and serious consequences for staff, people, goods and environment. They can generate four main events (escalation vectors); these escalation vectors are defined as physical effects of the primary events:

- Overpressure/blast waves;
- Heat load;
- Projection of fragments (missiles);
- Toxic release.

Several models have been developed for the assessment of the domino effects in the industrial plants caused by fires and explosions; therefore, we looked for some models dealing with this phenomenon in literature. We found models that are used to assess: i) the domino effect generated by heat load and overpressure, and ii) the domino effect caused by projection of fragments [6].

Khan et al. [13] designed a systematic methodology called Domino Effect Analysis (DEA) that serves for analyzing, assessing and preventing the accidents with the domino effect incidence in the industrial branches.
The tool DOMIFFECT (DOMIno eFFECT) was developed on the basis of the DEA method [14]. It is based on the deterministic models used in connection with the probability analysis. The DOMIFFECT is computer software with an object-oriented architecture coded in C ++. It consists of six main modules: Data, Emergency Scenario, Analysis, Domino, Graphics and User Interface.
Another software tool ARIPAR was developed for calculating the local, individual and social risk for transportation of hazardous substances [15]. The software assesses the corresponding vulnerability of the data through the probit correlation. The latest ARIPAR version implements the probabilistic methodology for the risk assessment for transportation of hazardous substances with the goal to achieve a number of the risk measures developed the ATLANTIDE software for assessing the

consequences of the accidental events that can occur during storing hazardous substances.

The usage of this tool is suitable for facilities that store and process LPG (dispersion of the fluid or gases and other phenomena, e.g. the BLEVE effect and fire ball). The software utilizes the event trees to assess all possible scenarios, from the initial accidental event, taking into account the weather and other properties typical for the particular type of the premises [17]. The objective of the tool DOMINOXL developed by Delvosalle [18], is to determine the possible domino effects that can lead to the internal and external cascade accidents. This calculation detects the vulnerability factor [16]. The software GeOsiris [19] was developed as a methodological tool for coping with major accidents with the domino effect that simulates the industrial accidents and quantifies their consequences from the point of view of effective distances, providing aid for making decisions and definers the implementation method and reaction time for realizing an effective intervention. The computer-programmed module MiniFFECT (MINImisation domino eFFECT) [20] enables determining the position of the chemical premises and optimal location to minimize the effects of a cascade event through non-linear programming approaches. The software MiniFFECT depicts the position of every device by the Cartesian coordinates. Three main factors of the domino effects are taken into account: a) thermal load, b) overpressure, c) the effect of the fractures.

Reniers [21] designed a software tool DomPrevPlanning for determining the domino effects with the priority sequence in the industrial plant and planning prevention of the domino effects. This software utilizes three main documents: Instrument Domino Effects (IDE), Manual for Quantity of the Failure Frequency and Instructions for Quantitative Risk Assessment. It serves as a support for making decisions about preventive and protection measures for mitigating the domino effect impacts in the chemical facilities. This software can analyze the risks connected with the domino effect, compare the equipment in the industrial premises and classify the chemical devices that probably cause the escalation effects. Khan and Abbasi [22] developed a computer automated tool MAXCRED (MAXi-mum CREDible accident analysis) for estimating the accidents where the toxic consequences, explosions and fire in the chemical plants develop [22]. This programme serves for a quick quantitative risk assessment of the domino effect development.

2. Approaches of some EU Member States to the prevention of Domino Effects in spatial planning

To reduce the probability of escalating domino effects, EU Member States are adopting strategies at national level in the context of spatial planning. This follows from Article 9 of the SEVESO III Directive itself when: 'Member States shall ensure, through the competent authorities and information from operators, the identification of lower- and upper-tier establishments or groups of establishments where the risk of a major industrial accident or its consequences could be exacerbated because of the geographical location and proximity of such establishments and their stocks of hazardous substances'. [2]

The following paragraphs briefly describe the national approach to spatial planning in relation to hazardous operations of SEVESO plants in some EU Member States.

Germany

The issue is based on the idea that hazardous operations should not endanger their surroundings beyond the boundaries of the SEVESO site, and the risk assessment approach based on the evaluation of the consequences of major industrial accidents is oriented towards this. The assessment and evaluation of "safe distances" using the consequence assessment approach is based on the maximum permissible quantity of hazardous substances, their temperature, pressure and the vulnerability of the surroundings. Consequences are expressed quantitatively in terms of the number of persons injured, killed, the extent of damage to equipment or other material damage.

Table 2. Reference - Threshold values for spatial plnning in the Federal republic of Germany [34]

Toxic threat	Heat radiation	Overpressure
ERPG – 2; ERPG – 3	1,6 [kW.m^{-2}]	10 [kPa]

Netherland

It represents the most rigorous approach in the assessment of domino effects - spatial planning and preventive measures in terms of the criteria imposed on new as well as existing plants. These processes have engineering approaches in place with the application of a strict probabilistic approach. The criteria and procedures mentioned above in the Netherlands require the calculation of individual and societal risk. For these purposes, SEVESO companies mandatorily apply the methodological guide "Purple Book CPR 18E", which has identified sources of risk for an objective assessment and comparison of risky technologies [33]. The reference thresholds set for individual risk in an urbanized area are at 10^{-6} [event . year^{-1}]. Hazard zones that have an individual risk greater than 10^{-5} are unacceptable in terms of encroachment into the urbanised area. The societal risk thresholds are set out in the risk criteria for activities, which are divided into twenty categories. They are defined by frequency of occurrence and acceptable consequences [34].

France

The French approach to risk assessment and management in the context of spatial planning and reduction of escalation of domino effects also focuses on environmental assessment as well as the assessment of the riskiest accident scenario. The competent French public and public authorities use a deterministic approach to assessing the risk of operations, and probabilistic engineering techniques have been actively implemented since the adoption of the transposed SEVESO III Directive. The deterministic approach is based on an assessment of the effects of accidents, i.e. the worst-case scenario for each source of risk must be identified from which the impacts of the hazard zones can be calculated. The worst-case scenario itself is selected based on the largest impacts of the hazard zones, regardless of the probability of occurrence.

Applying the French approach around the risk enterprises identifies two circular hazard zones with thresholds that are set by legislation. The thresholds are used to identify the zones of vulnerability:

- Zone Z1 (Inner Hazard Zone), which defines potentially lethal effects as well as destructive to equipment or property.
- Zone Z2 (External Threat Zone), which defines the impact of irreversible effects [34].

Italy

In the vicinity of hazardous operations, SEVESO enterprises require the identification of four consequence zones. The first zone, similar to the French approach, is defined by a high probability of mortality as well as severe damage to technology or property. The last fourth zone defines moderate reversible consequences. The thresholds for each of the three main cases of physical consequences of an accident (toxic dispersion, overpressure, radiant heat) are defined by legislation. The Italian approach is quite similar to the French approach described above, with the difference that the Italian approach does not require an assessment of individual and societal risk. For each accident scenario, consequence zones R1 - R4 are identified, based on the definition of physical effects thresholds. The probability for each accident scenario is then determined to be between 10^{-6} and > 10^{-3} [events . year^{-1}]. The assignment of the probability interval, the frequency of occurrence of a given scenario, is performed using a 4 x 4 matrix. This means 4 classes of probability of occurrence of an emergency scenario with 4 zones of physical effects consequences [34].

3. Materials and Methods

Currently there are several methodologies for the domino effects solving from the methodology of simple expansion of the accident (the primary accident arouses the second accident), through the multi-level simple catenation (the primary –

secondary – tertiary accident) up to the multi-level and multidirectional catenation [4]

When we assess the escalation – spreading the major industrial accident (MIA) impacts as a primary event, it is important to know if the possible domino effect will cause a secondary event or the secondary events with impacts and consequences will be only in the company. In the case there will be the intra-company impacts and consequences of the secondary or tertiary events in the premises controlled by the operator, then the operator (when assessing the MIA risk with a potential of the domino effect/s) will take into account this potential in such a way that he/she will "load" the frequency of the accident occurrence on the corresponding equipment by the value of the domino effect´s frequency value. The Figure 2 presents the possibilities of solving the domino effect.

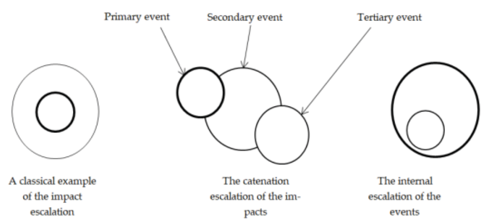

Fig. 2. Alternative possibilities of escalating the impacts of the primary, secondary and tertiary accidents.

It is necessary to realize that the usage of the multi-level methodologies for the primary accident development is already connected with the implementation of the complicated mathematical, physical and chemical models and in the Slovak conditions it does not have any importance. Out of the approximately 100 companies under the law about MIA prevention only 20 – 25 % has any company neighbors working with any greater amount of the hazardous substances. However, the problem is that only a small part of the companies under the law about MIA prevention uses for their analyses and assessment of the individual social risks other software products enabling to assess the accident consequences than the freely available software of the US agency EPA – the software ALOHA [24].

All domino effect models share common features the difference that make them more or less different is in the way the individual domino effects evolve within the sequences or values used to assess equipment failure. In general, research on domino effects focuses on quantitative risk assessment through methods [5]:

- Quantitative Risk Assessment (QRA) [5,7,8,9];
- Bayesian Networks (BN) [5, 12, 35];
- Monte Carlo Simulations (MCS) [5,10,11] ;
- System thinking;
- Gaming theory.

4. Results and Discussion

All companies under the law about prevention of major industrial accidents have to work out a risk assessment procedure that should define if in the case of an accident the undesirable effects of the representative emergency scenarios could spread outside the company premises or not. Except for the risk assessment the establishments should work out an evaluation of the possibility that a domino effect could develop during a major industrial accident. This assessment can be carried out according to the methodological manual by the Slovak Environment Agency [26]. The first methodological manual from 2005 [27] underwent an extensive adaptation. At the beginning a procedure for implementing the documentation of the prevention of major industrial accidents was defined Oravec et al. [28] and then the calculation of acceptability for the need of the law about MIA prevention [29]. In figure 3 there is presented approach for the domino effects assessment used in Slovak republic.

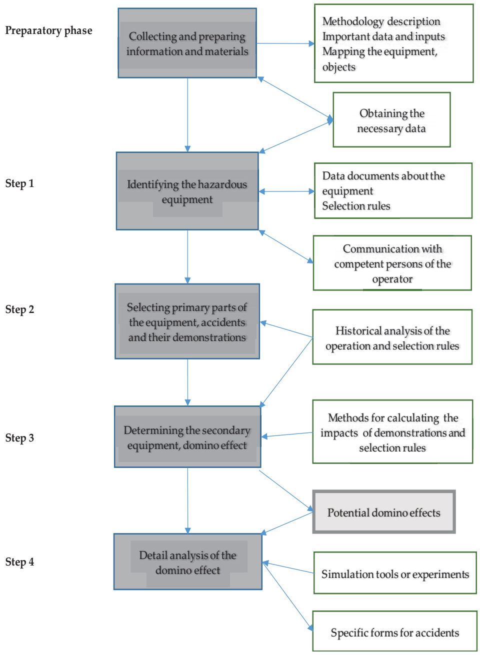

Fig. 3. Gradual steps of the methodology for assessing the possibility of developing a major industrial accident with the domino effect [26].

As it is a legislative obligation resulting from the law about prevention of the major industrial accidents all SEVESO establishments have to take into account also the undesirable impacts due to the potential domino effects already in the risk assessment or during its analysis and evaluation of the social acceptability of developing the major industrial accidents. Currently almost all 80 SEVESO establishments in Slovakia have identified the possible domino effects, however, in reality only the assessments of the category B companies are available for the public – they have to assess them in the Safety Report. The neighbouring companies with a potential to cause a domino effect have been also identified and are involved in the information system of preventing the major industrial accidents that is administered by the Slovak Environment Agency [31].

Table 3. Development of the number of companies determined according to § 13 of the law about accidents

Year	Number of companies		
	Category A (upper tier)	Category B (lower tier)	Total
2017	16	31	47
2018	17	27	44
2019	14	28	42
2020	16	29	45

According to the current findings the majority of the SEVESO establishments with neighbouring companies assess the implementation of the §13 of the law about accidents as an appropriate step and register an improvement of the mutual collaboration and awareness between the enterprises. The acquired data from the neighbours is important for the SEVESO establishments especially for the risk assessment purposes (Table 4).

Table 4. Development of the number of neighbouring companies determined according to the §13 of the law about accidents [36]

Year	Number of		
	neighbouring NON-SEVESO establishments	neighbouring SEVESO establishments	Total
2017	61	32	93
2018	45	23	68
2019	45	26	71
2020	45	29	74

In cooperation with Slovak Environmental Agency we ran the research of utilising the methodological manual presented in the chapter 3 for assessing and evaluating the undesirable impacts of the MIAs. The occurrence of the domino effects was realised in Slovakia through addressing the authorised persons holding the authorisation from the Ministry of Environment of the Slovak Republic according to the § 21 of the law 128/2015 Coll. [25].

5. Conclusions

Besides developing a major industrial accident in the company it is also necessary the possibilities of arising the domino effect in the company framework but also the neighbouring companies that could escalate the consequences of the major industrial accidents and deteriorate also the already hazardous situation.

The methodological manual provides the Slovak enterprises that are under the law about prevention of the major industrial accidents with a transparent, simply usable and systematic tool for assessing the neighbouring companies especially from the point of view of acquiring information about their hazardous equipment and activities. Based on the collected information the companies under the law about prevention of the major in-dustrial accidents can evaluate if the enterprise has a potential to cause the domino effect in the neighbouring companies by developing a major industrial accident. This methodology is not that exceptional in comparison with other similar methodologies, however, it is specific. It is simplified and understandable and solves only the primary domino effects because it has to take into consideration the real situation in this area in Slovakia. First of all it is necessary to understand that the initial conditions for the SEVESO establishments in Slovakia were different than the conditions in western and southern Europe. The transition of the ownership relations (the state-owned companies) to the private ownership had not any sufficient support of the public but also of the competent bodies of the state and public administration.

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