

PAPER • OPEN ACCESS

Assessing risk and resilience of critical infrastructures in the fuel and energy economy involving failure cascading effects

To cite this article: LV Poluyan 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **481** 012010

View the [article online](#) for updates and enhancements.

You may also like

- [Improving robustness of complex networks by a new capacity allocation strategy](#)
Jun Liu and
- [Preparing infrastructure for surprise: fusing synthetic network, interdependency, and cascading failure models](#)
Ryan M Hoff and Mikhail V Chester
- [Protection strategies of active defense in cyber-physical power systems](#)
Lei Chen, Sergey Gorbachev, Dong Yue et al.

PRIME
PACIFIC RIM MEETING
ON ELECTROCHEMICAL
AND SOLID STATE SCIENCE

HONOLULU, HI
Oct 6–11, 2024

Abstract submission deadline:
April 12, 2024

Learn more and submit!

Joint Meeting of
The Electrochemical Society
•
The Electrochemical Society of Japan
•
Korea Electrochemical Society

Assessing risk and resilience of critical infrastructures in the fuel and energy economy involving failure cascading effects

LV Poluyan^{1,2}

¹ Science and Engineering Centre «Reliability and Safety of Large Systems and Machines», Ural Branch, Russian Academy of Sciences, Studencheskaya, 54-A, Yekaterinburg, Russia, 620049

²Ural Federal University, Mira, 19, Yekaterinburg, Russia, 620002.

E-mail: sec@wekt.ru

Abstract. A practical procedure of risk and resilience assessment, with cascading failures occurring in the fuel and energy economy, is proposed. It is based on the threshold values and multi-energy methods. The probability analysis of the equipment damage is carried out using vulnerability models for various equipment classes and in the process the probit-functional analysis is applied. Resilience indices-criteria are used for assessing the resilience of plants as complex mechanical systems. The procedure proposed enables calculating threshold values of cascading failure; safe distances for equipments; probability assessment of failure propagation. It also adds to identifying the facilities triggering cascading effects; probability of the equipment damage; to assessing the amount of damage and the damage loss rate. The strategy (procedure) allows ranking the equipment as related to the risk of domino effects' occurrence; analyzing consequences for each cascade direction and the possibility of its propagation on to the following level; evaluating the resilience state of the plant as a technical system. The damage amount and damage loss rate are evaluated comparing the load received and predetermined threshold values of cascading failure for various equipment classes. The strategy (procedure) developed will allow judging about safety of one or other type of a tank farm containing hydrocarbons; the results obtained in the process and the actual data converge. This strategy (procedure) is strongly recommended to be applied by experts in the field of industrial safety in developing industrial safety manifests, safety justification as well as in developing safety registration certificates of critical infrastructures.

1. Introduction

About 90% of substances involved in cascading failures are combustible while toxic substances make up only 4%. Currently, there are no universal quantitative techniques considering the domino effect, which would be certified, approved and accepted for risk analysis and control [1 - 3]. Analysis of scientific papers has revealed that the methods and techniques based on various vulnerability criteria (50%) and the method of threshold values (39%) are the most widespread methods for taking into account domino effects [4 - 10]. Their common feature deals with the fact that they all consider "domino" scenarios as a separate analysis, starting with the results obtained while making the quantitative risk assessment [2, 11]. These methods do not provide any indication as to how the "domino" effect has to be incorporated into the well-established risk analysis structure. That is why there is an urgent need in integrated methods which clearly define how the "domino" effect can be identified within the frame of the conventional structure of the quantitative risk assessment. To make



sure the proposed strategy (procedure) is effective the following criteria have been deduced: it is to be applicable to the existing well-established methods of analysis; it must not involve complex algorithms of the events' chain analysis; it is to enable calculating risk indices for possible "domino" scenarios and safe distances to prevent property damage and "domino" effect occurrence, taking into consideration specific conditions for each plant. The strategy (procedure) reliability was evaluated comparing the results of the domino effect evaluation and results published in foreign resources. When comparing, symbols, designation, reference data, threshold values of cascading failures were taken from foreign resources.

2. Procedure stages

1. *Determination of threshold values of failure triggering and safe distances for the equipment.* Threshold values of failure triggering (TVFT) for various equipment classes and instructions for calculating safe distances to explosions and fires are taken from [2]. The multi-energy method is used to calculate safe distances (SD) [11]:

$$R_x = R/(E/P_0)^{1/3} \quad (1)$$

where R_x is the non-dimensional distance taken from [2]; R is the distance to the centre of explosion, m; P_0 is atmospheric pressure, $P_0 = 101325$ Pa, E is an effective mixture energy reserve, J , calculated by

$$E = M_T * E_{shc} \quad (2)$$

where M_T is the dry-and-ash-free fuel (combustible substance) in the cloud, which contributes to the explosion, kg; E_{shc} is the specific heat of combustion, $E_{shc} = 44$ MJ/kg for typical hydrocarbons.

In order to determine a SD in case of a failure triggered by an explosion, it is necessary to determine the value of R in (1). If the size of destruction areas at TVFT is greater than the SD values, then the value at which the destruction effects' values are lower than those of TVFT will be taken as a facility- to-facility SD. If necessary, the SD value is calculated with a reserve in order to take into consideration all possible conditions at the plant.

2. *Assessment of the possibility for failure propagation* is made comparing destruction areas obtained as a result of the initial failure consequences' analysis, using TVFT for the equipment and other auxiliary facilities (plants).

3. *Identification of the equipment contributing to failure triggering.* In identifying danger, TVFT can be used as a basis for critical areas identification on the plant's territory with reference to the "domino" effect as it is with the help of TVFT that the facility to facility SD can be calculated. If the propagation is recognized to be possible, another step to be taken is to analyze which of the initial equipment unit can trigger the secondary failure.

4. *Equipment classification with respect to the risk of the "domino" effect occurrence.* It is necessary to rank all the equipment with respect to the "domino" effect occurrence. The «Domino index», DI_k where k is the equipment unit under consideration ($k = 1...X$), X is the number of equipment units, is used to estimate the triggering potential. Effective distance (d_e) is the distance at which TVFT is observed. It is compared with the actual distance (d_f) between two units of the equipment under consideration. Depending upon their relation, the «Distance factor» (DF_{ij}) is determined, where i is the initiating equipment under consideration, while j is the injured equipment being considered ($i, j = 1, \dots, X$). At $i = j$ $DF_{ij} = 0$.

$$DF_{ij} = \begin{cases} (d_e - d_f)/d_e * 100, & d_f < d_e \\ 0, & d_f > d_e \end{cases} \quad (3)$$

Based on the distance factors received for each pair of reservoirs, a matrix of distance factors is built and the domino index is determined using the formula:

$$DI_k = \sum_{i,j=1}^X (DF_{kj} + DF_{ik}) \quad (4)$$

The domino index enables identifying the most hazardous equipment with regard to its capability to cause the “domino” chain and become the secondary, tertiary and further objects of failure triggering. The domino index makes it possible to judge about the equipment in terms of the “domino” effect occurrence and propagation and take every effort to manage the risk. For a reservoir having the highest domino index and when it is not possible to ensure the facility-to facility SD, feasibility for lowering the failure probability is to be considered using safety barriers among other things.

To avoid a cyclic analysis of the equipment it is advisable to analyze the whole possible chain of events which can take place after the initial failure, starting from the unit equipment having the highest potential for triggering. The analysis should be continued up to the units exhibiting the lowest potential for triggering. If the analysis of the whole possible chain of events shows that the equipment having the highest domino index cannot be damaged by the primary failure, it is possible to leave out this equipment and continue analyzing that one the domino index of which is lower but which will be located in the destruction area of the initial event. To avoid a cyclic analysis of the equipment, a representative scenario for the analysis is chosen, where the probability for the equipment to be damaged by vectors of triggering is calculated using probit-functions. This choice is made basing on the triggering potential of each unit equipment. The equipment chain should also be inspected, starting with the facility which doesn't possess the highest index but which can turn out to be a failure precursor on the unit with a higher potential. Such chain of events will lead to the most hazardous consequences. The scenarios where failures occur on several reservoirs right after the primary failure will be characterized by the lowest frequency of occurrence and, consequently, are taken into account only for the reason of necessity, basing on the calculation aims. It is worth noting that the occurrence rate of sequences with the lowest amount of the equipment damaged will always be higher. It is recommended to stop the calculation when the multi-level failure sequence is realized at the rate value lower than $10^{-6} \text{ year}^{-1}$.

5. *Probability of the equipment damage* is analyzed applying vulnerability models for various equipment classes, with the probit-functional analysis being used [2].

6. *The damage amount and the loss rate* are evaluated comparing the load received and predetermined TVFT for various equipment classes. There are various rates of containment losses (LOC), which are related to different damage states (DS). Frequencies of damage states and loss intensity are given in [12].

7. *Identification of triggering vectors*. Using the data obtained, it is possible to approximate the secondary loss of containment and to estimate the triggering vector. Given the substance properties and storage conditions, the triggering vectors obtained will enable assessing the subsequent failures. Failure rates caused by the corresponding containment rates are presented in [12].

8. *Analysis of consequences made for each triggering vector*. Analyzing the consequences of triggering vectors identified earlier it is possible to determine an additional destruction area for each scenario of the secondary failure. In its general view, the occurrence rate of the subsequent failure is calculated as in [2]:

$$f = f_{source} * P_{esc} \quad (5)$$

where f_{source} is the occurrence rate of the primary failure and the corresponding triggering vector; P_{esc} is the probability of triggering the subsequent failure due to the primary one, this probability is determined transforming the probit-function into probability percentage.

9. *Possibility for failure propagation on to the next level*. If additional damaged units are found in the destruction areas of the secondary failure triggering vectors, it is necessary to analyze the further level of triggering. The most quite clearly understandable and recommended approach to analyzing a chain of events is to analyze the tree of events for each representative scenario.

10. *Resilience (Robustness) assessment*. In our case partial resilience is assessed in the context of the domino effect occurrence for the equipment units under consideration. Index-criteria represent a widely-spread approach to assessing resilience of technical systems (TS) [13, 14]. In this research, the «Domino index» can be used to determine the triggering potential in accordance with (3).

In addition, the resilience index based on the ratio of direct and indirect damages can be chosen from the index-criteria list [4, 5]. A robust (survivable) system is considered to be the one where indirect risks do not contribute significantly to the total system risk. With this in mind, the following index of robustness I_{rob} is proposed, which measures the fraction of the total system risk resulting from direct consequences:

$$I_{rob} = R_{dir} / (R_{dir} + R_{ind}). \quad (6)$$

The index takes values from zero to one, depending upon the source of risk. If the system is completely robust and there is no risk caused by indirect consequences, then $I_{rob} = 1$. If all the risk is due to indirect consequences, then $I_{rob} = 0$.

Finally, this index can be easily extended to account for multiple exposures, or more complicated event trees. The robustness index will still be equal to the sum of direct risk divided by the sum of total risk:

Resilience is assessed in the context of the domino effect occurrence for the equipment units under consideration. Index-criteria represent a widely-spread approach to assessing resilience of technical systems (TS) [13, 14]. In this research, the «Domino index» can be used to determine the triggering potential in accordance with (3).

In addition, the resilience index based on the ratio of direct and indirect damages can be chosen from the index-criteria list [4, 5]. A robust (survivable) system is considered to be the one where indirect risks do not contribute significantly to the total system risk. With this in mind, the following index of robustness I_{rob} is proposed, which measures the fraction of the total system risk resulting from direct consequences:

$$I_{rob} = R_{dir} / (R_{dir} + R_{ind}). \quad (6)$$

The index takes values from zero to one, depending upon the source of risk. If the system is completely robust and there is no risk caused by indirect consequences, then $I_{rob} = 1$. If all the risk is due to indirect consequences, then $I_{rob} = 0$.

Finally, this index can be easily extended to account for multiple exposures, or more complicated event trees. The robustness index will still be equal to the sum of direct risk divided by the sum of total risk:

$$I_{rob} = \sum_i R_{dir_i} / \left(\sum_i R_{dir_i} + \sum_j R_{ind_j} \right). \quad (7)$$

3. Example

Comparison analysis of the procedures offered and developed in [15] has been conducted. The initial data was taken from the procedure used to analyze cascading effect vulnerability of industrial enterprises. A failure in the tank farm was investigated; there were eight similar reservoirs of 200 m³ (PBC-200) volume capacity at atmospheric pressure in the tank farm, containing benzol. The farm site plan is presented in Figure 1.

Constraints accepted. Spillage fire was dealt with. Heat radiation of $I = 15$ kWt/m² was taken as TVFT. Outflow out of the hole of 15 c diameter at the constant speed was chosen as the most likely reason for initiating failure at every level of triggering. Areas of destructive factors are calculated from the wall of reservoir T_i to the wall of reservoir T_j . The calculations were made using software ALOHA 5.4.7 [16, 17].

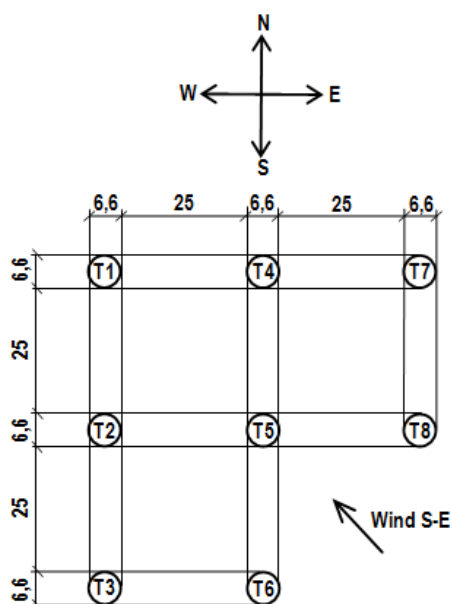


Figure 1. Farm site plan.

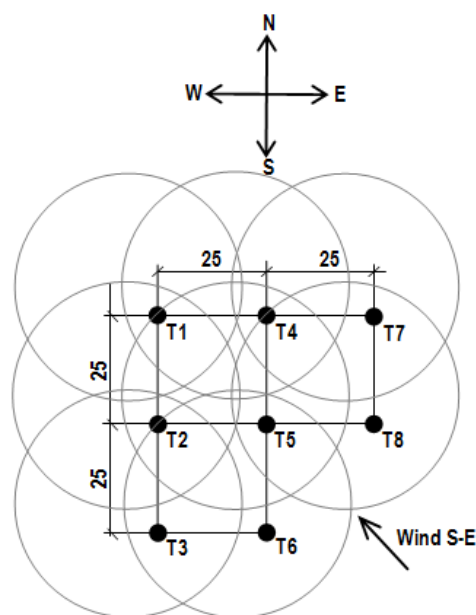


Figure 2. Destruction areas at $I = 15 \text{ kWt/m}^2$ of heat radiation intensity.

1. Assessment of the possibility for failure propagation. Table 1 demonstrates intensity values for all the units of the farm equipment, where the values exceeding the triggering threshold are given in the boldface type. Making a pattern of areas destroyed by the threshold values of triggering on the site plan will be the next step.

The results of patterning the destruction areas are shown in Figure 2, on the basis of which safe distances can be obtained with the aim of preventing the “domino” effect occurrence at the plant (farm). Thus, taking into consideration the minimum possible SDs between units of the equipment and using the destruction areas, we have $d = 32.4 \text{ m}$.

The maximal value of $d = \max(32.4; 55) = 55 \text{ m}$ is taken as SD. In order to completely eliminate the possibility of failure triggering and allow for various directions and the speed of wind over the course of a year, it is recommended to use the value of $d = 65 \text{ m}$ instead of $d = 55 \text{ m}$. The farm site plan obtained is demonstrated in Figure 3.

Table1. Heat radiation intensity (kWt/m^2) due to the influence of T_i on T_j

T_i	T_j							
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8
T_1	–	9.6	2.9	9.6	4.5	2.1	2.9	2.1
T_2	24.8	–	9.6	8.0	9.6	4.5	2.9	2.9
T_3	5.6	24.8	–	3.7	8.0	9.6	2.0	2.9
T_4	24.8	8.0	2.9	–	9.6	2.9	9.6	4.5
T_5	16.0	24.8	8.0	24.8	–	9.6	8.0	9.6
T_6	4.8	16.0	24.8	5.6	24.8	–	3.7	8.0
T_7	5.6	3.7	2.0	24.8	8.0	2.9	–	9.6
T_8	4.8	5.6	3.7	16.0	24.8	8.0	24.8	–

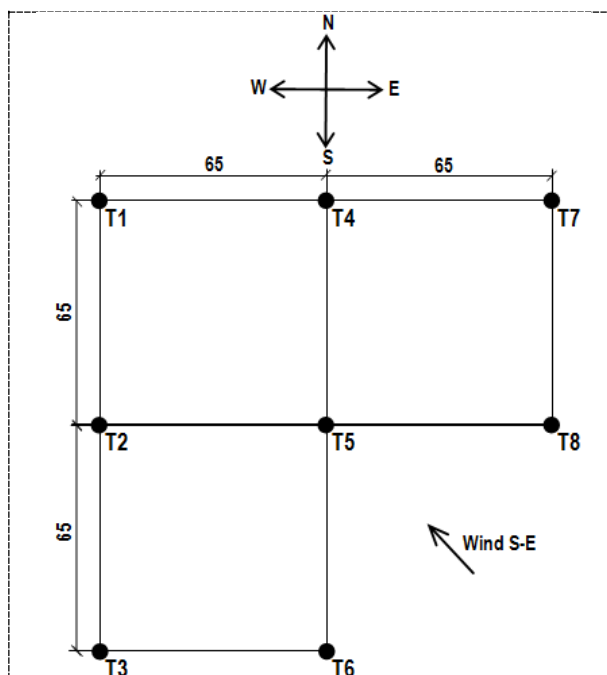


Figure 3. Site plan with regard to safe distances.

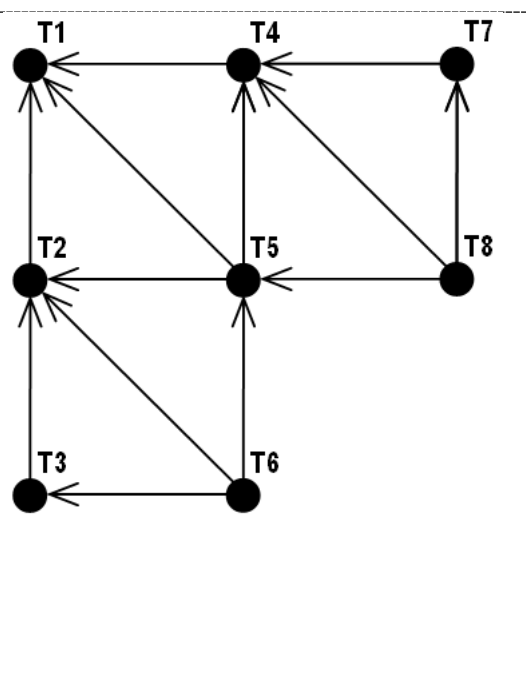


Figure 4. All possible triggering vector directions caused by spillage fire.

2. *Identification of the equipment contributing to failure triggering.* In order to find out which of the equipment units can contribute to the secondary failure occurrence, the data published in Table 1 and shown in Fig. 2 is used. The primary failure in the “domino” chain can be failures on reservoirs T_2 - T_8 . The failure on reservoir T_1 is not capable of becoming a trigger.

Comparing the data received it is possible to state that reservoirs T_5 , T_6 , T_8 will be the most hazardous units of the equipment as a failure on each of them can affect most of the similar units. All possible directions of the triggering vector caused by spillage fire on each equipment unit are designated by arrows in Figure 4.

3. *Equipment classification with respect to the risk of the “domino” effect occurrence.* Let’s assess the equipment that creates destruction areas which affect other units of the equipment or is located in an area destroyed by threshold values of failure triggering. Using 2.3 и 2.4, we rank the equipment with respect to the triggering potential.

Distance factors are then defined for reservoir T_5 , using Figure 2: $DF_{51} = (36 - 35.4)/36 * 100 = 1.7$; $DF_{52} = (32.4 - 25)/32.4 * 100 = 22.8$; $DF_{54} = (32.4 - 25)/32.4 * 100 = 22.8$. Similarly, we define distance factors for other units of the equipment. The results are given in Table 2.

Table 2. Matrix of distance factors DF_{ij} .

T_i	T_j							
	1	2	3	4	5	6	7	8
1	0	0	0	0	0	0	0	0
2	22.8	0	0	0	0	0	0	0
3	0	22.8	0	0	0	0	0	0
4	22.8	0	0	0	0	0	0	0
5	1.7	22.8	0	22.8	0	0	0	0
6	0	1.7	22.8	0	22.8	0	0	0
7	0	0	0	22.8	0	0	0	0
8	0	0	0	1.7	22.8	0	22.8	0

Let's determine the domino index for every unit of the equipment: $DI_1 = DI_6 = DI_8 = 47.3$; $DI_2 = DI_4 = 70.1$; $DI_3 = DI_7 = 45.6$; $DI_5 = 92.9$. The event chain being analyzed is $T_5 \rightarrow T_2/T_4 \rightarrow T_1$. It's worth noting that the most hazardous scenario where the "domino" effect reaches the third level of triggering and propagates involving only one subsequent unit of the equipment at each level will be $T_6/T_8 \rightarrow T_5 \rightarrow T_2/T_4 \rightarrow T_1$ (Figure4). Scenarios dealing with the occurrence probability less than $10^{-6} \text{ year}^{-1}$ are not considered.

4. *Analysis of the equipment damage probability.* The rate of the outflow from the hole at the constant speed is $f_i = 1 * 10^{-4} \text{ year}^{-1}$. To assess the probability P_{esc} of T_2/T_4 reservoir damage caused by the spillage fire on reservoir T_5 , the probit-function [67] $Y = 9.25 - 1.85 * \ln(ttf/60)$ is considered, where $\ln(ttf) = -1.13 * \ln(I) - 2.67 * 10^{-5} * V + 9.9$, ttf is the time in seconds till the failure, V is the reservoir volume (m^3), the heat flow is $I = 24.8 \text{ kWt/m}^2$. The calculations proved that $Y = 5.17, P_{esc} = 5.7 * 10^{-1}$.

5. *Assessment of the damage amount and the loss rate.* In accordance with the tabulated data on the relationship of threshold values and corresponding containment losses rates at the specified heat radiation, a reservoir will be damaged as a result of which its loss rate will be equal to LOC3 class, and the damage amount will be DS2 [18].

6. *Identification of triggering vectors.* The following triggering vectors [69] are possible for the reservoirs at atmospheric pressure and LOC3 containment loss rate: fire-flash of $P_{f.f.} = 0.8 * 10^{-1}$ probability and spillage fire of $P_{s.f.} = 2 * 10^{-1}$ probability.

7. *Analysis of consequences for each triggering vector.* Due to the constraints accepted earlier, the spillage fire and heat radiation are considered to be the only triggering vector of the injured equipment. Thus, $T_5 \rightarrow T_2/T_4$ failure occurrence rate without further triggering vectors is calculated in the following way: $f_{5-2/4} = f_i * P_{n.n} * P_{esc} = 1 * 10^{-4} \text{ year}^{-1} * 2 * 10^{-1} * 5.7 * 10^{-1} = 1.14 * 10^{-5} \text{ year}^{-1}$.

8. *Possibility for failure propagation on to the next level.* When there is a failure on T_2/T_4 reservoir, T_1 reservoir is affected by $I = 24.8 \text{ kWt/m}^2$ which is greater than the threshold value of 15 kWt/m^2 . Calculations will be similar to the previous ones and the probability will be $P_{esc} = 5.7 * 10^{-1}$.

Trees of events are used to make the analysis of the representative chain of events strikingly visual. In accordance with the constraints accepted, the tree of events for the case under consideration is given in Figure 5.

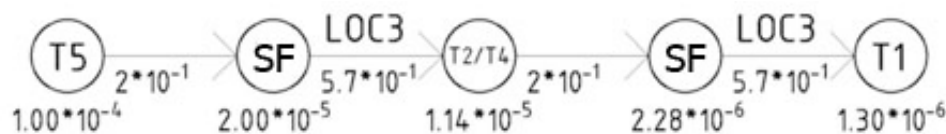


Figure 5. Tree of events for the "domino" chain under consideration.

In Figure 5 - $T_5, T_2/T_4, T_1$ nodes are reservoirs' designations; SF is spillage fire; LOC3 is the rate of the containment loss; the values given under the nodes represent rates of occurrence; the values located under the connecting ribs designate the probability of transition from the previous state to the following one. Thus, the estimated value of the representative $T_5 \rightarrow T_2/T_4 \rightarrow T_1$ scenario rate will be $f_{5-2/4-1} = f_i * P_{n.n.1} * P_{esc.1} * P_{n.n.2} * P_{esc.2} = 1 * 10^{-4} \text{ year}^{-1} * 2 * 10^{-1} * 5.7 * 10^{-1} * 2 * 10^{-1} * 5.7 * 10^{-1} = 1.3 * 10^{-6} \text{ year}^{-1}$. Comparison analysis of equipment ranking calculations based on the procedure developed and that presented in [2] correlate well with each other.

The ranking results agree very closely. The rates of the failure occurrence being considered are of one order $1.14 * 10^{-5} \text{ year}^{-1}$ and $2.92 * 10^{-5} \text{ year}^{-1}$ correspondingly, which is accounted for by

different calculation procedures as well as by redistribution of probabilities in the Bayesian Networks as a result of treating even the least probable scenarios.

4. Future work

Of particular urgency is programmed implementation of the strategy which enables increasing the number of equipment units used for quick assessment of cascading failure. As mathematics used is simple for understanding, the strategy algorithm is not complicated as well.

The programming code in combination with GIS-technologies will allow considering all possible chains of events and, in doing so, to improve the calculation accuracy.

5. Conclusion

The strategy developed can be integrated in to the conventional structure of risk analysis and assessment; its mathematics is easy to utilize and it is independent of complicated algorithms of the events' chain analysis. Using it, it is possible to determine rates and consequences of the "domino" effect for equipment, safe distances to prevent property damage and triggering the "domino" effect.

This procedure can be used by experts for obtaining quick assessments in estimating the danger in tank farms having up to 10 units of equipment.

Unlike other more complicated techniques (weighted graphs, Bayesian Networks), the procedure developed does not require time consuming modeling for every particular set of conditions at the plant. It can be used by experts in the field of industrial safety in developing industrial safety manifests, safety justification as well as in developing safety registration certificates of critical infrastructures.

References

- [1] Khakzad N, Reniers G, Abbassi R, Khan F 2016 Vulnerability analysis of process plants subject to domino effects *Reliability Engineering and System Safety* **154** pp 127-136
- [2] Casal J 2018 *Evaluation of the Effects and Consequences of Major Accidents in Industrial Plants* (Elsevier) Second edition 570 p.
- [3] Li J, Reniers G, Cozzani V, Khan F 2017 A bibliometric analysis of peer-reviewed publications on domino effects in the process industry *Journal of Loss Prevention in the Process Industries* **49** pp 103-110
- [4] Clini F, Darbra R M, Casal J 2010 Historical Analysis of Accidents Involving Domino Effect *Chemical Engineering Transactions* **19** pp 335-340
- [5] Darbra R M, Palacios A, Casal J 2010 Domino effect in chemical accidents: main features and accident sequences *Journal of Hazardous Materials* №**183** pp 565–573
- [6] Zi-jian Ni, Yanzhang Wang, Zhigang Yin 2016 Relative risk model for assessing domino effect in chemical process industry *Safety Science* **87** pp 156-166
- [7] Cozzani V, Gubinelli G, Antonioni G, Spadoni G, Zanelli S 2005 The assessment of risk caused by domino effect in quantitative area risk analysis *Journal of Hazardous Materials* **127** pp 14-30
- [8] de Lira-Flores J, Vazquez-Roman R, Lopez-Molina A, Mannan M S 2014 A MINLP approach for layout designs based on the domino hazard index *Journal of Loss Prevention in the Process Industries* **30** pp 219-227
- [9] Goodarzi M N, Farahani A F, Hosseini S E, Tavakoli M 2015 The Application of Domino Effect for Risk Analysis of Critical Assets in Oil Industry *International Journal of Biology, Pharmacy and Allied Sciences (IJBPAS)* №**4** pp 1850-1857
- [10] Mukhim E D, Abbasi T, Tauseef S M, Abbasi S A 2017 Domino effect in chemical process industries triggered by overpressure – Formulation of equipment-specific probits *Process Safety and Environmental Protection* **106** pp 263-273
- [11] The Russian State Standard Specification 12.3.047-2012. Occupational safety standards system. Fire safety of technological processes. General requirements. Methods of control

- [12] Bernechea E J, Vilchez J A, Arnaldos J. 2012 A model for estimating the impact of the domino effect on accident frequencies in quantitative risk assessments of storage facilities *Process Safety and Environmental Protection* **91** pp 423-437
- [13] Baker J W, Schubert M and Faber M H 2008 On the assessment of robustness *Structural Safety* **30** No.3 pp 253-267 doi:10.1016/j.strusafe.2006.11.004.
- [14] Schubert M, Faber M 2008 On the modeling and analysis of robustness of systems. Inaugural *Int. Conference of the Engineering Mechanics Institute*
- [15] Khakzad N, Reniers G 2015 Using graph theory to analyze the vulnerability of process plants in the context of cascading effects *Reliability Engineering and System Safety* **143** pp 63-73
- [16] Jones R, Lehr W, Simecek-Beatty D, Reynolds R M 2013 ALOHA®(Areal Locations of Hazardous Atmospheres)5.4.4:Technical Documentation U. S. Dept. Of Commerce, NOAA Technical Memorandum NOS OR&R 43.Seattle, WA: Emergency Response Division, NOAA. 96 p
- [17] The CAMEO Software Suite ALOHA® Example Scenarios National Oceanic and Atmospheric Administration Office of Response and Restoration Emergency Response Division Seattle, Washington. U.S. Environmental Protection Agency Office of Emergency Management Washington, D.C. 2016. 53 p.
- [18] Bernechea E J, Vilchez J A, Arnaldos J 2012 A model for estimating the impact of the domino effect on accident frequencies in quantitative risk assessments of storage facilities *Process Safety and Environmental Protection* **91** pp 423-437