Safety and Reliability – Safe Societies in a Changing World – Haugen et al. (Eds)
© 2018 Taylor & Francis Group, London, ISBN 978-0-8153-8682-7

Analysis of domino scenarios in chemical and process facilities operating in harsh environmental conditions

M. Bucelli
Alma Mater Studiorum—University of Bologna, Bologna, Italy
Norwegian University of Science and Technology NTNU, Trondheim, Norway
Safetec, Trondheim, Norway

G. Landucci
University of Pisa, Pisa, Italy
University of Leiden, Den Haag, The Netherlands

S. Haugen & N. Paltrinieri
Norwegian University of Science and Technology NTNU, Trondheim, Norway

V. Cozzani
Alma Mater Studiorum—University of Bologna, Bologna, Italy

ABSTRACT: In the framework of chemical and process industry, accidental fires may lead to damages to equipment with severe consequences and possible domino effects. The availability and effectiveness of safety measures, aimed at reducing the risk associated with this type of events, may be strongly affected and decreased if the facility is located in harsh environment, due to complicating meteorological factors and extreme temperatures. The present work is aimed at defining a structured approach to the quantitative assessment of fired domino events accounting for the influence of harsh environment conditions on safety barriers performance. A specific metric is defined in order to consider the external factors related to harsh environments on the determination of hardware and emergency safety barriers availability and effectiveness, with a specific focus on the evaluation of the time-scale of emergency response. A dedicated event tree analysis is then applied implementing the obtained performance values of the safety barriers, in order to support the quantitative assessment of accident frequency associated with domino scenarios. The present method is applied to the analysis of a chemical facility located in harsh environmental conditions.

1 INTRODUCTION

In the last decades, interest has been increasing for cascading events and the assessment of their possible risks. The chemical process industry has been hit by major accidents worldwide, some of which were completely disregarded by hazard identification techniques (Paltrinieri et al., 2010; Paltrinieri and Reniers, 2017). Among them, several domino events have been documented (Abdolhamidzadeh et al., 2011; Darbra et al., 2010; Delvosalle, 1996; Kourniotis et al., 2000; Lees, 1996; Rasmussen, 1996).

One of the most destructive cascading event disasters is the one that happened in Mexico City in 1984 (Pietersen, 1988). Europe recognized the hazard posed by domino events and specific requirements are stated in the article 9 of the latest Seveso Directive (European Commission, 2012). According to these, the risk of propagation of primary hazardous scenarios to nearby units is required to be assessed.

Different safety barriers are used and monitored in chemical process plants (Paltrinieri and Khan, 2016), such barriers defined to prevent escalation scenarios. These include active, passive and procedural protections. Examples include the water deluge system (WDS), fireproofing coating, pressure safety valves (PSVs) and the site emergency response plan. Different performance parameters in terms of availability (expressed as probability of failure on demand) and effectiveness are associated to every safety barrier.

However, barriers are subject to deterioration and depletion of their performance. Meteorological and climatological conditions are factors that can enhance these phenomena. For instance, cold temperatures, extreme wind and snowfall may either cause deterioration of hardware plant components or lead to difficulties for operators performing routine tasks and/or in emergency contingency situations (Bercha et al., 2003; Gao et al., 2010). The Arctic and sub-Arctic regions experience extremely unique weather conditions that may be challenging for technical barrier components as well as human intervention. However, a dedicated framework for the analysis of safety barriers performance degradation in harsh environment is still missing.

This work is aimed at investigating the safety barrier performance of chemical and process facilities operating in harsh environmental conditions, in order to evaluate the frequency and probability of escalation scenarios triggered by fire.

The paper is organized as follows: Section 2 provides a detailed overview of the methodology applied to assess the frequency of cascading events addressing the effect of severe environment on protection devices; Section 3 describes the reference case considered for the present analysis; the results of the application of the methodology to the reference case are shown in Section 4, while Section 5 provides room for their discussion. The paper ends with conclusions in Section 6.

2 METHODOLOGY

2.1 *Overview*

Figure 1 shows the flowchart of the methodology adopted in the present study. The methodology was developed for the oil and gas sector (Landucci et al., 2017) and it is hereby extended to chemical process industry. A detailed description of the methodology is provided in sections 2.2–2.5.

2.2 *Identification of reference safety barriers*

The first step of the methodology consists of a preliminary characterization of the safety barriers performance, with particular reference to the prevention and mitigation of cascading events triggered by fire. According to CCPS—Center of Chemical Process Safety (2000), barriers are classified as:

- Passive, which are in place and do not require external activation;
- Active, which require automatic and/or external activation;
- Procedural and emergency measures, which involve the intervention of operators and emergency teams.

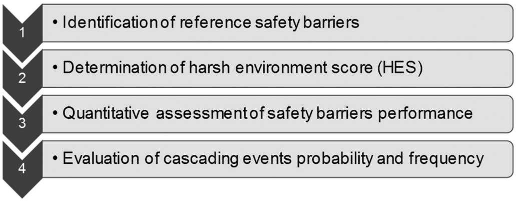


Figure 1. Flowchart of the methodology.

This step is based on the application of a previously developed methodology (Landucci et al., 2016) in which the evaluation of safety barriers performance in the framework of escalation is aimed at quantifying:

- availability, defined as the probability of failure on demand (*PFD*) of the safety barriers;
- effectiveness (η), defined as the probability that the safety barrier, once successfully activated, will be able to prevent the escalation.

Once the parameters needed to support the quantitative evaluation of safety barriers are defined, the influence of harsh environmental conditions on their performance is inferred in the following steps.

2.3 *Definition of Harsh Environment Score (HES)*

The Harsh Environment Score (*HES*) is a preliminary metric aimed at describing the harshness of the environment and it is used to assess the influence of weather conditions on safety devices performance. *HES* consists of a combination of different site-specific environmental parameters, such as, for instance, temperature and wind velocity.

The approach for the *HES* evaluation is based on the identification of stressors. They are factors that mostly affect the human performance during operations in extreme weather conditions (Section 2.4.1) but are adopted in the present study also to address the influence of extreme weather conditions on hardware barriers performance (Section 2.4.2).

Musharraf et al. (2013) identify the significant stressors for harsh environment as coldness, ice slippery, difficulty in breathing, combined weather effect, low visibility and remoteness. The present approach associates one or more external factors (EFs) to each stressor. EFs are climate or environmental conditions that can be measured and/or quantified. To each EF, a non-dimensional penalty, namely a score S_i, is assigned. Scores represent the distance from favorable conditions. They vary from 0 to 1, where 0 represents good favorable conditions and 1 the worst ones. Table 1 lists the EFs and relative scoring system applied in the present study.

Table 1. Summary of external factors and scores adopted for HES evaluation (adapted from Landucci et al., 2017).

External factor	ID	Range	S_i
Temperature (°C)	1	>45	0.4
		4 to 45	0
		–4 to 4	0.2
		–10 to –4	0.6
		–30 to –10	0.8
		<–30	1
Extreme wind speed (m/s)	2	0 to 3.3	0
		3.3 to 5.5	0.2
		5.5 to 8	0.4
		8 to 10.8	0.6
		10.8 to 13.9	0.8
		>13.9	1
Snowfall (m/year)	3	0 to 0.125	0
		0.125 to 0.5	0.2
		0.5 to 1	0.4
		1 to 1.5	0.6
		1.5 to 2	0.8
		>2	1
Visibility (fog/snow) (m)	4	<50	1
		50 to 200	0.8
		200 to 500	0.6
		500 to 1000	0.4
		1000 to 2000	0.2
		>2000	0
Sunlight hours (h/year)	5	<1200	1
		1200 to 1600	0.8
		1600 to 2000	0.6
		2000 to 2400	0.4
		2400 to 3000	0.2
		>3000	0
Remoteness	6	Low	0
		Medium	0.5
		High	1

More detailed information about the scores assignment process and the EFs may be retrieved in a previous study (Landucci et al., 2017). The scores are assigned according to extensive literature surveys about the effects of different physical factors on technical and human behavior (American Petroleum Institute, 2000; DOA—Department of Army, 1982; Kunkel et al., 2007; Landsberg and Pinna, 1978; Musharraf et al., 2013; Shaw and Austin, 1919).

Finally, *HES* is obtained as a weighted summation of the assessed scores, as follows:

$$HES = \sum_{i=1}^{N} w_i S_i \tag{1}$$

where S_i and w_i are respectively the score and the weight associated to the *i*-th EF. In the present analysis, a preliminary set of weights is assigned by using the Zipf's law (Zipf, 1949).

2.4 *Barrier performance assessment*

2.4.1 *Hardware barriers*

According to Gao et al. (2010), extreme environmental conditions may affect hardware barrier availability but they have no significant effect on their effectiveness. The depletion of barrier performance is strictly related to environmental temperature. Recommended Practices 581 by American Petroleum Institute (2000) identify a threshold value of −6.7°C for considerable effect on protection performance. This value corresponds to a penalty $S_1 = 0.6$ or higher according to Table 1. This framework addresses the depletion in barrier availability using the proportional hazard model (Cox, 1972) as suggested by Gao et al. (2010). The failure rate of a generic component, λ, increases in harsh environment according to the following relationship:

$$\lambda(z) = \lambda_0 \, e^{-1.409 z_1 - 1.013 z_2} \tag{2}$$

where λ_0 is the failure rate in normal environment (namely, the baseline value), assumed hereby as constant during the entire lifecycle of the facility. The factors z_1 and z_2 are the named covariates; z_1 describes the protection conditions and z_2 the equipment quality, respectively. Covariates are considered as binary and they can assume the value +1 or −1. The positive value is associated with good quality of protections and equipment. The base relationship for the estimation of tested component unavailability (Lees, 1996) is applied to obtain the barrier *PFD* describing, from this analysis perspective, the barrier availability.

The present work considers that the effectiveness of the barriers is not affected by environmental conditions. Once activated, hardware barriers perform as in the case of normal environment (Landucci et al., 2016).

The reference active safety barriers analyzed in the present study are water deluge systems (WDS) aimed at attenuating heat radiation from fires affecting process units. According to different experimental studies (Hankinson and Lowesmith, 2004; Roberts, 2004a, 2004b; Shirvill, 2004), the heat-load reduction on a target due to presence of WDS is about 50% compared to the unmitigated case. Hence, Q_{WDS} (the heat load received by a fired target in case of available WDS) is expressed as follows:

$$Q_{WDS} = 0.5\, Q_{HL} \tag{3}$$

where Q_{HL} represents the heat-load affecting the target due to the primary fire scenario.

Passive safety protections include the PSV and the fireproofing coating. Birk (2006) proved that the presence of the PSV alone does not delay significantly the time to failure (*TTF*) of the target equipment. In that case, the PSV effectiveness is considered as unitary but the TTF is evaluated assuming that the vessel is unprotected (Landucci et al., 2009). Fireproofing coatings are instead able to delay the vessel failure. Their effectiveness is set as 1. The *TTF* of the target vessel in case of presence of protective coatings is evaluated by adding a further term, TTF_C, as shown in Eq. (4), which represents the delay action of the coating:

$$TTF = TTF_{unprotected} + TTF_C \tag{4}$$

The TTF_C is evaluated according to a simplified approach considering the quality of the materials used as coating. For high performance materials (intumescent, vermiculite spray, fibrous mineral wool) the TTF_C is set conservatively as 70 minutes. TTF_C is equal to 0 minutes in case of use as coatings of common insulating materials (glass wool, rock wool).

2.4.2 *Procedural barriers*

Human reliability may be significantly affected by extreme weather (Musharraf et al., 2013).

A customized version of the Success Likelihood Index Methodology (SLIM) (Embrey, 1986) is adopted in the present framework to evaluate the deterioration of emergency response availability (e.g. in terms of *PFD*). *HES* is considered as a simplified ranking of performance shaping factors affecting the emergency response in harsh environment (Landucci et al., 2017). The higher the *HES* the lower the probability of success of the emergency team intervention. The *PFD* is then evaluated as:

$$\log_{10} PFD = \mathrm{a}\left(1 - \mathrm{HES}\right) + \mathrm{b} \tag{5}$$

where *a* and *b* are –0.954 and –0.046 respectively. They have been determined by setting the *PFD* equal to 0.1 in case of favorable environmental conditions ($HES = 0$) and by setting the *PFD* as 0.9 in worst case environmental conditions ($HES = 1$) (Landucci et al., 2016).

The evaluation of the emergency response effectiveness is carried out by following the approach suggested by Landucci et al. (2017). The evaluation is based on the comparison between the *TTF* of the target equipment and the Time for Final Mitigation (*TFM*) required to the emergency team to extinguish the primary fire. The *TFM* is defined as the sum of different times for emergency operations as follows:

$$TFM = \sum_{j=1, j\neq 2}^{6} \tau_j \tag{6}$$

The times are defined according to Table 2 (Landucci et al., 2017), where also the different relationships applied to account for the delay due to harsh environment are shown. The effectiveness of the emergency response is set equal to 1 or 0 by comparison between *TFM* and *TTF* of the target equipment. When *TFM* is lower than *TTF* of the target equipment, the emergency response effectiveness is set as unitary, otherwise it is zero.

2.5 *Evaluation of escalation probability*

A customized Event Tree Analysis (ETA) is adopted in order to evaluate the frequency (and probability) of domino escalation triggered by fire. The availability and effectiveness of barriers evaluated as described in Section 2.4 are addressed in the ETA by using dedicated logic gates, as shown in Table 3.

Further detailed information about gate definitions may be retrieved elsewhere (Landucci et al., 2016).

Gate A represents a simple composite probability. In this case, the availability (expressed in terms of PFD) is multiplied by a single probability value expressing the probability of barrier success in the prevention of the escalation.

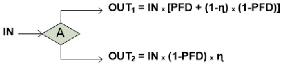
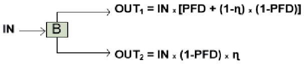
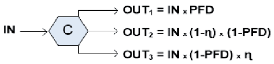
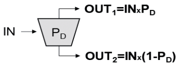
Gate B represents a composite probability distribution. In this case, the PFD is multiplied by a

Table 2. Time scale for emergency operations and simplified relationship for the estimation of time increment due to harsh environment (adapted from Landucci et al., 2017). The baseline is the time required in normal environment (HES = 0).

ID	Name	Baseline (min)	Simplified relationship (τ in min)
τ_1	Time to alert	5	$\log_{10} \tau_1 = -0.3\left(\mathrm{I} - \mathrm{HES}\right) + 1$
τ_2	Time to onsite mitigation	20	$\log_{10} \tau_2 = -0.3\left(\mathrm{I} - \mathrm{HES}\right) + 1.6$
τ_3	Time for external team intervention	12	$\log_{10} \tau_3 = -0.3\left(\mathrm{I} - \mathrm{HES}\right) + 1.38$
τ_4	Time for equipment deployment	7	$\log_{10} \tau_4 = -0.3\left(\mathrm{I} - \mathrm{HES}\right) + 1.15$
τ_5	Time for extra set-up operations	8	$\log_{10} \tau_5 = -0.3\left(\mathrm{I} - \mathrm{HES}\right) + 1.2$
τ_6	Additional time in case of need of interregional assistance	30–60[a]	$\log_{10} \tau_1 = -0.3\left(\mathrm{I} - \mathrm{HES}\right) + 2.08$

[a] Depending on the type of location.

Table 3. Summary of gates introduced in the ETA to account of barrier performance (adapted from (Landucci et al., 2016)).

Gate type	Graphical representation
A	
B	
C	
D	

probability distribution expressing the probability of barrier success in the prevention of escalation, thus obtaining a composite probability of barrier failure on demand. In this work, the integrated probability is adopted, obtaining the rule for gate quantification reported in Table 3.

Gate C is associated with a discrete probability distribution.

Finally, Gate D incorporates equipment vulnerability models based on probit approaches for the estimation of P_D (the probability of vessel failure). The effect of harsh environmental conditions has been addressed in the probit models in describing the vessel resistance behaviour. More details on vessel fragility models are extensively described in previous works (Landucci et al., 2009).

3 CASE STUDY

3.1 *Overview*

The reference case study refers to a production plant for the production of personal and home hygiene products. The plant uses as main raw materials ethanol and propane and, for the quantities stored, it is subject to fulfill the Seveso Directive requirements concerning hazardous materials (European Commission, 2012). The field is located in harsh environment (see Section 3.2). The methodology described in Section 2 is applied to estimate the frequency of domino events triggered by fire and thus providing a more complete risk picture of the facility.

Figure 2 shows the layout considered in the analysis of the case study. Ethanol is stored in three underground tanks (T1, T2, T3) with an overall volume of 90 m^3 and kept at 15°C. Ethanol is transferred to the processing area (see Fig. 2) through a pipeline featuring 20 m length and a nominal diameter of 100 mm. Full-bore rupture of the pipeline is considered to derive the features of the primary scenario potentially triggering the domino escalation. In particular, a non-confined pool fire following immediate ignition of the spilled ethanol is taken into account. A standard frequency of $3.9 \cdot 10^{-7}$ y^{-1} has been assumed from literature analysis for pool-fire. The physical effects associated with the pool fire have been analyzed applying the conventional literature integral models implemented in the DNV GL Phast 7.11 commercial software. According to consequence assessment results, the pool fire affects the target propane storage tank (V1, see Fig. 2), which is exposed to about 48 kW/m^2.

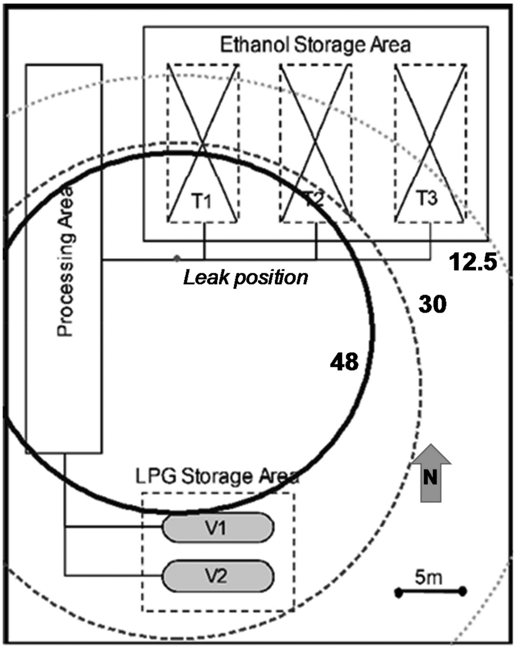


Figure 2. Layout defined for the case study associated with a non-confined pool-fire following the rupture of the process ethanol pipeline.

The safety barriers in place to protect V1 are listed in Table 4. They are defined on the basis of different regulations for fire protection of liquefied petroleum gas storage units (American Petroleum Institute, 1996; National Fire Protection Agency (NFPA), 2018, 2017). The results of their performance assessment (in normal and harsh environments) are shown in Section 4. The quality of both the target equipment V1 and its protection devices is assumed as low following a conservative approach.

Table 4. Summary of fire protection devices for horizontal LPG storage tank (American Petroleum Institute, 1996; National Fire Protection Agency (NFPA), 2018, 2017).

Target	Active barriers	Passive barriers	Procedural barriers
V1	Water deluge system (WDS-V1)	Pressure safety valve (PSV-V1) Fireproofing coating (PFP-V1) (2 h rating)	Emergency response (ER-01)

3.2 *Environmental and meteorological conditions*

The reference production plant is located in an industrial site close to Bodø just North of the Arctic Circle, in Norway. The climatic conditions in the reference area can be characterized as severe. Table 5 summarizes the meteorological and climatological conditions experienced in that area and adopted for the determination of *HES* and, thus, to derive performance data in harsh environment.

4 RESULTS

4.1 *Performance assessment of safety barriers*

Adverse meteorological conditions significantly affect the protection effect of safety devices. In order to account for this effect, the methodology described in Section 2 has been applied to the reference chemical processing plant described in Section 3.

According to the meteorological and climatological data summarized in Table 5 and to the scoring system described in Section 2.3, the estimated *HES* is 0.43 for the considered case. This value is implemented to evaluate the performance of the safety barrier protecting the target tank V1. Since the score associated with the external temperature $S_1 = 0.6$, a degradation of hardware barrier availability must also be considered (see Section 2.4.1).

Data were also calculated for normal environmental conditions for sake of comparison (thus, featuring *HES* = 0). The time for external emergency response is calculated according to the guidelines described in Section 2.4. It increases from 77 minutes (normal environmental conditions, HES = 0) to 124 minutes (harsh environmental conditions, HES = 0.43).

Table 6 summarizes the results of performance assessment in normal and harsh environment and it shows the gates associated with each barrier.

Table 5. Summary of meteorological and climatological conditions experienced in Bodø.

Factor	Meteorological data	Reference
Temperature	Coldest month: January Minimum average temperature: –11.8°C Typical value: –2.2°C	(Norwegian Meteorological Institute, 2017)
Wind speed	Harsh month: January Maximum wind speed: 24.4 m/s (10 m above sea level) Annual range: 8.9 m/s	(Norwegian Meteorological Institute, 2017)
Snow	Duration: 6 months (October-April) Average snowfall per day: 2.54 cm	(weatherspark.com, 2017)
Fog/snow effect	Visibility lower than 2000 m	(ISO-International standardization organization, 2010)
Sunlight hours	1200–1600 h/year	(Landsberg and Pinna, 1978)
Remoteness	The plant is located in an industrial site close to cities and amenities. The remoteness is considered to be low.	(Suedfeld and Steel, 2000)

Table 6. Summary of data adopted for the quantification of the ETA in the present case study. HES = 0: normal environment; HES = 0.43: harsh environment.

Barrier	Gate type	PFD		Effectiveness	
		HES = 0	HES = 0.43	HES = 0	HES= 0.43
WDS-V1	A	$4.33\ 10^{-2}$	$5.57\ 10^{-1}$	1	1
PSV-V1	A	$1\ 10^{-2}$	$1.29\ 10^{-1}$	1	1
PFP-V1	A	$1\ 10^{-3}$	$1.29\ 10^{-2}$	1	1
ER-01	C	$1\ 10^{-1}$	$2.57\ 10^{-1}$	0; 1[a]	0; 1[a]

[a] Depending on the comparison between TFM and TTF.

4.2 *Evaluation of escalation probability*

The customized ETA approach for the evaluation of the escalation probability and frequency has been carried out starting from the frequency and consequence assessment of the primary scenario (ethanol non-confined pool-fire).

Figure 3 shows an extract of the ETA developed for harsh environmental conditions (*HES* = 0.43). Each branch in the event tree is quantified according to the rules described in Section 2. A similar event tree is derived for the normal environment case.

Three different scenarios arising from unconfined pool fire are analyzed in both normal and harsh environment. These scenarios are:

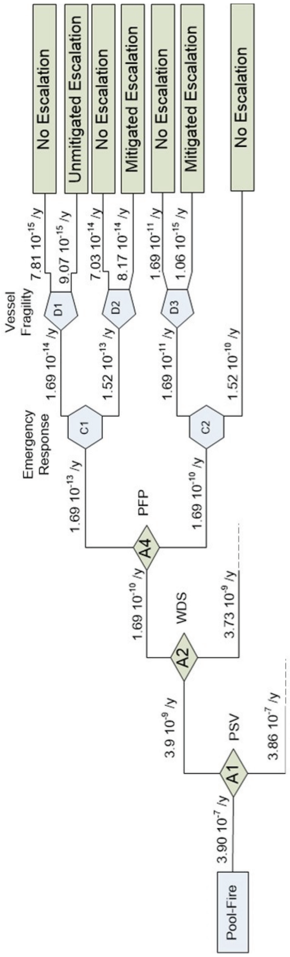


Figure 3. Extract of the ETA for the evaluation of cascading event probability/frequency for the target tank V1. It refers to the case of harsh environment, with *HES* = 0.43.

1. Unmitigated domino (not effective activation of safety barriers);
2. Mitigated domino (partial or ineffective activation of one or more safety barriers);
3. No domino scenario (barriers effectively mitigate/suppress the primary fire and avoid escalation).

The target equipment V1 may withstand the fire even in the absence of barrier activation. Also in these cases, escalation is excluded.

Figure 4 shows the result of the analysis in terms of frequency and probability of the three examined scenarios. The "No safety barrier" scenario has been considered for sake of comparison, e.g. based on the method developed in a previous work (Landucci et al., 2009).

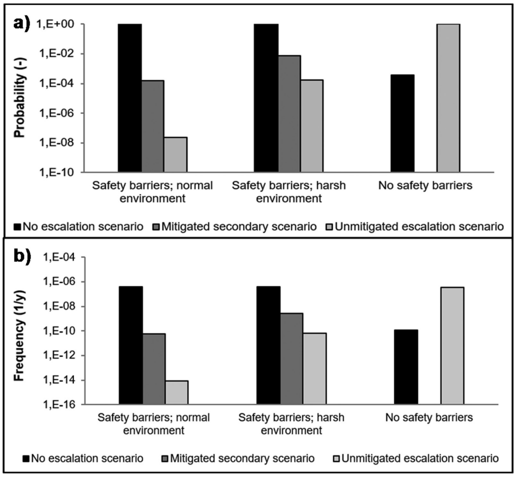


Figure 4. a) Probability and b) frequency of secondary scenarios.

5 DISCUSSION

The analysis of the case study demonstrates the potentialities of the methodology in the assessment of domino scenarios for chemical facilities located in harsh environments. As shown in Figure 4, a significant increase in escalation probability and frequency is predicted in harsh environment operation with respect to normal environment. When safety barriers are considered, unmitigated domino scenario is the less credible, both in normal and harsh environments. Anyway, the degradation of barrier performance in harsh environment leads to higher frequency values. In particular, reduction of four orders of magnitude with respect to the case without protection is obtained for harsh environment. In normal environment, the reduction is of eight orders of magnitude.

This is due to the depletion in the barrier performance in harsh environment, as documented in the analysis shown Section 4.1. In particular, procedural and emergency measures are significantly affected by cold environmental conditions. In fact, the time for external emergency response increases about 60% compared to the value in normal environment. This is due to delays and difficulties in carrying out emergency actions.

The escalation frequency results obtained from the ETA analysis shown in Section 4.2 may be implemented in detailed quantitative risk assessment studies. In this way, a more detailed risk picture of the facility may be evaluated, thus including escalation scenarios. The necessary input to apply the method, as exemplified in Sections 3 and 4, is normally available from conventional risk analysis studies and therefore no additional work needs to be carried out for collecting input data. The meteorological and climatological data for the HES assessment are site-specific, but easily retrievable from national institutes (see the example dataset gathered in Table 5).

It is worth mentioning that the methodology addresses human factor and deterioration of barrier phenomena in a very simplified way, despite these issues featuring relevant complexity. For that reason, the so evaluated escalation probabilities and frequencies should be considered on the safe side.

The methodology allows room for further refinement of data and for using different available methods. In particular, for human reliability, more advanced techniques may be implemented supporting the evaluation of operators' performance and error probability given the environmental stressors; on the same time, emergency response analysis may be improved with site specific response time data for a more accurate effectiveness estimation.

Finally, for hardware barriers, further review of the methodology should be considered when site-specific performance data will be available from facilities operating in harsh cold environments.

6 CONCLUSIONS

The present contribution shows a systematic approach for the quantification of domino event frequency and probability for chemical facilities operating in harsh environmental conditions. The approach accounts for the deterioration of safety barriers performance due to extreme climate conditions. A dedicated metric is used as preliminary index to assess the influence of environmental conditions on barrier performance, thus allowing for a modification of barriers availability and effectiveness. The modified values of barrier performance data allow for a more detailed probability and frequency assessment of cascading scenarios triggered by fire.

The outcomes of the methodology may drive the design of hardware barrier components and improvement of emergency procedures in order to decrement the risk of severe accidental scenarios in chemical facilities operating in harsh environments.

REFERENCES

Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D., Abbasi, S.A., 2011. Domino effect in process industry—an inventory of past events and identification of some patterns. J. Loss Prev. Process Ind. 24, 575–593.

American Petroleum Institute, 2000. API Publication 581. Risk-based inspection base resource document.

American Petroleum Institute, 1996. Fire-protection considerations for the design and operation of liquified petroleum gas (LPG) storage facilities—Standard API2510A.

Bercha, F., Brooks, C., Leafloor, F., 2003. Human performance in arctic offshore escape, in: Proceedings of the Thirteenth International Offshore and Polar Engineering Conference. International Society of Offshore and Polar Engineers (ISOPE), Cupertino, Ca. USA, Honululu, Hawaii, USA, pp. 2755–2762.

Birk, A.M., 2006. Fire testing and computer modelling of rail tank-cars engulfed in fires: literature review. Ottawa, Canada.

CCPS—Center of Chemical Process Safety, 2000. Guidelines for chemical process quantitative risk analysis. American Institute of Chemical Engineers—Center of Chemical Process Safety, New York.

Cox, D.R., 1972. Regression Models and Life-Tables. J.R. Stat. Soc. Ser. B 34, 187–220.

Darbra, R.M., Palacios, A., Casal, J., 2010. Domino effect in chemical accidents: main features and accident sequences. J. Hazard. Mater. 183, 565–573.

Delvosalle, C., 1996. Domino effect phenomena: definition, overview and classification, in: Proceedings of European Seminar on Domino Effects. Leuven (B), pp. 5–10.

DOA—Department of Army, 1982. FM 6-16-2 Tables for Artillery Meteorology (Visual) Ballistic Type 3 and Computer Messages and Limited Surface Observations. Washington DC.

Embrey, D.E., 1986. SLIM-MAUD: a computer based technique for human reliability assessment. Int. J. Qual. Reliab. Manag. 3, 15–12.

European Commission, 2012. European Parliament and Council Directive 2012/18/EU of 4 July 2012 on control of major-accident hazards involving dangerous substances, amending and subsequently repealing council directive 96/82/EC. Off. J. Eur. Communities L197, 1–37.

Gao, X., Barabady, J., Markeset, T., 2010. An approach for prediction of petroleum production facility performance considering Arctic influence factors. Reliab. Eng. Syst. Saf. 95, 837–846.

Hankinson, G., Lowesmith, B.J., 2004. Effectiveness of area and dedicated water deluge in protecting objects impacted by crude oil/gas jet fires on offshore installations. J. Loss Prev. Process Ind. 17, 119–125.

ISO-International standardization organization, 2010. ISO 19906:2010 Petroleum and natural gas industries—Arctic and offshore structures.

Kourniotis, S.P., Kiranoudis, C.T., Markatos, N.C., 2000. Statistical analysis of domino chemical accidents. J. Hazard. Mater. 71, 239–252.

Kunkel, K.E., Palecki, M.A., Hubbard, K.G., Robinson, D.A., Redmont, K.T., Easterling, D.R., 2007. Trend identification in twentieth-century U.S. snowfall: the challenges. J. Atmos. Ocean. Technol. 24, 64–73.

Landsberg, H., Pinna, M., 1978. L'atmosfera e il clima. Torino, Italy.

Landucci, G., Gubinelli, G., Antonioni, G., Cozzani, V., 2009. The assessment of the damage probability of storage tanks in domino events triggered by fire 41, 1206–1215. doi:10.1016/j.aap.2008.05.006.

Landucci, G., Necci, A., Antonioni, G., Argenti, F., Cozzani, V., 2017. Risk assessment of mitigated domino scenarios in process facilities. Reliab. Eng. Syst. Saf. 160, 37–53. doi:10.1016/j.ress.2016.11.023.

Landucci, G., Argenti, F., Spadoni, G., Cozzani, V., 2016. Domino effect frequency assessment : The role of safety barriers. J. Loss Prev. Process Ind. 44, 706–717. doi:10.1016/j.jlp.2016.03.006.

Lees, F.P., 1996. Loss prevention in the process industries, 2nd ed. Butterworth—Heinemann, Oxford.

Musharraf, M., Khan, F., Veitch, B., Mackinnon, S., Imtiaz, S., 2013. Human factor risk assessment during emergency condition in harsh environment, in: Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2013), June 9–14, 2013, Nantes, France. American Society of Mechanical Engineers, New York, NY, pp. 1–9. doi:DOI: 10.1115/OMAE2013-10867.

National Fire Protection Agency (NFPA), 2018. Utility LP-gas plant code—NFPA 59.

National Fire Protection Agency (NFPA), 2017. Liquified petroleum gas code—NFPA 58.

Norwegian Meteorological Institute, 2017. www.yr.no [WWW Document].

Paltrinieri, N., Cozzani, V., Wardman, M., Dechy, N., Salzano, E., 2010. Atypical major hazard scenarios and their inclusion in risk analysis and safety assessment, in: Reliability, Risk and Safety: Back to the Future.

Paltrinieri, N., Khan, F., 2016. Dynamic Risk Analysis in the Chemical and Petroleum Industry: Evolution and Interaction with Parallel Disciplines in the Perspective of Industrial Application, 1st ed. Elsevier Science.

Paltrinieri, N., Reniers, G., 2017. Dynamic risk analysis for Seveso sites. J. Loss Prev. Process Ind. 49, 111–119. doi:10.1016/J.JLP.2017.03.023.

Pietersen, C.M., 1988. Analysis of the LPG-disaster in Mexico City. J. Hazard. Mater. 20, 85–107.

Rasmussen, K., 1996. The experience with the Major Accident Reporting System from 1984 to 1993. Luxemburg, Luxemburg.

Roberts, T., 2004a. Directed deluge system designs and determination of the effectiveness of the currently recommended minimum deluge rate for the protection of LPG tanks. J. Loss Prev. Process Ind. 17, 103–109.

Roberts, T., 2004b. Effectiveness of an enhanced deluge system to protect LPG tanks and sensitivity to blocked nozzles and delayed deluge initiation. J. Loss Prev. Process Ind. 17, 151–158.

Shaw, N., Austin, E.J., 1919. Manual of meteorology: comparative meteorology. Cambridge, UK.

Shirvill, L., 2004. Efficacy of water spray protection against propane and butane jet fires impinging on LPG storage tanks. J. Loss Prev. Process Ind. 17, 111–118.

Suedfeld, P., Steel, G.D., 2000. The environmental psychology of capsule habitats. Annu. Rev. Psychol. 51, 227–253.

weatherspark.com, 2017. www.weatherspark.com [WWW Document].

Zipf, G.K., 1949. Human Behaviour and the Principles of Least Effort. Addison-Wesley, Cambridge, MA.