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Highlights

- The temporal changes in the performance of fire protection systems have been investigated.
- Event tree and dynamic Bayesian network have been employed to model degradation of fire protection systems.
- Spatial and temporal escalation of domino effects have been modeled under the impact of fire protection systems.

Application of dynamic Bayesian network to performance assessment of fire protection systems during domino effects

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Abstract

The propagation of fire in chemical plants – also known as fire domino effects - largely depends on the performance of add-on passive and active protection systems such as sprinkler systems, water deluge systems, emergency shut down and emergency blow down systems, fireproofing, and emergency response. Although such safety barriers are widely employed to prevent or delay the initiation or escalation of fire domino effects, their inclusion in the modeling and risk assessment of fire domino effects has hardly been taken into account. In the present study, the dynamic evolution of fire protection systems has been investigated qualitatively using event tree analysis. To quantify the temporal changes and their impact on the escalation of fire domino effects, a dynamic Bayesian network methodology has been developed. The application of the methodology has been demonstrated using an illustrativecase study, considering a variety of fire scenarios, target installations, and firefighting systems.

Keywords: Fire domino effects; Fire protection systems; Quantitative risk assessment; Event tree analysis; Dynamic Bayesian network.

1. Introduction

Domino effects occur when a primary accident propagates from one unit (the primary unit)to other neighboring units, resulting in the amplification of the consequences [1]. This type of accidental scenarios has been associated with a number of catastrophic accidents in the chemical and process industry [2–5].

The last European directive (Seveso Directive III) for the control of major accident hazards and land-use planning in the vicinity of hazardous industrial sites [6] requires that all the possible accidental scenarios caused by domino effects are taken into account. Pioneering studies, mainly carried out between 1980 and 2000, to model and evaluate the risk of domino effect scenarios were based on conservative and oversimplifying assumptions [7–12]. However, as pointed out in [1,13], during the past decade, a number of advanced tools have been developed based on quantitative risk assessment procedures [14,15], Monte Carlo simulations [16], graphs metrics [17], and Bayesian network (BN) [18,19] to tackle the risk of domino effects in hazardous industries.

Although technical standards require the adoption of safety barriers in industrial installations – in order to either prevent the escalation or mitigate the effects of secondary scenarios [20–22] – a majority of previous works has neglected the incorporation of safety barriers in domino effect modeling and risk assessment. This negligence, in turn, could have resulted in not only an inaccurate prediction of escalation pattern but also an overestimation of domino effect risk as some safety measures such as fireproofing or firefighting systems are especially dedicated to limit the risk of domino effect scenarios [23].

To address the key role of safety measures in propagation and risk assessment of domino effects, recent works have been devoted to the quantitative assessment of safety barriers in domino effect risk studies. Janssens et al. [24] proposed a model for the allocation of safety barriers for the prevention of escalation based on cost criteria. Landucci and coworkers [25,26] proposed a method to quantify the performance of safety barriers introducing the concept of barriers' availability and effectiveness and providing a specific data repository. Khakzad and coworkers investigated the application of BN, graph theory, and multi-criteria decision making to optimal allocation of safety barriers to support land use planning studies [15,27] and to reduce the vulnerability of industrial sites [28].

Among the developed methodologies, BN has proven as a robust and sophisticated technique in modeling the conditional dependencies and complicated interactions in the risk assessment of domino effects. However, as already mentioned, in the previous works the contribution of safety barriers has hardly been taken into account [18,19], via oversimplified assumptions [27] or neglecting the possible degradation of the barriers during domino events [29]. In fact, the dynamic evolution of mitigated domino scenarios, to the best of the authors' knowledge, has never been included so far.

The present work is aimed at developing a Dynamic Bayesian network (DBN) methodology to model evolution of fire domino scenarios (propagation of fire)– mainly based on previous works of Khakzad et al. [18,19] and Landucci et al. [25,26] – taking into account the role of safety barriers in preventing the escalation of accidents. The application of DBN allows the temporal evolution of domino effect as well as the time dependency of fire protection systems' performance to be taken into account in the modeling. This dynamic aspect of DBN which explicitly accounts for time in the analysis is a unique modeling feature not offered by conventional BN.

Section 2 is devoted to the performance assessment of fire protection systems mainly based on a degradation-mode-effect-analysis and event tree analysis. In Section 3, the fundamentals of BN and DBN are provide, while in Section 4 the implementation of fire protection systems in DBN will be demonstrated using an illustrative case study. The discussion and future remarks are presented in Section 5; conclusions are given in Section 6.

2. Performance assessment of safety barriers

According to CCPS (Center of Chemical Process Safety) [23], safety layers may be classified in four categories: i) inherently safer design, ii) passive protection systems, iii) active protection systems, and iv) procedural and emergency measures. Inherently safer design is not analyzed in the present study, since its application is limited to the early design steps of the facility, when domino effect may be prevented via adopting less hazardous materials/operations and safety distances [30–33]. On the other hand, the focus of the present study will be on passive, active and emergency response measures.

Fireproofing protection (FPP) is analyzed as a reference passive fire protection. Fireproofing is applied on process vessels in order to reduce the incoming heat flux due to external fire, and consequently to mitigate the vessel heat-up and avoid the catastrophic failure [34–40].

Regarding active barriers, two types of active protections are considered: i) active protections aimed at suppressing the fire such as water/foam sprinklers mounted on atmospheric tanks; ii) active protections aimed at isolating process unit using, for example, emergency shut down (ESD) systems or to depressurize them using emergency blow down (EBD) and emergency drainage (ED) systems. It is worth mentioning that while both EBD and pressure safety valve system are aimed at depressurising the vessel, the former is an active barrier whereas the latter is a passive barrier.

Finally, procedural and emergency measures can be integrated with passive and/or active measures so as to support the management and control of scenarios that may escalate to a domino effect [4]. Emergency response (ER) can be provided by internal and/or external firefighting teams [4].

To qualitatively assess the performance of the safety barriers, a FMEA (failure modes and effects analysis) is tailored in order to address the temporal degradation/depletion of safety barriers after their effective activation. This qualitative analysis is indicated in the following as a DMEA (degradation modes and effects analysis). The results of the DMEA study are reported in Appendix A and have been used to determine the dynamic factors affecting the failure probabilitiesof the barriers and thus those of the targets.

2.1 Firefighting systems based on water supply

The mitigation action associated with sprinklers and WDSs was investigated in a previous work [28] based on a comprehensive literature analysis [22,41–43].

Water/foam sprinkler systems are primarily aimed at controlling and, eventually, suppressing pool fires or tank fires. These devices are typically installed on atmospheric tanks. However, it is usually conservatively assumed that the effect of sprinklers consists of a reduction of the emitted heat flux (Q_f) from the pool or tank fire (mitigated fire). In particular, the mitigated heat flux (Q_m) can be computed as follows [44]:

$$Q_m = (1 - \eta\varphi_1)Q_f \qquad (1)$$

in which φ_1 is the radiation reduction factor, and η is an effectiveness parameter. An average value of φ_1 = 60% for a flame assimilated as a black body at 1100K may be achieved due to water mist mitigation [44]. In the present study, a conservative value of η = 75% is considered for the effectiveness in Eq. (1) [28].

According to the typical design features of fixed firefighting systems for Oil&Gas installations [45], one main storage tank for water supply is considered for the entire facility, shared by all sprinklers in place. This water tank should be sufficient in order to suppress/control one major fire event and to keep cool the neighboring units for as minimum as 4hr. The respective degradation modes and their effects on the performance of the firefighting system are summarized in Table A.1.

Clearly enough, an inherent degradation of firefighting system is water consumption. When water is totally consumed, mitigation is not further possible, and this is a key element for the dynamic evolution of domino scenarios. In the present work, for the sake of simplicity, the water tank is connected to a theoretically infinite water reservoir (river, lake, etc.), acting as a buffer to provide enough water head for the pump and the firefighting network distribution [45]. However, the tank might get drained due to internal causes (fatigue, corrosion, spurious opening of drain, etc.) or get damaged due to the heat radiation of external fires, leading to an instantaneous loss of firefighting waterand the connection with the main water reservoir. To avoid the latter damage, a minimum distance of 60m is usually adopted [45] from the “hazardous area”[1]. At this distance, however, the effects of a strong fire (or synergistic effects of concurrent fires) might not be neglected.

[1] This terminology is adopted in [8] to indicate the location of unit containing hazardous materials.

Finally, other degradation modes identified through DMEA (see Table A.1) are related to the performance of other elements of firefighting systems. In fact, a pressure decrease in water distribution pipes (due to, for example, the failure of pipes or the water pump) may reduce the effectiveness of firefighting system. Likewise, if an obstruction in the nozzles takes place, the reduced flow may not be sufficient to guarantee the mitigation of fire or the reduction of incoming heat flux as intended. It is worth mentioning that the abovementioned failure and degradation modes can be repaired, restoring the water flow to the original design value during the fire scenario. However, this latter possibility was neglected in the quantitative analysis.
The qualitative degradation events identified through DMEA were implemented into a quantitative framework using event tree analysis (ETA). To illustrate the ETA level of detail, a simple example is depicted in Fig. 1(a). A primary fire occurs in the atmospheric storage tank A, affecting both a secondary storagetank Band the water storage tank W. The correspondent ETA for this situation is shown in Fig. 1(b), assuming that the water tank receives water from a river (theoretically infinite amount of water). A specific discussion is provided in Section 5.3 in order to support the extension on the present approach to the case of finite water resources.
In case the sprinkler is effectively activated on demand, water is fed to tank A to suppress/mitigate the fire. The reliability of the firefighting system affects the possibility of leakage from the tank, decrement of flow or pressure due to pump failure and the eventual obstruction in the water delivery parts. For all these events, which are conservatively considered as a series, the exponential failure may be assumed to estimate the failure probability P during time t:

$$P(t) = 1 - \exp(-\lambda t) \quad (2)$$

where the equivalent failure rates λ of the main components were determined based on literature data (see the example in Section 4). It is worth mentioning that the detailed reliability study of the system is beyond the scope of the present work. A detailed fault tree analysis was carried out elsewhere in order to provide more detailed data [44].

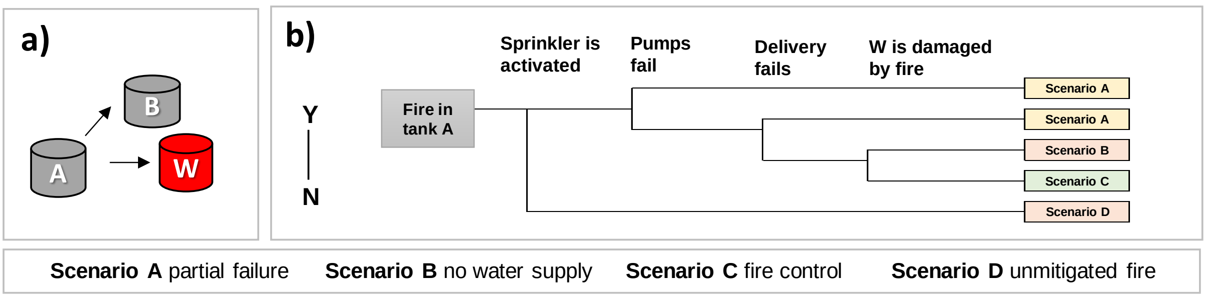


Figure 1.Definition of a simple example to support the event tree analysis exemplification: a) sketch of the problem; b) event tree analysisin case of infinite water source.

In case of failure of pumps or delivery system, the flow and/or the pressure are reduced with insufficient water distribution. Although a “partial failure” is indicated in Fig. 1(b) (scenario A), it was conservatively assumed that the mitigation action is not efficient and the primary fire will emit the full heat radiation, as in the unmitigated case (η=0 in Eq. (1)).
Finally, in case tank W is damaged by the fire, no more firefighting water is provided since the tank connections with the main water reservoir are damaged, thus the primary scenario is unmitigated. The failure probability of W can be estimated though fragility models, described in Appendix B.

2.2 Emergency isolation and depressurization systems

The results of the qualitative DMEA for ESD, EBD, and ED are reported in Appendix A, Table A.2.
It is worth mentioning that ESD and EBD are only installed on pressurized vessels [46–49], while for atmospheric tanks the emergency drainage (ED) of the content into a safe tank may be instead carried out in order to remove the tank inventory [4].

In the case of pressurized vessels, EBD is accounted for emergency depressurization of targets, leading to the decrement of inventory and thus reducing the possibility of escalation in case of rupture. ESD is, on the other hand, aimed at isolating critical units and pipes, decreasing the duration of primary fires such as torch or jet flames [4]. For ESD, if successfully activated (i.e., closure of shut-off valves), the associated degradation mode is a possible spurious opening of valves (see Table A.2). On the contrary, for EBD, the spurious closure of the blow down valve once opened is the main cause of degradation (see Table A.2). It is worth mentioning that possible spurious signals affecting both systems are excluded. Moreover, the failure due to lack of instrument air and/or electricity is not addressed, since the valves are mounted in safe positions[2].

ED can be used to drain either the primary unit on fire or the target units exposed to the primary fire. In the former, the primary fire duration may be reduced whereas in the latter the possibility of fire escalation totarget units will be reduced (there will not be secondary fire even if the target units are damaged). In both cases, a failure may occur to the transfer line during the drainage operation. This may lead to a release of hazardous materials, in case of transfer line rupture, or to insufficient transfer, in case of plugged line (see Table A.2).

An interaction matrix was adopted (Table 1) in order to define the gates for the implementation of the ET. According to the combinations reported in Table 1, six possible ET blocks may be identified, three for primary fire suppression (i = 1, 2, 3) and three for preventing the fire escalation (j = 1, 2, 3), which can be coupled in nine combinations based on the specific primary-secondary unit types. An example of coupling of ETA blocks is shown in Fig. 2; this case is discussed in detail in Section 4. The gates reported in the figurefor each protection type represents the following condition: “failure on demand or failure while running after successful activation”.

Table 1. Matrix for the identification of protection action of emergency depressurization and isolation of units. Each cell contains two elements: $\mathbf{s_i}$ = system used to suppress primary fire, and $\mathbf{e_j}$ = systemused to prevent the escalation of fire.

Primary fire	**Target unit**		
	Process pipes/ pressurized storage tanks	Pressurized vessels	Atmospheric tanks
Jet/pool fire from pipe or pressurized storage leak	$\mathbf{s_1}$= ESD $\mathbf{e_1}$ = N/A**	$\mathbf{s_1}$= ESD $\mathbf{e_2}$ = EBD	$\mathbf{s_1}$= ESD $\mathbf{e_3}$ = ED
Jet fire from process pressurized vessels*	$\mathbf{s_2}$= ESD, EBD $\mathbf{e_1}$ = N/A**	$\mathbf{s_2}$= ESD, EBD $\mathbf{e_2}$ = EBD	$\mathbf{s_2}$= ESD,EBD $\mathbf{e_3}$ = ED
Pool fire from atmospheric tanks	$\mathbf{s_3}$= ED $\mathbf{e_1}$ = N/A**	$\mathbf{s_3}$= ED $\mathbf{e_2}$ = EBD	$\mathbf{s_3}$= ED $\mathbf{e_3}$ = ED

* Pool fire is excluded following immediate ignition

** Not Applicable

Even in case of positive response on demand, the safety barrier will not respond for a short time lapse t_a (lag time due to slow closure of ESD, slow opening of EBD, sensor response, etc.); thus, for $t < t_a$ it can be assumed that $P_{up}(t) = 1$ and $P_{low}(t) = 0$, where P_{up} and P_{low} are the probabilities to have upper and lower branches, respectively, in the outcomes of each gate (see Fig. 2).

For $t > t_a$, the probability of the outcomes of each fire suppression gate (s1, s2, s3) assigned to the primary fires[3] can be quantified considering that the protection may fail either on demand or during the operation with an exponential probability distribution. This can be summarized as:

[2] Typically, shut down valves are installed in “fail to close” configuration, while blow down valves are in “fail to open” configuration.

[3]The number of gates for fire suppression equals the number of units on fire. The type of gates (s1, s2, s3) depends on the type of primary fire and the unit on fire.

$$P_{up}(t) = PFD \quad \text{if the protection has not yet activated at time t} \quad (3a)$$
$$P_{up}(t) = 1 - \exp(-\lambda\, t) \quad \text{if the protection has been activated in a previous time step} \quad (3b)$$
$$P_{up}(t) = 1 \quad \text{if the protection failed to activate in a previous time step} \quad (3c)$$

$$P_{low}(t) = 1 - P_{up}(t) \quad (4)$$

where PFD is the probability of failure on demand of the protection, and λ is the equivalent failure rate of the system, both determined based on literature data [25,26,50]. Following a simplified but conservative assumption, if the protection fails on demand, it cannot be restored, since the maintenance team would be involved in emergency response rather than in routine activities.It is implicitly assumed that once each barrier is in working state, the effectiveness is unitary [25].
Depending on the barrier type, the lower branch of eachgate leads to the suppression of the domino chain associated to the primary unit, while in case of barrier failure (upper branch), the gateshould be followed by escalation prevention gates associated with target units.
Following the procedure developed forfire suppression gates, the probability of each branch of each escalation prevention gate can be quantified assuming exponential failure distribution via Eqs. (3) and (4). In this case, it is also assumed that once each barrier is in a working state, the effectiveness is unitary [25].

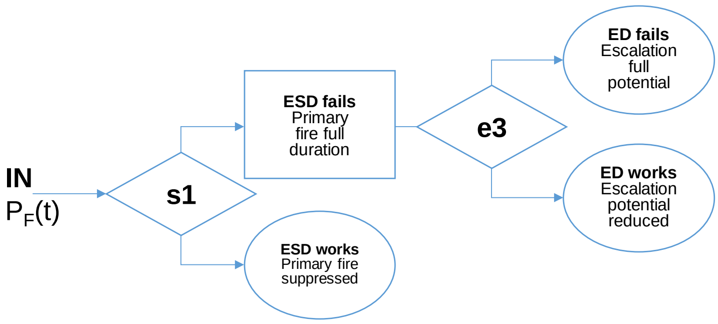


Figure 2.Example of combination of fire suppression and escalation prevention blocks. Refer to Table 1 for s_i and e_j identification. P_F = probability of having a primary fire at time t.

2.3 Passive fire protections

The results of the qualitative DMEA for passive fire protections are reported in Table A.3. As mentioned in Section 2.2, the present analysis focused on fireproofing as a means of passive protection.The effects of pressure safety valves as another means of passive fire protection are not addressed in the present work.
Fireproofing coatingis normally rated for 2h fire resistance, which may be achieved only by installing high performance fireproof materials, specifically designed to withstand severe fires [51]. According to a simplified approach developed by Landucci et al. [25], the effect of fireproofing is to increase the time to failure (TTF). This way, the protection time provided by fireproofing, θ, can be added to TTF. In case of ideal fireproofing, θ is equal to the rated time, i.e., 2 h.
However, incipient degradation and devolatilization phenomena may alter the nominal behavior of the fireproofing coating during fire exposure [52–55] (see Table A.3). Therefore, these phenomena should be taken into account considering that the thermal properties of the coating degrade in time with a direct effect on the vulnerability of the protected vessel. In case of the degradation of the coating, the value of θ is progressively reduced during fire exposure, affecting the probability of failure of the vessel.
Due to the relevant uncertainties in gathering input data and the multiple scenarios to be analyzed within the risk assessment of industrial facilities, a conservative method was developed based on previous studies [56,57] in order to provide simple analytical functions for the temporal changes of θ. The method is described in Appendix B, with a sample application.

In order to calculate the failure probability accounting for the coating degradation, the event tree shown in Fig. 3 can be employed.

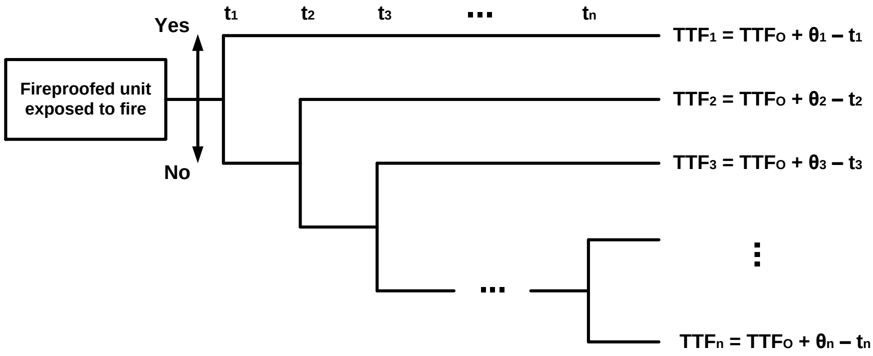


Figure 3. Event tree for the analysis of the dynamic degradation of fireproofing.

Following the indications reported in [23], since passive fire protections do not need external activation, a unitary value may be considered for their availability. As such, the possibility of an ineffective thermal protection due to erosion, corrosion, wrong installation, defects, insufficient maintenance, etc. can be neglected, assuming that the only mechanism affecting the coating performance is progressive deterioration (see Fig. 3).
At the generic i-th time t_i, a deteriorated θ_i can be estimated through the simplified approach described in Appendix B as $\theta_i = f(t_i)$.As a result, the TTF of the fireproofed vessel can be estimated by improving a previously developed approach [25], as follows:

$$TTF_i = TTF_O + \theta_i - t_i \quad (5)$$

where t_i is the time lapse since the exposure to the fire; θ_i is the protection time provided by the fireproofing at the time t_i, and TTF_O is the time to failure of the target vessel in the absence of thermal protection, which can be estimated with the simplified correlations summarized in Appendix B.
Once the TTF_i is estimated at each time step, the probability of failure can be computed through the fragility models [58,59] (Appendix B).

2.4 Procedural measures: analysis of emergency response

This study focused only on external emergency teams which use water resources to cool the target vessels or to suppress the fire. According to [60], it is a common practice to aim the firefighting response in suppressing pool fires, while jet fires are left free to burn till exhaust. In the latter, water resources are used to cool the target vessels instead of suppressing the fire.
The qualitative considerations made for active systems providing firefighting agents may be extended to the dynamic performance of emergency teams (see Table A.4). However, a deterministic approach was adopted for the present analysis (Fig. 4), following the approach developed in previous studies [25,26].

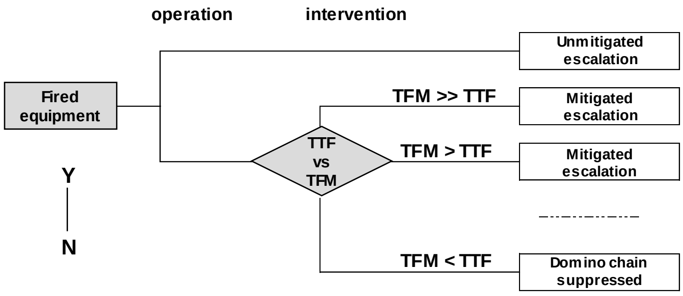


Figure 4. Event tree for the analysis of the emergency response assessment.

As shown in Fig. 4, emergency response (ER) may fail on demand, and this is strongly influenced by the skills and the level of preparedness of emergency responders [61]. This is taken into account with the gate "failure of operation". A single point probability of failure (PFD_{er}) was assigned to the gate using the conservative value associated with human errors in LOPA literature [23]. If the emergency response is not activated or not available, escalation will occur (see Fig. 4).

In the case of successful activation and availability of emergency teams, the effectiveness of the response needs to be accounted for. Hence, a time scale for emergency intervention was used for a direct comparison with the time available for mitigation, represented by TTF, to estimate the effectiveness and quantify the gate shown in Fig. 4. The time scale for emergency is based on the different actions required to perform the fire mitigation (alerting, deploying on-site measures, provide required amount of water, etc.) [4]. The time scale is site-specific and needs to be assessed in the site of interest, determining the time for final mitigation (TFM). Hence, the final outcomes can be quantified comparing TTF and TFM.

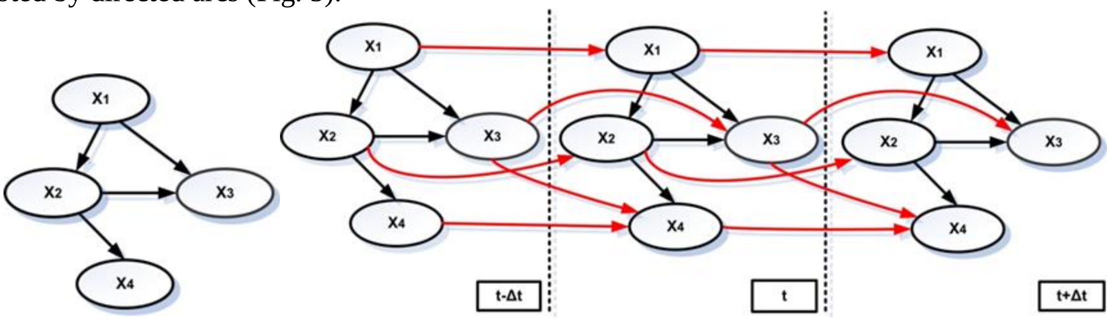
Landucci et al. [25] provided a simplified estimation of TFM, based on the type of target vessel, the fire mitigation strategy, and the facility location. The approach is briefly recalled in Appendix B, with a quantified example.

A residual mitigation action due the positive (but delayed) intervention of emergency response teams may be considered in the consequence assessment of escalation scenarios. For example, the primary fire might be partially suppressed or the BLEVE[4]/fireball associated with a pressurized vessel might be less severe than in the case without emergency intervention [62,63]. This effect is qualitatively considered in Fig. 4 (see different discrete states for escalation) but the quantitative assessment was merely based on the two possible states:

- If TFM < TTF, the mitigation action is successful and the fire escalation is prevented.
- If TFM > TTF, the emergency response would be too late to prevent/mitigate the escalation.

3. Dynamic Bayesian networks

BN is a probabilistic method for reasoning under uncertainty [64] in which random variables are represented by nodes while the conditional dependencies or cause-effect relationships among them are denoted by directed arcs (Fig. 5).



(a) (b)

Figure 5. Schematic of (a) conventional Bayesian network and (b) dynamic Bayesian network

The type and strength of the dependencies can be encoded in form of conditional probability tables assigned to the nodes. Using the chain rule and the concept of d-separation [64], the joint probability of a set of random variable $U = \{X_1, X_2, \ldots, X_n\}$ can be factorized as the product of marginal and local conditional probabilities:

$$P(U) = \prod_{i=1}^{n} P(X_i|\pi(X_i)) \quad (6)$$

[4] Boiling liquid expanding vapor explosion

where $\pi(X_i)$ is the parent set of the node X_i. For instance, the joint probability distribution of the random variables X_1, X_2, X_3 and X_4 in the BN of Fig. 5 can exclusively be expanded as $P(X_1, X_2, X_3, X_4) = P(X_1)\, P(X_2|X_1)\, P(X_3|X_1, X_2)\, P(X_4|X_2)$.
The main application of BN is in probability updating by mean of Bayes' theorem when some new information, so-called evidence E, becomes available:

$$P(U|E) = \frac{P(U)P(E|U)}{P(E)} = \frac{P(U,E)}{\sum_U P(U,E)} \tag{7}$$

For example, assuming binary random variables $X_4 = (x_4, \overline{x_4})$ and $X_1 = (x_1, \overline{x_1})$ and knowing that the random variable X_4 is in the state $\overline{x_4}$, the updated probability of X_1 being in the state x_1 can be calculated as $P(X_1 = x_1 | X_4 = \overline{x_4}) = \frac{\sum_{X_2,X_3} P(x_1,X_2,X_3,\overline{x_4})}{\sum_{X_1,X_2,X_3} P(X_1,X_2,X_3,\overline{x_4})}$.
Owing to their flexible graphical structure and the robust probabilistic engine, BN has been widely used in a variety of domains, including accident scenario modeling, risk assessment, and decision making.
DBN is an extension of ordinary BN that, compared to its ancestor, facilitates explicit modeling of temporal evolution of random variables over a discretized timeline (Fig. 5(b)). Dividing the timeline to a number of time slices, DBN allows a node at i[th] time slice to be conditionally dependent not only on its parents at the same time slice but also on its parents and itself at previous time slices:

$$P\left(U^{t+\Delta t}\right) = \prod_{i=1}^{n} P(X_i^{t+\Delta t} | X_i^t, \pi(X_i^t), \pi(X_i^{t+\Delta t})) \tag{8}$$

According to the DBN in Fig. 5(b), the conditional probability of X_4, for example, at the time slice $t + \Delta t$ is $P(X_4^{t+\Delta t} | X_2^{t+\Delta t}, X_3^t, X_4^t)$. For the sake of brevity, the DBN in Fig. 5(b) can be depicted in an abstract from, as shown in Fig. 6, where the numbers within the squares refer to the number of time slice taken into account in temporal dependencies.

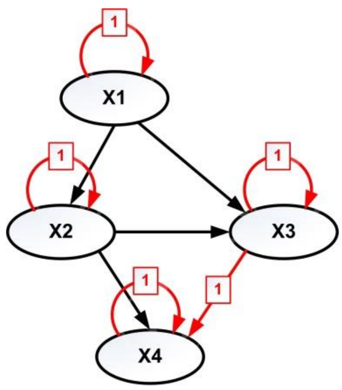


Figure6. Abstract representation of DBN in Fig. 5(b). The numbers attached to the temporal arcs indicate the number of previous time slices to be taken into account in temporal dependencies.

4. Implementation of safety barriers in dynamic Bayesian network

4.1. Demonstrative case studies

The plant considered for the application of the present methodology is shown in Fig. 7, consisting of three atmospheric crude oil tanks (T1, T2, T3) in their catch basins, one pressurized propane tank (T4), and a pressurized natural gas pipeline P1 along withan atmospheric the water storage tank (Tw). The locations and directions of jet fires for T4 and P1 have been identified in the figure as well.
The features of the tanks together with their respective protection systems are reported in Table 2.

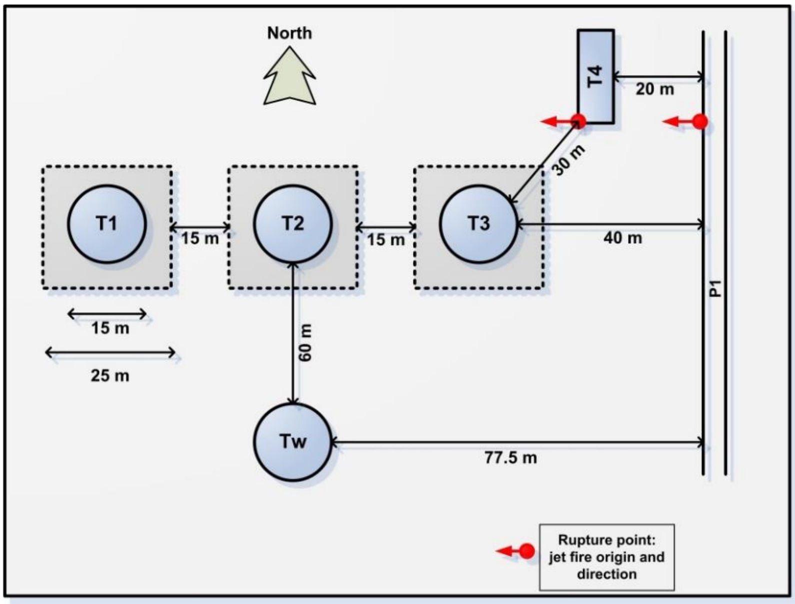


Figure 7. Layout adopted for the demonstration of the methodology. Units are expressed in meters. For vessels ID see Table 2.

Table 2. Main features of the tanks considered for the case study. Nominal capacity is obtained considering a maximum filling level of 75%. Cells marked with an X indicate a safety device present on the considered unit; n.r. = not relevant for the analysis; SP = sprinkler system; FPP = fireproofing protection; ESD = emergency shut down; EBD = emergency blow-down; ED = emergency drainage.

ID	Content	Diameter (m)	Height/ length (m)	Capacity (m^3)	Pressure* (barg)	SP	FPP	ESD	EBD or ED
T1	Crude oil	15	16.2	2150	0.02	X			
T2	Crude oil	15	16.2	2150	0.02	X			
T3	Crude oil	15	16.2	2150	0.02	X			X
T4	Propane	3	18	110	7.5		X	X	
P1	Natural gas	0.1	200	n.r.	34			X	
Tw	Firefighting water	21	12.6	3200	0.02				

* Design pressure

The accident scenarios associated with the units in the facility are summarized in Table 3. The indication of "primary" scenario denotes the fact that the scenario is the initiating event of fire domino effect. On the other hand, the indication of "escalation" scenario refers to events triggered by fire domino effect.

Table 3. Accident scenarios associated with the equipment considered in the facility. IDs are reported in Table 2.

ID	Primary scenario	Annual probability (P_f)	Escalation scenario
T1, T2, T3	Pool fire in the catch basin	10^{-5}	Pool fire in the catch basin
T4	Jet fire, 1" release diameter	10^{-4}	Fireball
P1	Jet fire, 1" release diameter	10^{-4}	Jet fire, full bore rupture*

[a] The pipe rupture point is shown in Fig. 7

For each scenario, consequence assessment was carried out through literature integral models for consequence analysis [65], considering a wind gusting from North at 5 m/s, stability class D, 20°C ambient temperature with 50% relative humidity.
The heat radiation values predicted through integral models are shown in Table 4 for primary (part a) and escalation (part b) scenarios. According to the results, the burnout of each atmospheric tank's pool fire takes more than 6hr (considering a 340 m^3/h burning rate).
For the sake of simplicity, several simplified demonstrative cases were defined, in each of which one or more items were excluded. This allowed focusing on the effect of each individual protection type:

- *Case 1*: Domino effect initiating at T1 and affecting T2 and T3, only accounting for the mitigation effect of sprinkler system (ED of T3 is not considered in this case).
- *Case 2*: Domino effect initiating at T4 and affecting T3, accounting for ESD of T4 and ED of T3.
- *Case 3*: Domino effect initiating at P1 and affecting T4, accounting for ESD of P1 and FPP of T4. In this case, the effect of emergency response (ER) on T4 will also be considered.

In order to determine whether or not other units will be affected by a primary fire, the threshold based approach developed by Cozzani and coworkers was adopted as a preliminary screening [66]. In particular, domino effect is credible for the following threshold values:

- 15 kW/m^2 for atmospheric equipment
- 45 kW/m^2 for pressurized equipment

As shown in Table 4 (part a), the water tank (an atmospheric cylindrical vessel) is potentially affected by the pool fire following the rupture of T2 (the received heat radiation is 16.7 kW/m^2), and thus its potential failure is taken into account in Case 1.
In order to implement the dynamic behavior of the sprinklers, the amounts of reduced heat flux due to the suppression effect of sprinklers were evaluated and presented in the brackets in Table 4 (part a). In this case, none of the tanks is affected by heat radiation of a single primary fire, except T4 that can be damaged if exposed to the jet fire of P1. Nevertheless, even given the suppression of the sprinkles, the synergistic effects of more than one primary fire will be sufficient to make credible damage to the atmospheric storage tanks [18,19]. Such synergistic effects will be considered in Section 4.2 when developing the DBNs.
In order to quantify the DBN for the analysis of the abovementioned cases, the input data summarized in Table 5 are considered.

Table 4. Heat radiation (kW/m^2) computed through integral models [65] for a) primary scenarios without mitigation (and with mitigation); b) escalation scenarios. For unit ID see Table 2.

a) Primary scenarios without sprinkler mitigation (with sprinkler mitigation)						
Unit ↓	Target					
	T1	T2	T3	T4	P1	Tw
T1	-	35.4 (14.2)	9.1 (3.6)	4.4 (1.8)	3.2 (1.3)	11.7 (4.7)
T2	35.4 (14.2)	-	35.4 (14.2)	10.0 (4.0)	11.0 (4.4)	16.7 (6.7)
T3	9.1 (3.6)	35.4 (14.2)	-	28.4 (11.4)	20.0 (8.0)	11.7 (4.7)
T4*	1.0	2.0	21.4	-	12.8	1.0
P1*	0.5	0.5	2.0	150.0	-	0.5
b) Escalation scenarios						
Unit ↓	Target					
	T1	T2	T3	T4	P1	Tw
T1	-	35.4	9.1	4.4	3.2	11.7
T2	35.4	-	35.4	10.0	11.0	16.7
T3	9.1	35.4	-	28.4	20.0	11.7
T4	368.0	368.0	368.0	-	368.0.	87.5
P1	6.8	30.7	40.5	150.0	-	3.0

* not affected by sprinkler mitigation

Table 5. Input data for the quantitative deterministic and probabilistic assessment of the case studies. C = calculated value based on 1 yeartest interval;A = assumed value.

Item	Value	Description	Ref
λ_{sp} (y^{-1})	2.0×10^{-2}	Failure rate of sprinkler system	[43]
λ_{wp} (y^{-1})	6.2×10^{-3}	Failure rate of water pump	[43]
λ_{esd} (y^{-1})	7.44	Failure rate of ESD (based on PFD_{s1})[5]	C
λ_{ed} (y^{-1})	4.32	Failure rate of ED transfer pump	[67]
PFD_{esd}	3.72×10^{-4}	Probability of failure on demand of ESD system	[25]
PFD_{ed}	2.16×10^{-1}	Failure probability on demand of ED's transfer pump	C
PFD_{er}	1.00×10^{-1}	Failure probability on demand of ER (emergency response)	[25]
PFD_{sp}	1.0×10^{-2}	Failure probability on demand of sprinkler (based on λ_{sp})[5]	C
t_a (min)	5	Activation time for ESD	A
t_{ed} (min)	60	Time for emergency liquid transfer from T3	A
t_{esd} (min)	30	Time to empty T4 in case of ESD activation (T4 will be isolated in 30 min)	A
t_o (min)	120	Maximum fire duration in the unmitigated case (T4 is not isolated)	A
TFM (min)	N (μ= 40, σ= 10)*	Time for final mitigation, based on the time evaluation required by external emergency teams	Appendix B.3

* Normal distribution featuring mean μ and variance σ.

4.2Results

4.2.1 Case 1

In this case, for illustrative purposes, a pool fire at T1 is considered as the initiating event. For the sake of simplicity, T4 and P1 were excluded from the analysis in the present case. Tw is considered to be connected to an infinite water resource; thus, the ETA shown in Fig. 1(b) is considered in the development of DBN. Considering the heat radiation intensities in Table 4 and adopting the BN methodology developed in [18,19], the temporal and spatial escalation of the fire from T1 to T2, T3, and Tw can be modeled using the DBN in Fig. 8(a).

In order to implement the sprinkler system in the DBN, T1 and the associated sprinkler SP1 can be modelled using chance nodes. Since a sprinkler is aimed at mitigating the fire at its origin, there should be an arc from T1 to SP1, indicating that the latter can be activated with a probability equal to 1- PFD_{sp} if there is a fire at the former. Likewise, since the performance of SP1 also depends on the function of the water distribution pump, P, and the availability of water in Tw, there should be arcs from P and Tw to SP1 as well. The mitigation effect of SP1 on T1, i.e., the mitigated heat radiation, can be articulated using the auxiliary node T1'. As the emitted heat radiation from T1' can cause damage to the other storage tanks and the water tank, arcs are drawn from T1' to T2, T3, and Tw. It is to be noted that although T1' alone cannot damage T3 (see Table 4), there should be an arc from T1' to T3 to account for the synergistic effect of T1' and T2' on T3 [18,19].

In Fig. 8(a), the random failure of a component due to internal causes – not the fire at T1 – has been denoted by a temporal arc from the component to itself. Since the failures are assumed to be exponential (constant failure rates in Table 5), the failure probability of each component at a time step is only dependent on the component's state at the previous time step, known as the property of memorylessness; this is why the temporal arcs refer to one time step (note the numbers attached to temporal arcs in Fig. 8(a)). Considering 30-min time steps, the conditional probabilities of pool fires at T2 and T3 have been calculated and presented for a 12-hr period in Fig. 8(b).

[5]An equivalent failure rate λ was derived applying the base relationship for the estimation of tested components unavailability [4]: $PFD \cong 1/2 \times \lambda \times d$, where d is the test interval assumed equal to 1 year (8760 h) for industrial facilities, and PFD is the value obtained for EBD and ESD from Landucci et al. [25].

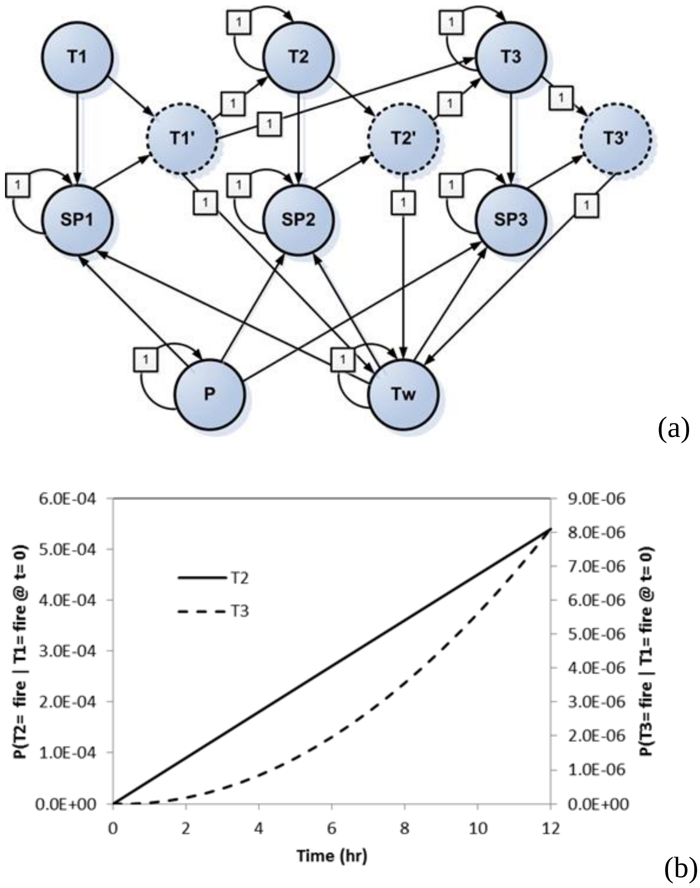
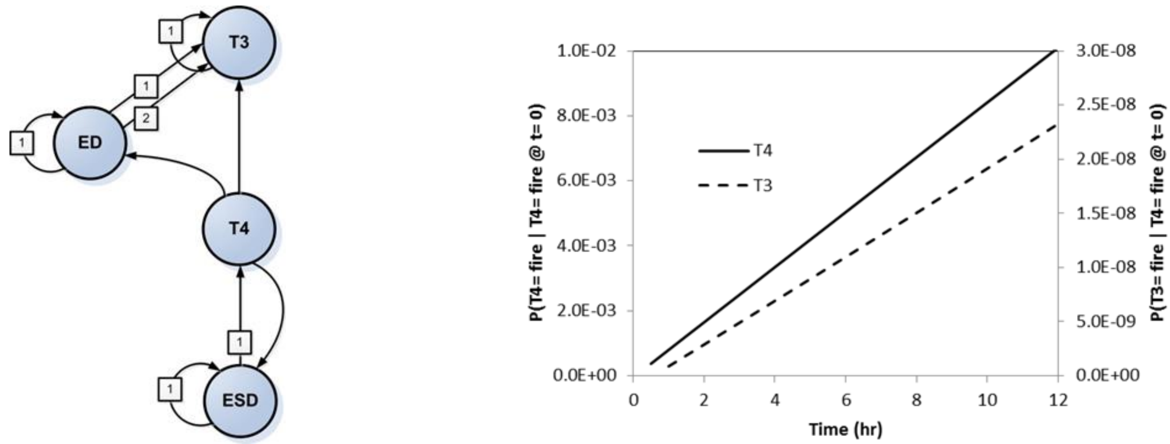


Figure8. a) DBN to model fire domino effect starting at T1 in the presence of sprinkler system; b) conditional probabilities of fire at T2 and T3 given a pool fire at T1.

4.2.2 Case 2

In this case, it has been assumed that the domino initiating event would be a jet fire at T4. According to Table 4, T3 is the only storage tank exposed to credible heat radiation. Considering T4, T3, and their respective safety barriers (Table 2), ESD and ED may be selected as the relevant safety barriers for T4 and T3, respectively, according to the combination (s1; e3) in Table 1 and the ET in Fig. 2. For illustrative purposes, the effect of higher level domino effects is neglected in the present case.
In order to apply the dynamic analysis, the failure rate of ESD, λ_{esd}, has been derived from the generic PFD_{esd} of emergency isolation and depressurization [25] as shown in Table 5. In case of ESD failure, the primary fire is not mitigated, thus the full duration of the fire scenario is considered (t_o = 120 min). In case the ESD is activated, the full content of T4 will be discharged during t_{esd} = 30 min (assuming a situation of limited filling level).
For what concerns the emergency drainage of T3, for illustrative purposes, it is assumed that the transfer pump is the main component for the emergency transfer. The failure rate of the pump, λ_{ed}, was determined from [68] while the corresponding PDF_{ed} was calculated based on λ_{ed} [4], using and a test interval of 1 year (Table 5). The pump is designed to discharge the entire inventory in t_{ed} = 60 min.
Having the probabilities and the dependencies among the components, the DBN developed in Fig. 9(a) can be used to simulate the fire escalation.



(a) (b)

Figure 9. a) DBN to model fire domino effect which starts at T4 in the presence of emergency shut down (ESD) and emergency drainage (ED); b) Conditional probabilities of fire at T4 and T3 given an initial jet fire at T4.

Similar to Case 1, in Fig. 9(a) the random failures of T3, ED, and ESD have been assumed to follow exponential distribution, denoted by one-time-step temporal arcs. Further, since the time needed by ESD and ED to isolate/empty the respective storage tanks are 30 and 60 min, respectively, the temporal arc from ESD to T4 accounts for one time step, whereas the ones from ED to T3 take into account two time steps. It should be noted that because no higher order domino effects will be considered in this case (e.g., neglecting the escalation of fire from T3 to T2), the impact of SP3 has not been taken into account in mitigating the heat radiation emitted from T3.
Using the DBN, the conditional probabilities of fire at T4 and T3 given a jet fire at T4 at t= 0 have been depicted in Fig.9(b). It is worth noting that despite an initial jet fire at T4, the successful activation of ESD can isolate T4 in a 30-min time (after one time step) and thus substantially reducing the probability of fire.

4.2.3 Case 3

In this case, assuming an initial jet fire at P1, the effects of ESD, FPP, and ER on the escalation of fire to T4 have been investigated. For the sake of clarity, in the first stage of the modeling only the impact of ESD and FPP has been taken into account (Fig. 10(a)).
The effect of fireproofing degradation is accounted for through the procedure described in Section 3 and Appendix B. In order to account for the protection time, θ, provided by FPP in sequential time steps, θ can be discretized (Appendix B, Fig. B.2(b)). According to Fig. B.2(a), the value of θ after being exposed to heat radiation for as long as 0, 30, and 60 min equals 60, 45, and 35 min, respectively. Thus, the average value of θ in each time step due to degradation will be:

- $\theta = 0.5\,(60 + 45) = 52.5$ min if $0 < t \leq 30$
- $\theta = 0.5\,(45 + 35) = 40$ min if $30 < t \leq 60$
- $\theta = 0$ if $60 < t$

As such, when the FPP is exposed to an external fire, for the first time interval ($0 < t \leq 30$), θ added to the TTF is 52.5 min. For the second time interval ($30 < t \leq 60$), the θ added to the TTF is 40 min, but since 30 min has already passed by, the total added value will be 40 - 30= 10 min. As the FPP is not supposed to protect T4 for more than 60 min, in the third interval ($60 < t$) the added θ is equal to 0.
The conditional probabilities of fire at the pipeline and T4 given a jet fire at the pipeline at t= 0 have been depicted in Fig. 10(c) as solid and dashed curves, respectively.

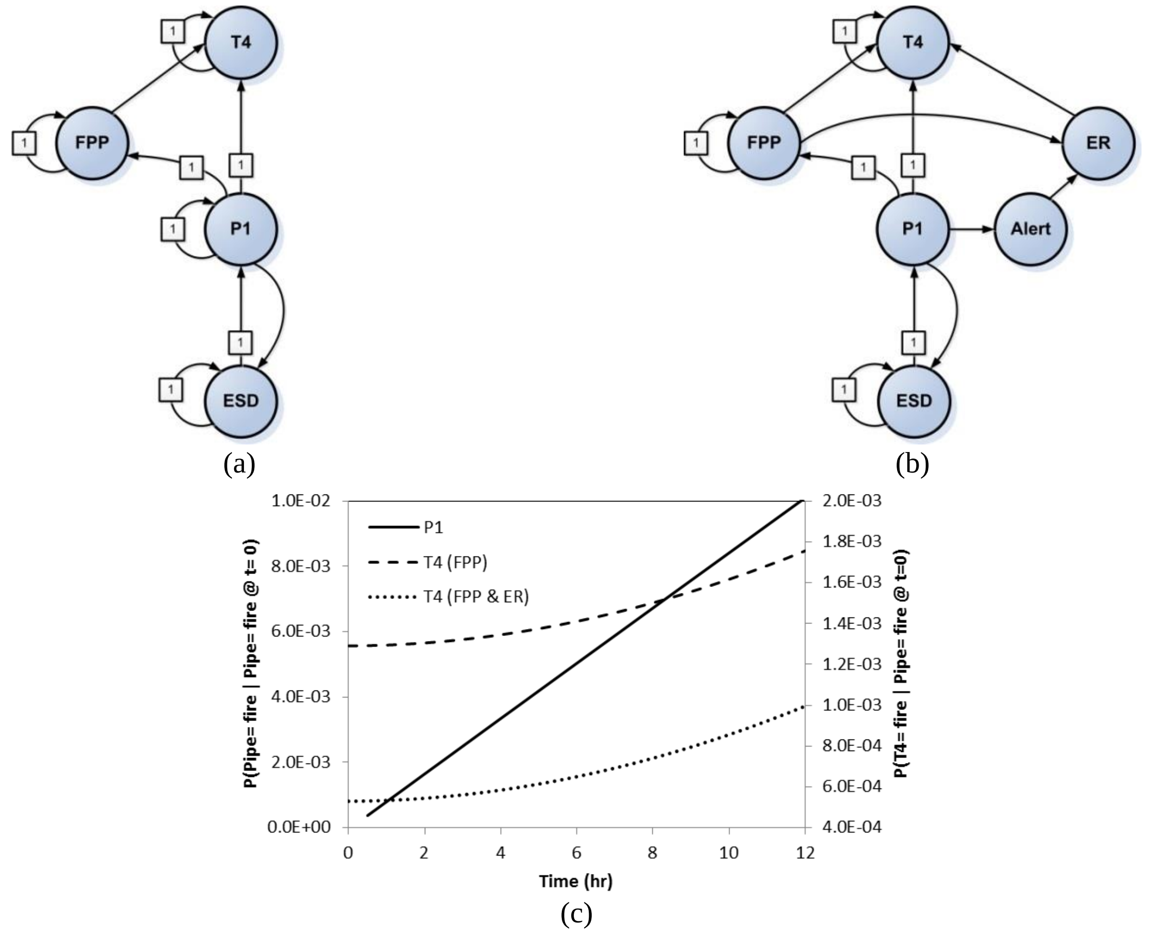


Figure 10. DBN to model the escalation of an initial jet fire at P1 (a) without and (b) with the intervention of ER. The node "Alert" represents the failure of ER on demand (PFD_{er}= 0.1 in Table 5); c) conditional probabilities of fire at P1 and T4 given an initial jet fire at P1.

To model the mitigation effect of ER, it is assumed that the TFM follows a normal distribution[6] TFM ~ N (μ= 40 min, σ= 10 min), instead of TFM =50 min as reported in Table B.2 (Appendix B). This helps taking into account the uncertainties in different operational times constituting the TFM. This way, if the provided time by FPP and the target itself is greater than the TFM, T4 will be saved and the fire is not escalated; otherwise, T4 will be damaged, leading to the secondary fire. The modeling of ER in the DBN has been presented in Fig. 10(b), in which the node "Alert" accounts for the probability of failure to call ER (failure on demand). The mitigation effect of ER on the fire escalation has been depicted in Fig. 10(c) as a dotted curve. As can be noted, the intervention of ER would reduce the failure probability of T4 to half.

5. Discussion and future remarks

5.1 Overestimation of domino probabilities

As mentioned earlier, most of previous work devoted to domino effects disregarded the role of safety barriers in place. This could result in an overestimation of failure probabilities and thus of the calculated risks. To demonstrate the key role of safety barriers in modeling and risk assessment of domino effects, the probability of fire escalation Case 1 was recalculated ignoring the mitigation effect of sprinkler systems. For this purpose, in the DBN of Fig. 8(a) the states of SP1, SP2, and SP3 were set to "fail". The conditional probabilities of fire at T2 and T3 have been depicted in Fig. 11 in the absence of the sprinklers and given a pool fire at T1. Comparing Fig. 11 and Fig. 8(b), it can be

[6] Considering the fact that TFM is the summation of a number of different activities' times.

noted that the probabilities of fire escalation, both at T2 and T3, in the absence of the sprinkler systems are two orders of magnitude larger than in the presence of the sprinklers.

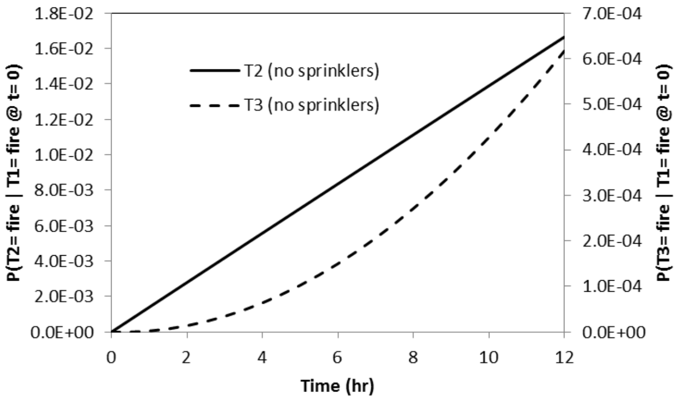


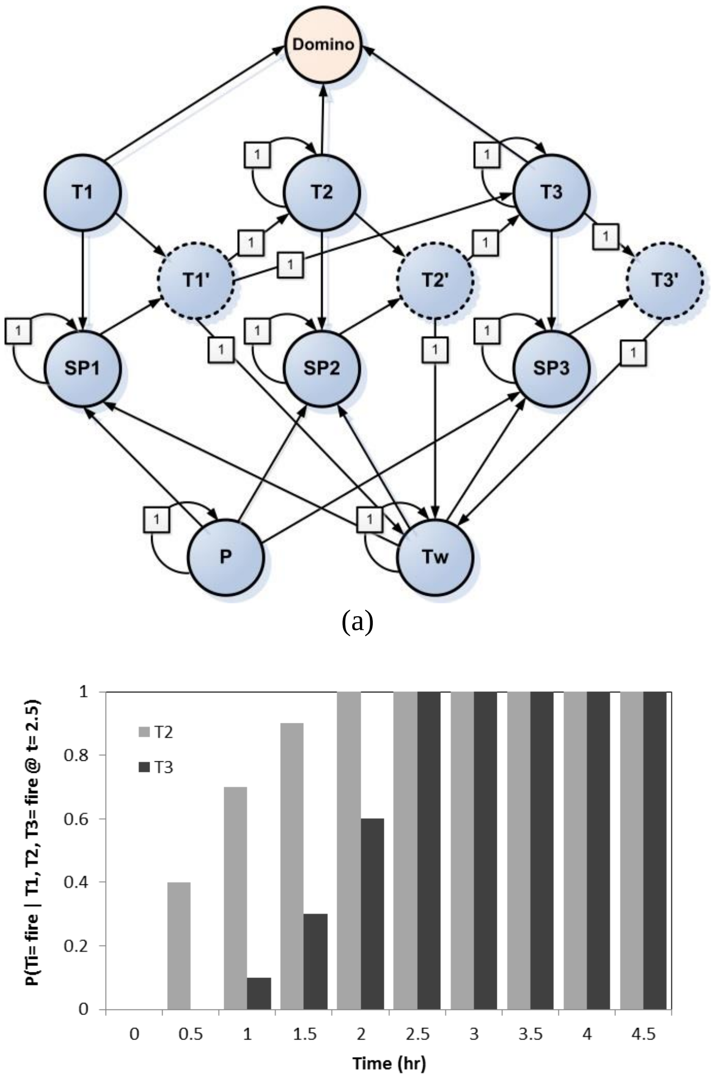
Figure11. Conditional probabilities of fire at T2 and T3 in the absence of sprinklers and given a pool fire at T1.

5.2. Probability updating

The application of DBN to the modeling of fire domino effect not only facilitates the incorporation of complicated interdependencies but also enables conducting probability updating using either real or virtual evidence. This latter aspect of DBN is of great importance in the spatial and temporal identification of critical events and failures. For illustrative purposes, the DBN in Fig. 8(a) can be modified by adding a node "Domino" as shown in Fig. 12(a).

This way, it is possible to calculate the probability of different combinations of T1, T2, and T3 at each time step. Given a virtual evidence that T1, T2, and T3 all are on fire at t= 2.5h, the updated probabilities (posteriors) of T2 and T3 have been displayed in Fig. 12(b). Given this type of evidence, the temporal evolution of fire escalation at T2 and T3 can be calculated in sequential time steps, with T2 and T3 catching fire the most probably at t= 2h and 2.5h, respectively.

Foreseeing the temporal sequence of the storage tanks in a (virtual) domino effect enables one to rank order the tanks based on their priority so that in the face of limited resources an optimal decision can be made. As an example, considering Fig. 12(b), an ER team with limited staff and water reservoir arriving at the plant at t= 1.5h (1.5 hour after fire at T1 is reported) will try to keep T2 cool instead of T3 (the likelihood of fire at T2 at t= 1.5h is much higher than that of T3) while suppressing the fire at T1.



(a)

(b)

Figure 12. a) Modified DBN for inserting virtual evidence and probability updating; b) Posterior probabilities of T2 and T3 given that all the atmospheric tanks are on fire at t= 2.5 h.

5.3. Finite source of water for firefighting

Another issue to consider in the temporal degradation of the firefighting systems is the consumption of the water reservoir – Tw in Fig. 8(a) – due to the functioning of the sprinklers. Although in the present study Tw was assumed to be connected to a theoretically infinite source of water (river), in many cases the limited amount of water in Tw is the only water available for firefighting. In such cases, the amount of water of Tw can be modeled as a stochastic variable with a finite set of states. The temporal transition from one state to the other (decrement of water) during the time steps can be modeled as a function of the available water at a time step and the number of sprinkler systems functioning at the same time step. This way, not only the amount of water of Tw affects the successful operation of the sprinklers (denoted by arcs from Tw to SP1, SP2, and SP3 in Fig. 13) but also the functioning of the sprinklers impact the amount of water in Tw (denoted by arcs SP1, SP2, and SP3 to Tw in Fig. 13).

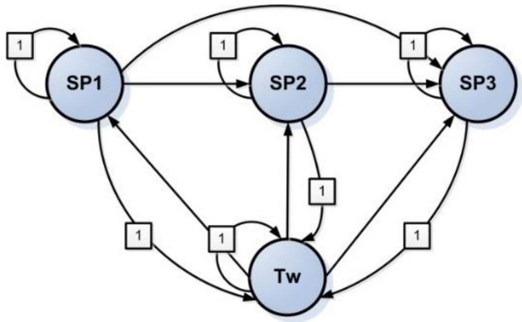
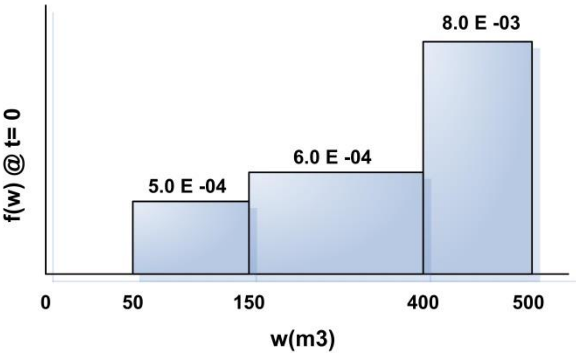


Figure13. Stochastic modeling of water consumption in case of finite source of water.

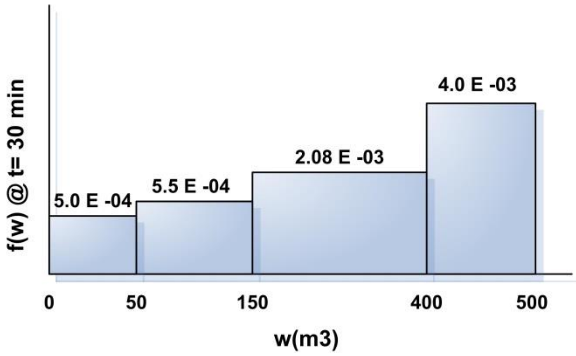
Likewise, there should be arcs both from SP1 to SP2 and SP3 and from SP2 to SP3 to account for the priority of each sprinkler in case of water scarcity. Nevertheless, the main challenge in modeling Tw as a stochastic node will be the identification of conditional probabilities. We show this dilemma using an illustrative example where the total (finite) amount of water in Tw is assumed to be 500 m^3 while the water consumption of each sprinkler is equal to 100 m^3/hr. Assume that at t= 0 the probability distribution of water, w^0, in Tw can be predicted as:

$P(400 < w^0 < 500) = 0.8$
$P(150 < w^0 < 400) = 0.15$
$P(50 < w^0 < 150) = 0.05$
$P(0 < w^0 < 50) = 0.0$

Assuming a uniform distribution – for illustrative purposes – in each water interval, the probability distribution can be presented in Fig. 14(a).



(a)



(b)

Figure 14. Probability distribution of water amount in Tw given the operation of SP1 at a) t= 0 and b) t= 30 min

Assuming that at t= 0 only SP1 is working, and SP2 and SP3 are still dormant, the water consumption after the first time step (30 min) will be 50 m^3. Having the probability distribution of w^0 in Fig. 14(a), the updated probability distribution of water at t= 30 min (second time interval), w^1, can be represented as Fig. 14(b).

For example, the updated probability of Tw being in the third state, that is $P(150 < w^1 < 450)$, we have:

$P(150 < w^1 < 400) = P(150 < w^0 - 50 < 400) = P(200 < w^0 < 450) = P(200 < w^0 < 400) + P(400 < w^0 < 450) = 200 \times 6.0\, E - 04 + 50 \times 8.0\, E - 03 = 0.52.$

Considering a uniform distribution, the updated probability distribution function of water $f(w^1)$ for $150 < w^1 < 400$ can be calculated as $f(w^1) = \frac{0.52}{400-150} = 2.08\, E - 03$ (Fig. 14(b)).

Following the same procedure, the updated probabilities for the states of Tw will be:

$P(400 < w^1 < 500) = 0.4$
$P(150 < w^1 < 400) = 0.52$
$P(50 < w^1 < 150) = 0.055$
$P(0 < w^1 < 50) = 0.025.$

Comparing Fig. 14(a)and Fig. 14(b), it can be noted that even in a simple case[7] the stochastic variation of water amount includes the temporal changes in both the probabilities and the probability distributions which can easily become too cumbersome and intractable.

6. Conclusions

In the present study, the dynamic evolution of the performance (availability and effectiveness) of protection measures and related impact on the escalation of fire domino effects was illustrated using event tree analysis. To quantify both the dynamic changes in the performance of firefighting systems and the temporal dependencies among the events during fire escalation, a dynamic Bayesian network methodology was developed based on the event tree analysis. The application of the methodology to an illustrative chemical plant demonstrated the key role of the firefighting systems in reducing the probability of fire escalation by several orders of magnitude, which is usually disregarded in domino effect modeling and risk assessment, leading to the overestimation of the probability of domino effect and thus the risks. It was also illustrated that the developed dynamic Bayesian network can be employed for probability updating and, thus, identification of critical events during fire escalation, which can be vital i) during emergency response activities, and ii) as a decision making support tool for the management of the safety barriers in chemical plants.

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Appendix A

A systematic identification of the time-evolving events, parameters, interactions, etc. affecting each safety barrier for protecting process equipment against fire was carried out through a DMEA (degradation modes and effects analysis) study (see Section 2). The present appendix shows the tables of the DMEA analysis, in particular:

- Firefighting active devices, such as foam/water sprinklers and WDS, are analyzed in Table A.1;
- Emergency isolation (ESD) and depressurization (BDV) systems are analyzed in Table A.2;
- Passive protections, such as fireproofing and pressure relief valves (PSV) are analyzed in Table A.3;
- Emergency response is analysed in Table A.4.

The results allowed supporting the performance analysis described in Section 2.

Table A.1. Degradation modes and effect analysis (DMEA): sprinkler and WDS system.

COMPONENT	DEGRADATION MODE	LOCAL EFFECT	GLOBAL EFFECT	NOTES
Water tank	Consumption of water	No effect on system performance if level decreases	When water is finished, unmitigated fire	Firefighting system is designed to withstand limited scenarios with a flowrate of about 800-1200 m^3/h[45]
	Leakage and release of firefighting water	Same as above	When water is finished, unmitigated fire	In this case, the water consumption rate increases. Estimate the probability of leak and the released flowrate
	Rupture of the tank affected by fire	No water feed in the pumps	Unmitigated fire	Water tank is located at 60m from "hazardous area" of the plant. Evaluate the damage probability for water tank
Foam tank	Consumption of foam	No effect on system performance if level decreases	Firefighting with water	Assume that even water may have a benefit on heat flux reduction, eventually neglect foam in the analysis
	Leakage and release of powder	Same as above	Same as above	Same as above
	Rupture of the tank affected by fire	No foam is produced	Same as above	Same as above
Delivery pump	Provide insufficient flowrate for firefighting water (fail while running)	Insufficient water for extinguishment	Reduction of protection, higher heat radiation from damaged unit	Estimate the effect of water flowrate reduction. Conservative assumption: no heat flux reduction (not adequate)
Delivery and jockey pump	Provide insufficient pressure for firefighting water (fail while running)	Insufficient foam mixing	Same as above	Same as above
Foam pourer and delivery (for sprinkler)	Progressive obstruction during fire-fighting agents delivery	Decrement of delivery flowrate	Same as above	Same as above
Nozzles and water distribution (for WDS)	Same as above	Same as above	Same as above	Same as above

Table A.2. Degradation modes and effect analysis (DMEA): Emergency isolation (ESD) and depressurization (BDV) systems.

COMPONENT	DEGRADATION MODE	LOCAL EFFECT	GLOBAL EFFECT	NOTES
Emergency shut down valve (SDV)	Partial/no closure in shut down phase	Flow in pipe and units are not isolated	Major severity of primary event	Critical for jet fire duration pool fire may extend to other units
	Failure of actuator and opening	Same as above	Same as above	Same as above
	Spurious signal of opening	Same as above	Same as above	Same as above
Emergency blow down valve (BDV)	Partial opening in blow down phase	Increment of depressurization time, high inventory in target units and pipes	Escalation potential is not reduced, primary fire is not suppressed through venting	Valid only for pressurized equipment (pipe rack or tanks)
	Failure of actuator and closure	Same as above	Same as above	Same as above
	Spurious signal of closure	Same as above	Same as above	Same as above
Drainage and reduction of inventory of critical units	Possible failure during transfer of goods to safe location	High inventory in target or primary units, spillage of hazardous chemicals	Escalation potential is not reduced, burnout time is not reduced	Valid only for atmospheric tanks or units
	Reduced amount due to line problem (pump, valve blockage, etc.)	High inventory in target or primary units, spillage of hazardous chemicals	Same as above	Same as above

Table A.3. Degradation modes and effect analysis (DMEA): passive fire protections.

COMPONENT	DEGRADATION MODE	LOCAL EFFECT	GLOBAL EFFECT	NOTES
Passive fire protection (PFP) insulant (high resistance)	Depletion of protective properties, increment of thermal conductivity, time degradation	Increment of temperature and pressure in the tank	Reduction of protection time, increment of failure probability	The effectiveness is still not affected by the fire intensity. A progressive increment of conductivity leads to a decrement in protection time
PSV	Spring softening	Opening at reduced pressure, decrement of venting capacity	Not affecting escalation, affected only by PFP	Not considered in the analysis

Table A.4. Degradation modes and effect analysis (DMEA): emergency response.

COMPONENT	DEGRADATION MODE	LOCAL EFFECT	GLOBAL EFFECT	NOTES
Emergency water delivery system	Insufficient water flowrate (fail while running)	Increment of temperature and pressure in the tank	Reduction of protection time, increment of failure probability	Not considered in the analysis; only availability is given
	Absence of water additional supply	Insufficient water to extinguish fire	Reduction of protection, higher heat radiation from damaged unit	Same as above
Emergency team	Ineffective resource allocation	Same as above	Same as above	Evaluate the effect of different configurations

Appendix B

B.1 Description of vessels fragility models

The present appendix summarizes the vulnerability or fragility models adopted in the present study for the estimation of failure probability of equipment exposed to fire, based on probit models. The models are extensively described in [58] and were recently updated [25].The robustness of the approach was documented in the literature through the application in several risk studies [1,2,68–72]. A summary of the proposed models is reported in Table B.1, while in the following their main characteristics are illustrated.

Probit models were developed considering that the higher the vessel resistance to an external fire, the lower the likelihood of a failure, hence less credible the escalation. Vessel resistance may be synthetically expressed in terms of the TTF (Time to Failure), which is the time lapse between the external fire start and the fired vessel failure, induced by heat-up and consequent pressurization [73]. High TTF values will allow for external emergency timely intervention before the failure, thus reducing the probability of damage and escalation. Therefore, according to [58], the probability of failure (P_d) was estimated through a simplified approach based on the comparison among the TTF and characteristic times required for successful mitigation (see Table B.1).

TTF evaluation isa complex task which involves the analysis of the thermal and mechanical response of target equipment exposed to fire [59]. However, a detailed thermal and stress analysis for each possible target equipment in a chemical facility would require a prohibitive run time, not justified in a QRA framework due to the uncertainties that usually affect the characterization of the fire scenarios.Hence, the simplified correlations shown Table B.1 and developed in a previous work [58] allowed for a straightforward conservative TTF estimation.

Tworeference times for emergency response were identified: the maximum time required to start the emergency operations or time to alert (τ_1= 5min) and the maximum time required for onsite mitigation (τ_2 = 20min). The values of τ_1 and τ_2 were derived from expert judgment, based on a survey of the times needed for the arrival of internal emergency teams in different locations of refineries tank farms (see [58] for more details). Therefore, assuming a log-normal distribution of failure probability, P_d = 0.1 was assumed for TTF = τ_2, and P_d = 0.9 was assumed for TTF=τ_2, allowing for the quantification of probit constants ($\zeta_{1,}$ ζ_2) shown in Table B.1.

Table B.1. Fragility models and input parameters for the calculation of failure probability of pressurized and atmospheric tanks due to fire exposure.

Item	Definition	Value/Equation
Y	Probit value obtained through the fragility model[a]	$Y = \zeta_1 \times \ln(TTF) + \zeta_2$
ζ_1	First probit coefficient	$\zeta_1 = [3.718 \ln(\tau_1) - 6.283 \ln(\tau_2)] / [\ln(\tau_1) - \ln(\tau_2)]$
ζ_2	Second probit coefficient	$\zeta_2 = 2.565 / [\ln(\tau_1) - \ln(\tau_2)]$
τ_1	Time to alert	5 min [58]
τ_2	Time to onsite mitigation	20 min[58]
TTF	Time to failure of fired vessel (min)	$TTF = TTF_t + \theta$
TTF_t	Time to failure of unprotected tank (min)	Simplified correlation for pressurized vessels [58]: $TTF_t = 2.783 \times 10^{-4} \times \exp\left(8.845 V^{0.032} - 0.95 \ln(Q_r)\right)$
		Simplified correlation for atmospheric vessels [58]: $TTF_t = 2.783 \times 10^{-4} \times \exp\left(-2.67 \times 10^{-5} V - 1.13 \ln(Q_r) + 9.877\right)$
θ	Protection time guaranteed by the fireproofing (min)	See Section B.2
Q_r	Heat load due to the fire (kW/m^2)	Q_r is evaluated considering that active protections may mitigate the fire and/or shield the target, see Eq. (2)
V	Vessel volume in m^3	-

[a]Probit is directly converted to vessel failure probability P_d (see [4]).

As shown in Table B.1, the effect of fireproofing is implemented in the methodology following the approach developed by Landucci et al. [25] adding a protection time (θ) which extends the TTF. This protection time may be strongly reduced in case of fireproofing ineffective performance, due to erosion, corrosion, wrong installation, insufficient maintenance, etc. However, for the sake of simplicity it was assumed an effective coating, with unitary efficiency. Therefore, only three possible states are associated with the coating: i) intact; ii) degraded; iii) failed (after a maximum working time). Section B.2 describes a simplified approach adopted for the evaluation of the term θ, specifically addressing degradation phenomena to support the dynamic probabilistic assessment (see Section 2).

B.2 Simplified approach for the estimation of fireproofing protection time (θ)

Several degradation phenomena may lead to a change in the thermal properties of the coating while exposed to the fire. Several literature studies focused on this issue [51,55] and a detailed analysis is out of the scope of the present work. In this work, the transient degradation of the coating was associated with an increment of effective thermal conductivity, which may increase up to one order of magnitude with respect to the nominal value during fire exposure [51,55]. The higher the thermal conductivity (namely, k), the lower will be the θ, up to a total absence of protection (e.g., failure state of the coating). Landucci et al. [56] performed FEM (finite elements modelling) simulations of fireproofed LPG tanks, calculating the reduction of θ in case of increment in k. Based on these results, a simplified procedure was adopted in this study (see Fig. B.1)

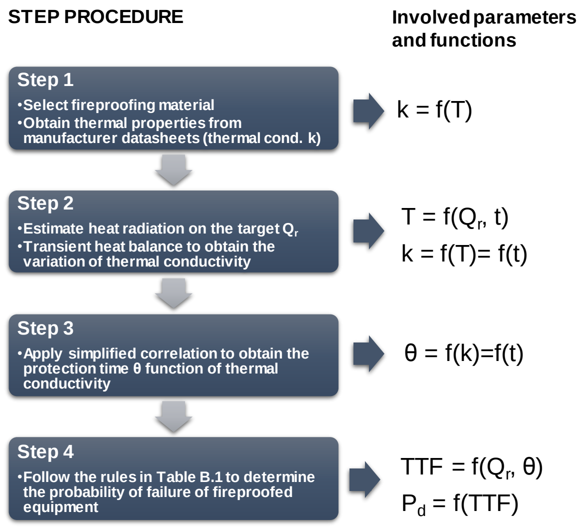

Figure B.1. Step procedure for the estimation of fireproofed vessels failure probability, accounting for the degradation of thermal protection; k = thermal conductivity; P_d = probability of failure; Q_r = heat radiation on the target; T = temperature; t = time; TTF = time to failure; θ = fireproofing protection time.

This approach is valid for inorganic fireproofing. Organic fireproofing (typically intumescent materials) feature a complex behavior which is not addressed for the sake of simplicity, but further studies may allow the integration in the current method [55].

Given a primary fire (or multiple synergistic fires) resulting in a total heat flux Q_r on the fireproofing material, a previously developed mono-dimensional approach is firstly adopted (Step 2 in Fig. B.1). The model, extensively described in [57] together with the validation against experimental data, is based on a heat balance on an inorganic fireproofing board. The model allows obtaining the temperature vs time evolution of the material (e.g., T(t)), as well as the dynamic growth of thermal conductivity k(t), since the temperature variation of thermal conductivity (e.g., k(T)) is given by manufacturers and gathered in Step 1 (see Fig. B.1).

Then, in order to perform a straightforward assessment of k(t) effect on θ, FEM results shown in [56] were interpolated obtaining the simplified conservative θ vs k correlation for fireproofed large scale storage tanks (60-150 m^3) exposed to severe heat radiation (up to 180 kW/m^2):

$$\theta(k) = 150.10\,k^2 - 262.98\,k + 115.28 \qquad \text{(B.1)}$$

where θ is in min and k in W/(mK). In case a piece of equipment is exposed to a less severe heat radiation, Eq. (B.1) may be adopted on the safe side.

The present method is applied for the analysis of Case 3, described in Section 4. In the present case, the pressurized tank T4 is exposed to a severe jet fire, with an incoming heat flux of 150 kW/m^2. A fireproofing coating (10 mm thickness) made of silica needled filaments is installed to protect T4. The dynamic simulation of coating behavior and available protection time was performed following the method represented in Fig. B.1, based on the application of the thermal model described in [57]. The results are reported in Fig. B.2a. The predicted thermal conductivity (dashed line in Fig. B.2a) allowed estimating the available protection timeθ (solid line). The variation of θ was discretized (see Fig. B.2b) in order to apply the calculation procedure shown in Table B.1 for the estimation ofequipment time to failure, supporting the probabilistic assessment of Case 3 through dynamic Bayesian networks (see Section 4).

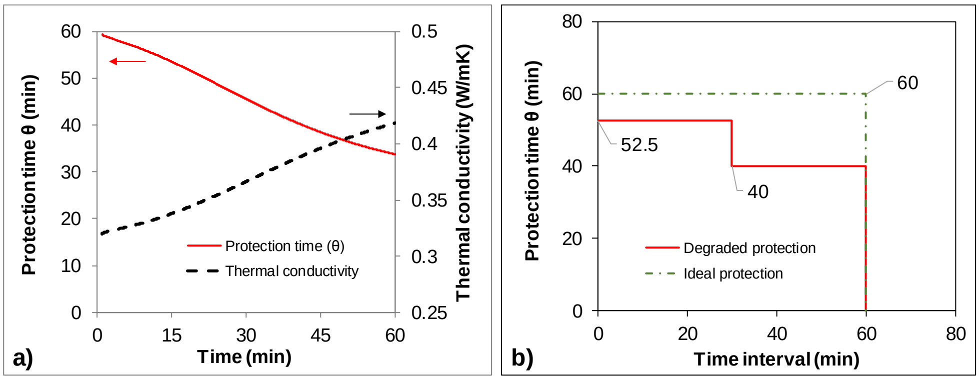

Figure B.2. a) Results of the simulation for the heat resistant coating exposed to 150 kW/m^2 heat radiation. Details on the thermal model are extensively reported in [57]; b) discretization of the protection time in the present study based on the results of the thermal simulation.

B.3 Simplified approach for the estimation of time for final mitigation (TFM)

The effect of emergency team intervention is taken into account in the probabilistic assessment by determining the time for final mitigation parameter (TFM), which is implemented in the approach described in Section 2 (see Fig.3). A demonstration case is defined in order to exemplify the procedure for TFM evaluation proposed by Landucci et al. [25], assuming that the measures put in place by emergency teams are aimed to effectively cool the target. The target is tank T4 considered in Case 3 (see Section 4).The method is based on the determination of the water requirement for the emergency operation (G_{em}). The following relationship is adopted to estimate G_{em}:

$$G_{em} = \omega_{EP} \cdot A_{target} \cdot SF \qquad \text{(B.2)}$$

where ω_{EP} (= 10.0 L $min^{-1}m^{-2}$) is the required application density for target exposure protection, as given in NFPA 15 [20], A_{target} is the cross sectional area of the target vessel (thus, A_{target} = 54 m^2 based on the dimensions of tank T4 shown in Table 2), SF (= 3) is a safety factor used to take into account the necessity of keeping a uniform water film over the whole vessel surface [25]. Based on the considered input data, a required water flowrate of approximately 100 m^3/h is obtained.

Thus, emergency teams need secondary water supply systems (each one with minimal capacity of 90 m^3/h) [74] located within 1 km distance from the installation. Thus, a water transport system (WTS 1000) covering the above mentioned distance of 1 km, together with the fire engines required for its proper functioning, are necessary in order to have an effective emergency response [74].

Based on these considerations, and summing up the required time to complete each operation summarized in Table B.2, TFM = 50 min is obtained for Case 3.

Table B.2. Timing of all operations required for final mitigation by external emergency teams. WTS = water transport system.

Operation	**Time (min)**
Alerting fire brigades	5
Arrival of WTS 1000 together with four fire engines required for its proper functioning	15
Deployment time for fire-fighting devices belonging to WTS 1000	15
Deployment time for fire-fighting devices	7
Time to carry out extra operations	8
Total	*50*