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Which Fire to Extinguish First? A Risk-Informed Approach to Emergency Response in Oil Terminals

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The performance of fire protection measures plays a key role in the prevention and mitigation of fire escalation (fire domino effect) in process plants. In addition to passive and active safety measures, the intervention of firefighting teams can have a great impact on fire propagation. In the present study, we have demonstrated an application of dynamic Bayesian network to modeling and safety assessment of fire domino effect in oil terminals while considering the effect of safety measures in place. The results of the developed dynamic Bayesian network—prior and posterior probabilities—have been combined with information theory, in the form of mutual information, to identify optimal firefighting strategies, especially when the number of fire trucks is not sufficient to handle all the vessels in danger.

KEY WORDS: Domino effect; dynamic Bayesian network; entropy; firefighting; mutual information; oil terminal

1. INTRODUCTION

Domino effects where a primary fire or explosion at a vessel (e.g., storage tank) propagates to neighboring vessels and triggers secondary fires or explosions have been responsible for some catastrophic industrial accidents, especially in the chemical and process industries due to large inventories of flammable and explosive materials.(1–3) Due to their low-probability yet catastrophic consequences, the European Council Directive for the control of major accident hazards (also known as Seveso III)(4) requires the owners/managers of hazardous plants to consider possible accidental scenarios caused by domino effects in safety assessment and management plans.

In the field of domino effects, a number of methodologies has been developed based on simplifying assumptions either for estimating the damage probabilities (escalation probabilities) of process units in case of external fires and explosions or for modeling domino effect scenarios.(5–10) During the past decade, a few attempts have been made to model the sequence of events in domino effect scenarios and to estimate respective probabilities.(11–14)

In case of fire domino effects (a chain of fires), the presence of safety protection systems such as sprinkler systems, water deluge systems, fireproofing, and firefighting teams can not only prevent the initiation or propagation of domino effects but also effectively reduce respective probabilities. Design standards and safety regulations(15) have mandated chemical and process plants to consider fire protection measures as an integral part of plants' safety management. However, only a few of previous studies have taken into account the influence of such safety measures on the escalation probabilities and the propagation of domino effect scenarios.(16,17)

The present study aims to demonstrate an application of dynamic Bayesian network (DBN) to address the drawbacks of previous studies, while (i) accounting for time-dependent failure of fire protection measures, and (ii) modeling the influence of fire

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protection measures on fire propagation. DBN is an advanced extension of BN to model temporal dependencies embedded in stochastic events or to model sequence of failures in dynamic systems.(14,18–21) A conventional BN can be viewed as a snapshot where the interactions among the components of a system are modeled within a certain time interval. In a DBN, on the other hand, the interactions and dependencies not only within a certain time interval but also from previous time intervals (in case of discrete DBNs) can be taken into account.

The flexible structure and probabilistic reasoning engine of DBN can facilitate incorporating spatial and temporal dependencies and interactions among the parameters of domino effects; more importantly, the probability updating feature of DBN, given a set of observations at a certain time, when combined by information theory, provides a strong reasoning tool for predicting the behavior of the domino effect in next time intervals and thus taking optimal mitigating strategies via emergency response firefighting.

When the number of firefighting crew and required equipment are sufficient, all burning units as well as adjacent units that are exposed to fire should be suppressed and protected, respectively, to prevent or reduce the possibility of fire propagation. However, the main challenge arises when the number of units in danger—both on fire and exposed to fire—exceeds available firefighting resources (staff, equipment, etc.). Accordingly, setting optimal firefighting strategies for which burning unit to suppress and which exposed unit to protect can become challenging.

The rest of this article is organized as follows: in Section 2, two types of common fire protection measures, among others, sprinkler systems and emergency response firefighting, are discussed. Section 3 briefs the fundamentals of DBN as the main probabilistic technique for domino effect modeling and analysis in this study along with mutual information as an auxiliary reasoning technique in quantifying correlations. The methodology is developed in Section 4, while its application to a fuel storage plant is demonstrated in Section 5; the conclusions are in Section 6.

2. FIRE PROTECTION IN OIL TERMINALS

Fire protection measures are aimed at delaying or preventing escalation during fire domino effects. Inherently safer design (ISD) techniques(22) such as minimization of hazardous substances or provision of adequate separation distances among hazardous units have been proposed as the most effective ways to eliminate or reduce the risk of domino effects.(23) ISD techniques are, however, among macro-layout modifications, which are usually limited to the design phase of chemical and process plants and cannot easily be applied to existing plants. Apart from ISD measures, three categories of fire protection measures—(i) passive fire protection measures, (ii) active fire protection measures, and (iii) procedural and emergency response measures—can be identified.(24)

Unlike passive fire protection measures (e.g., fireproofing), active protection systems such as sprinklers and deluge systems require external activation or human intervention to perform the protection action. Active protection systems usually consist of a fire/smoke detection system, a treatment system (logic solver), and an actuation system (mechanical, electrical, or human), functioning in series. Emergency response measures such as evacuation and firefighting are usually deemed as last resort provided that the passive and active safety measures in place fall short in suppressing or controlling the propagation of fire.

Sprinkler systems are usually aimed at providing a firefighting agent (e.g., water or water-based foam) in order to suppress the primary fire, and are typically considered for atmospheric storage tanks for low flash point flammable liquids.(25) Water deluge systems, on the other hand, are aimed at providing a spray curtain in order to shield a target vessel from the heat radiation emitted from a primary fire, and are mainly used for pressurized target vessels.(16) Similar to deluge systems, fireproof coating of process vessels (usually pressurized vessels) is performed with the aim of reducing the heat radiation the target installation receives.(16)

In case engineering passive and active fire protection measures fail to adequately suppress and control the fires, emergency response measures such as plant evacuation and emergency firefighting are considered. The main goal of firefighting is to extinguish small fires before they become large (except for jet fires from pressurized vessels, which should be allowed to burn out) or to control large fires and protect (cool) adjacent vessels exposed to fires until emergency response resources are adequate to handle all vessels both on fire and exposed to fires.(26) In the present study, for the sake of brevity, only sprinkler systems and firefighting will be considered for a demonstrative oil terminal comprising of atmospheric storage tanks.

2.1. Sprinkler Systems

Sprinkler systems are aimed at suppressing a primary fire and preventing its spread to nearby vessels; according to international standards and current industrial practice,(15,27) sprinkler systems should be installed on atmospheric storage tanks containing flammable liquids. Although the aim of this type of safety measure is to control and, eventually, suppress the fire, it is conservatively assumed that sprinkler systems mitigate the heat radiation emitted from the fire instead of entirely suppressing it. The mitigated heat radiation Q_m due to successful activation of a sprinkler system can conservatively be assumed as 40% of the original heat radiation as $Q_m = 0.4\ Q_o$.(28,29)

Similar to any active safety barrier, for a sprinkler system different failure rates can be considered in standby (λ_S) and operational (λ_O) states as well as a probability of failure on demand (PFD). Operational and standby failure rates refer to random failures of a component when operating and idling, respectively. Furthermore, components that operate cyclically may fail when switching from a standby to an operational mode. For components with constant failure rates, a constant PFD can be assumed.(30) For components with constant failure rates, an exponential cumulative distribution function $F(t) = 1 - \exp(-\lambda_O t)$ can be used to estimate the failure probability of the component, where t is the operational time.(30) Having the operational failure rate, the relationship given by Lees(31) can be used for the estimation of PFD as PFD $= 0.5\ \lambda_O\ T$, where T is the test interval.

Assuming that the sprinkler system would not fail while in standby state, $\lambda_S = 0.0$ (year^{-1}), a constant operational failure rate $\lambda_O = 2.0 \times 10^{-2}$ (year^{-1}) can be considered.(16,32) That is, even if the sprinkler is activated successfully (with a probability of 1- PFD), there is a chance of failure $F(t) = 1 - \exp(-0.02t)$ as operational time t passes. Using the relationship given by Lees(31) and considering a one-year (8,760 hour) test interval for industrial facilities, a PFD of 0.01 would be estimated.

2.2. Firefighting

Firefighting is usually aimed at suppressing pool fires, while jet fires are left free to burn till exhausted. In addition to fire suppression, firefighting teams may make an attempt to cool the exposed vessels to prevent further damage and escalation of fire. Cooling adjacent units is more common in case of jet fires instead of suppressing the fire. The effectiveness of firefighting strongly depends on the skills and the level of preparedness of emergency responders as well as the number of firefighting engines (trucks)(33) and distance of water resources from the plant.(16) Depending on whether the firefighting team is called upon and arrives at the scene in time, fire escalation may successfully or partly be controlled.(16,33)

Landucci *et al.*(16) have investigated the effectiveness of firefighting based on a comparison between the time to failure of exposed vessels and a simplified estimation of time for mitigation of fire, taking into account such factors as the type of target vessels, the fire mitigation strategy, and the facility location. Considering two main tasks for firefighting teams as (i) mitigating burning vessels and (ii) cooling exposed vessels, both at a time, we, for illustrative purposes, assume that cooling an exposed vessel would prevent it from damage, whereas the mitigation of a burning vessel would reduce the emitting heat radiation below a credible threshold required for damaging exposed vessels; such thresholds can be considered as 15 kW/m^2 and 45 kW/m^2 for atmospheric and pressurized vessels, respectively.(23) As we will see later, the main challenge in setting firefighting strategies arises when the number of vessels in danger exceeds the number of available firefighting trucks. As such, making decisions as to which burning vessels to mitigate and which exposed vessels to cool can become a dilemma.

3. PROBABILISTIC REASONING

3.1. DBN

BN is a directed acyclic graph that can be used for probabilistic prognosis and diagnosis;(34,35) in a BN, random variables are represented as nodes and the conditional dependencies among them are denoted by directed arcs. Using the chain rule and the concept of d-separation, the joint probability of a set of random variables $U = \{X_1, X_2, \ldots, X_n\}$ can be factorized as the product of marginal and conditional probabilities:

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

where $\pi(X_i)$ is the parent set of the node X_i.

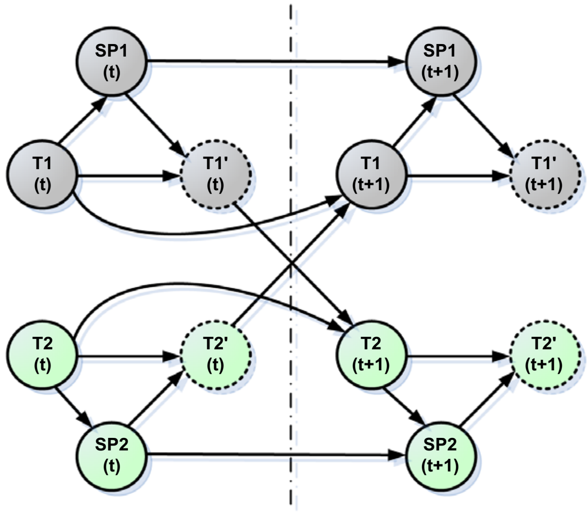

Fig. 1. Modeling of fire propagation in DBN in presence of sprinkler system.

BN employs Bayes's theorem to update probabilities when some new information, so-called evidence E, becomes available:

$$P(U|E) = \frac{P(U)P(E|U)}{P(E)} = \frac{P(U,E)}{\sum_U P(U,E)}. \quad (2)$$

DBN is an extension of BN that facilitates explicit modeling of temporal evolution of random variables over a discretized timeline. Dividing the timeline into a number of time intervals, DBN allows a node at ith time interval to be conditionally dependent not only on its parents at the same time interval but also on its parents and even itself at previous time intervals:

$$P(U^{t+1}) = \prod_{i=1}^{n} P\left(X_i^{t+1}|X_i^t, \pi(X_i^t), \pi\left(X_i^{t+1}\right)\right). \quad (3)$$

When failure rates are constant (i.e., for exponential probability distribution), the conditional probabilities can be calculated merely based on two sequential time intervals, simplifying the modeling of DBN to a large extent. Fig. 1 depicts a DBN over two sequential time intervals, where the conditional probabilities assigned to node T2 at the second time interval would be P(T2^{t+1} | T2^{t}, T1'^{t}). Due to its flexible structure and probabilistic reasoning engine, DBN has widely been used in system safety and reliability analysis.(14,19–21,36)

3.2. Information Theory

Considering a multistate random variable such as $X = \{x1, x2, \ldots, xn\}$ with the probability mass function of P(X), the amount of uncertainty associated with X can be measured using the concept of entropy $H(X)$ as:(37)

$$H(X) = -\sum_{x\in X} P(x)\ \log P(x). \quad (4)$$

The conditional entropy of X given another random variable Y can be defined as:

$$H(X|Y) = -\sum_{x\in X,\ y\in Y} P(x,y)\log\frac{P(x,y)}{P(y)}. \quad (5)$$

The mutual information of X and Y, $I\ (X,Y)$, can be defined as the reduction in the uncertainty of X given some information about Y (e.g., if $Y = y1$):

$$\begin{aligned} I(X,Y) &= H(X) - H(X|Y) \\ &= \sum_{x\in X,\ y\in Y} P(x,y)\log\frac{P(x,y)}{P(x)P(y)}. \end{aligned} \quad (6)$$

Using the chain rule, the mutual information can be rearranged as:

$$I(X,Y) = \sum_{x\in X,\ y\in Y} P(y)P(x|y)\log\frac{P(x|y)}{P(x)}. \quad (7)$$

Mutual information can be used to identify the amount of correlation (influence) among random variables of a BN.

4. METHODOLOGY

Khakzad *et al.*(17) introduced a methodology based on conventional BN to model the impact of active fire protection measures such as sprinkler systems and water deluge systems as well as passive fire protection measures such as fireproofing on domino effect probability and propagation. However, due to the modeling limitation of conventional BN, only PFD and effectiveness of safety barriers were taken into account at a time snapshot, ignoring the temporal changes of failure probabilities (owing to λ_O).

Following the methodology developed by Khakzad *et al.*,(17) fire propagation in the presence of sprinkler systems can be modeled using the DBN in Fig. 1, in which only two sequential time slices t and $t + 1$ have been illustrated. It should be noted that the notions of $t + 1$ and t do not necessarily imply a unit time difference between two sequential time

Table I. Conditional Probability Table for P(SP1(t) | T1(t))

SP1 (t) ↓ T1(t)→	Burning	Not Burning
Not working	PFD	1
Working	1 – PFD	0

Table II. Conditional Probability Table for P(SP1($t+1$) | SP1(t))

SP1 ($t+1$)↓ SP1(t)→	Not Working	Working
Not working	1	$1 - \exp(-\lambda_O \tau)$
Working*	0	$\exp(-\lambda_O \tau)$

*τ is the time difference between two sequential time slices: $\tau = (t+1) - (t)$.

Table III. Conditional Probability Table for P(T1'(t) | T1(t), SP1(t))

T1(t)	Burning		Not Burning	
T1′(t)↓ SP1(t)→	Not Working	Working	Not Working	Working
Original heat (Q_o)	1	0	0	0
Mitigated heat (Q_m)	0	1	0	0
No heat (NH)	0	0	1	1

Table IV. Conditional Probability Table for P(T1($t+1$) | T1(t), T2'(t))

T1(t)	Burning			Not Burning		
T1($t+1$)↓ T2′(t)→	Q_o	Q_m	NH	Q_o	Q_m	NH
Burning	1	1	1	P1	P2	0
Not burning	0	0	0	1 – P1	1 – P2	1

intervals. To develop the DBN and establish respective conditional probability tables, the following steps have been taken (not necessarily in a chronological order though):

- The arc from vessel T1 at time t, T1(t), to the respective sprinkler system at the same time slice, SP1 (t), denotes the dependence of the latter on the former in the sense that SP1 (t) can be activated with a probability of 1 – PFD given a fire at T1; such conditional dependency can be captured using the conditional probability table reported in Table I.
- The arc from SP1 at time t, SP1(t), to SP1 at next time slice, SP1($t+1$) denotes the temporal change in the failure probability of the sprinkler system when successfully activated; such conditional dependency can be incorporated in the DBN using the conditional probability table in Table II.
- The mitigating effect of SP1(t) on T1(t) can be modeled using an auxiliary node T1'(t); drawing arcs from T1(t) and SP1(t) to T1'(t), the corresponding conditional dependency can be modeled in the DBN via Table III. Considering the states in Table III, it should be noted that given a tank fire at T1, i.e., T1(t) = Burning, the amount of heat radiation emitted from T1, which is presented as the states of T1'(t), depends on the state of the sprinkler system SP1(t). For example, if T1 is burning and SP1 is working, the amount of emitted heat radiation would be mitigated (Q_m).
- Given the states of T1(t) = (Burning, Not burning) and having the amount of heat radiation emitted from T2(t), that is, T2'(t) = (Q_o, Q_m, *NH*), the updated probabilities of the states of T1 in the next time slice, i.e., T1($t + 1$), can be embedded in the DBN using the conditional probability table reported in Table IV. The arcs drawn from T1(t) and T2'(t) to T1($t + 1$) represent such conditional dependency. The inclusion of one time interval to see the effect of T2'(t) on T1($t+1$) implies the fact that fire at T2 would not immediately escalate to T1 as some time is needed (from 5 to 20 minutes, depending on the fire severity and the characteristics of exposed vessel) to increase the shell temperature or inside pressure of T1 beyond a critical threshold.

In Table IV, given that the amount of heat radiation, Q_o or Q_m, is beyond a credible threshold, e.g., 15 kW/m^2 and 45 kW/m^2, for atmospheric and pressurized vessels, respectively,(23) probit functions can be used to calculate escalation probabilities P1 and P2. In the present study, the probit functions developed by Landucci *et al.*(10) are employed.

It should be noted that the DBN depicted in Fig. 1 has been developed for a general case where the primary fire initiating the domino effect can occur at T1 or T2; that is why there are also arcs from T2(t) and T1'(t) to T2($t + 1$). The possibility of presenting such mutual interaction between T1 and T2

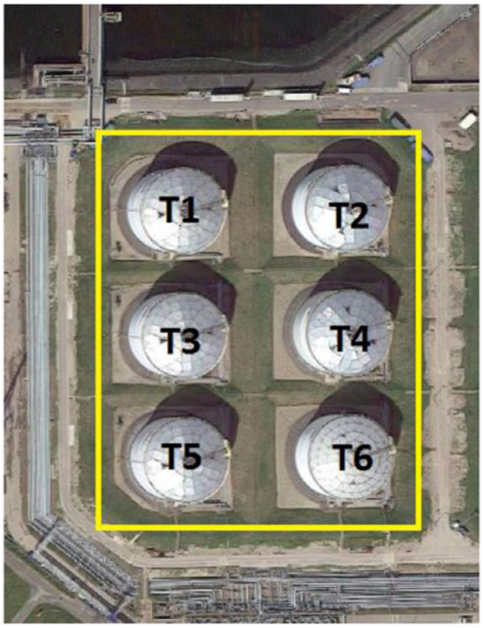

Fig. 2. Gasoline storage plant.

is a unique modeling feature of DBN that cannot be offered by BN.

Using the DBN, the mutual information of, among others, T1 and T2 at the sequential time slices can be calculated using Equation (7) as:

$$I\left(T2^{t+1}, T1^{t}\right) = \sum_{T1^{t}=Not\ burning}^{T1^{t}=Burning} \sum_{T2^{t+1}=Not\ burning}^{T2^{t+1}=Burning} \times P\left(T1^{t}\right)\ P\left(T2^{t+1} \mid T1^{t}\right) \times \log \frac{P\left(T2^{t+1} \mid T1^{t}\right)}{P\left(T2^{t+1}\right)}. \tag{8}$$

5. DEMONSTRATIVE EXAMPLE

5.1. Case Study

To demonstrate the application of DBN to modeling fire propagation and estimating the probabilities in the presence of fire protection measures, consider the gasoline storage plant in Fig. 2. The plant consists of six identical atmospheric storage tanks, each with a diameter of $D = 33.5$ m, height of $H = 9.1$ m, and capacity of $V = 8000$ m^3. Considering a plan view of the plant, the horizontal and vertical distances from rim to rim of the storage tanks are 30 m and 15 m, respectively (approximate measurements using Google Maps). All the tanks are equipped with sprinkler systems with a PFD = 0.01 and $\lambda o = 2.0 \times 10^{-2}$ (year^{-1}).

Table V. Heat Radiation Intensity (kW/m^2) Tj Receives from a Tank Fire at Ti

Tj↓ Ti→	T1	T2	T3	T4	T5	T6
T1	–	22	38	13	–	–
T2	22	–	13	38	–	–
T3	38	13	–	22	38	13
T4	13	38	22	–	13	38
T5	–	–	38	13	–	22
T6	–	–	13	38	22	–

Note: The values less than 10 kW/m^2 have not been taken into account.

In case of tank fire, the amount of heat radiation Tank Tj receives from Tank Ti has been calculated using the ALOHA software(38) as listed in Table V, assuming tanks full to their 75% capacity, wind speed of 2 m/sec gusting from Northwest, air temperature of 15°C, and relative humidity of 25%. Further, the effect of varying parameters such as wind speed and direction and air temperature on the amount of heat radiation has not been considered in the present study. Since all the vessels are atmospheric, the heat radiation threshold capable of causing damage and thus escalating the fire has been taken as 15 kW/m^2.(23) However, due to the possibility of synergistic effects during fire propagation, the values greater than 10 kW/m^2 have also been presented in Table V.

5.2. Domino Effect Modeling

Employing the methodology developed in Section 4, the fire propagation through the storage plant given a primary tank fire at T1 has been modeled using DBN in the GeNIe software(39) (Fig. 3). Considering time increments of $\tau = 10$ minutes, the conditional probabilities of fire escalation to tanks T2–T6 given a tank fire in T1 at time 0, that is, P(Tj^t = Burning | T1^0 = Burning), were calculated using the DBN. For illustrative purposes, the results at the end of 30-minute intervals have been reported in Table VI and also displayed in Fig. 4 for the first 270 minutes since the start of fire at T1.

As can be seen from Fig. 4, during the first 30 minutes, the tank fire at T1 is more likely to escalate to T3 than T2 due to a larger amount of heat radiation T3 receives from T1. Although there is still a

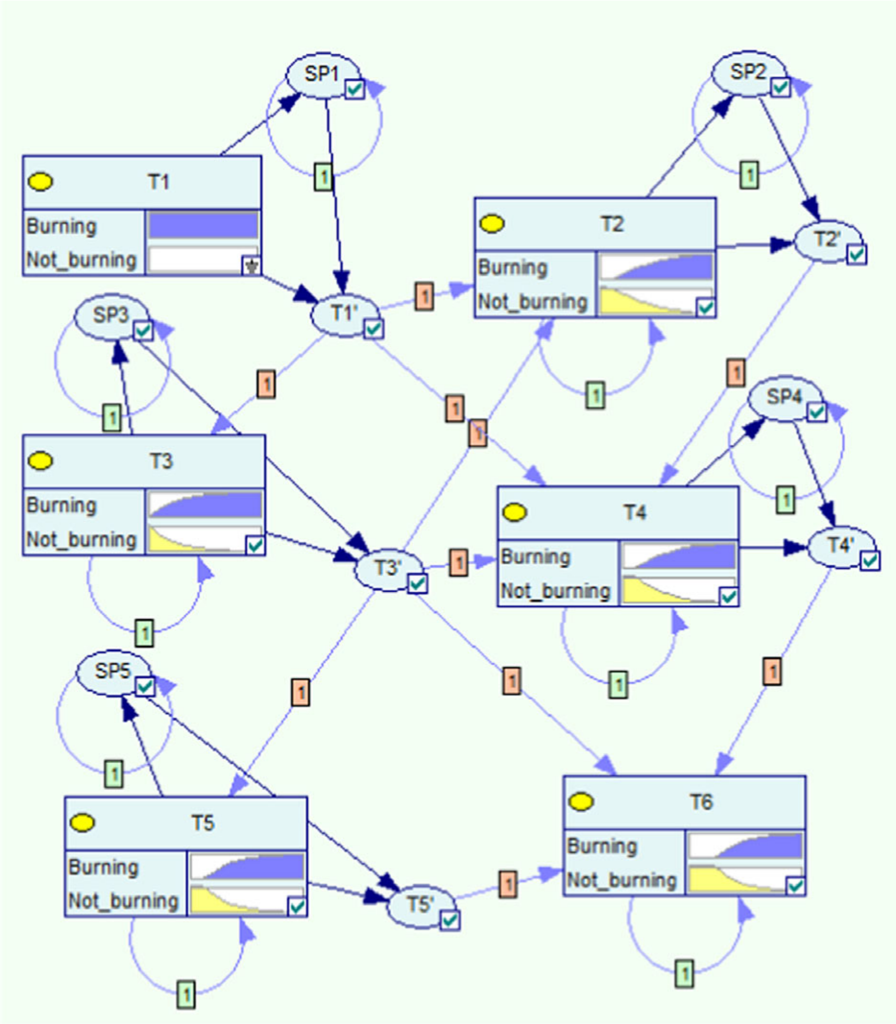

Fig. 3. Modeling of fire propagation as a DBN in GeNIe.(39)

Table VI. Temporal Evolution of Fire Escalation Probabilities Given a Tank Fire at T1 at *t* = 0

t (min)	T2	T3	T4	T5	T6
0	0.000	0.000	0.000	0.000	0.000
30	0.013	0.365	0.000	0.000	0.000
60	0.296	0.590	0.244	0.343	0.000
90	0.541	0.735	0.468	0.575	0.355
120	0.703	0.829	0.641	0.725	0.584
150	0.808	0.889	0.763	0.823	0.731
180	0.876	0.929	0.845	0.885	0.826
210	0.920	0.954	0.899	0.926	0.888
240	0.948	0.970	0.934	0.952	0.927
270	0.966	0.981	0.958	0.969	0.953

small probability that T2 catches fire in the first time interval, from the second time interval onwards the likelihood of fire at T5 slightly exceeds that of T2, followed by T4 and T6 as the less likely tanks among the others.

Considering Fig. 4, at the first glimpse, the escalation probabilities may seem odd as, for example, the escalation probability of T5 is slightly higher than those of T2 and T4 despite its longer distance from the primary fire at T1. The reason for higher escalation probabilities of the tanks along T1, i.e., T3 and T5, than the tanks across T1, i.e., T2, T4, and T6, lies in the fact that the amount of heat radiation emitted along T1 (i.e., T1 → T3 → T5) is higher than the heat radiation across T1 (i.e., T1 → T2, T3 → T4, T5 → T6). This explains the higher probability of T5 than T2 since T5 receives the heat radiation of 38 kW/m^2 from T3, whereas T2 receives the heat radiation of

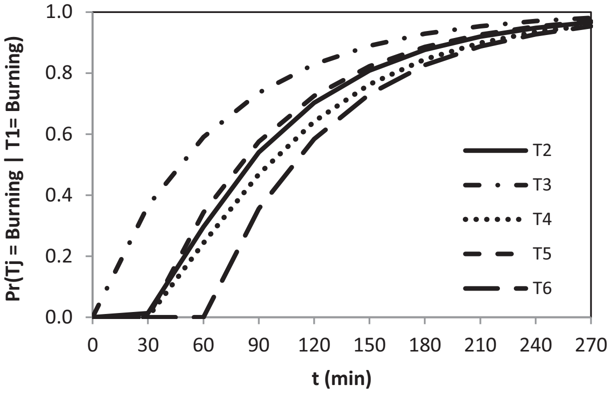

Fig. 4. Temporal evolution of fire escalation probabilities given a tank fire at T1 at $t = 0$.

22 kW/m^2 from T1. However, as can be seen from Fig. 4 (and also Table VI), the longer distance of T5 from T1 would have caused a later escalation of T5 than that of T2. That is, T2 is entailed in the domino effect 30 minutes sooner than T5: P(T2^{30} = Burning) = 0.013, whereas P(T5^{30} = Burning) = 0.00.

The temporal variation of escalation probabilities depicted in Fig. 4 can also be used to foresee emergency firefighting strategies at different time lapse given the fire at T1 at $t = 0$. For instance, setting P(Tj^t = Burning | T1^0 = Burning) ≥ 0.5 as a predictive probability that tank Tj would catch fire at time t, the firefighting team could expect tank fires at T3 (P = 0.735), T5 (P = 0.575), and T2 (P = 0.541), and an imminent fire at T4 (P = 0.468)—if it had not caught fire yet—if they arrive at the plant 90 minutes after initiation of the tank fire at T1 (see the 4th row of Table VI).

5.3. Optimal Emergency Firefighting

If the number of firefighting crew and equipment is sufficient, firefighting will include the suppression of all burning units and protection of all exposed units. However, when the number of firefighting trucks is not sufficient to handle all such units, the identification of units the suppressing/cooling of which would reduce the probability of fire escalation as much as possible can become very challenging. To make the discussion more concrete, in the following sections, we consider two cases where the number of firefighting trucks is not adequate.

Table VII. Updated Escalation Probabilities Given (T2^{60} = Burning, T3^{60} = Burning, T4^{60} = Not Burning, T5^{60} = Not Burning, T6^{60} = Not Burning)

Time	T2	T3	T4	T5	T6
0	0.000	0.000	0.000	0.000	0.000
30	0.004	0.911	0.000	0.000	0.000
60	**1.000**	**1.000**	**0.000**	**0.000**	**0.000**
90	1.000	1.000	0.996	0.938	0.000
120	1.000	1.000	1.000	0.996	0.997

Note: Observation made by the firefighters (the evidence) has been identified with bold numbers.

5.3.1. *Case 1.*

Consider a case where the firefighting team with two fire trucks arrives at the storage plant 60 minutes (response time = 60 minutes) after the initiation of a tank fire at T1 (assume no time lapse between the start of fire at T1 and alerting the firefighting team), observing tanks T2 and T3 burning, whereas T4, T5, and T6 being still safe (not burning). Having such evidence (T2^{60} = Burning, T3^{60} = Burning, T4^{60} = Not burning, T5^{60} = Not burning, T6^{60} = Not burning),[1] the updated escalation probabilities can be calculated using the developed DBN as partially reported in Table VII, in which the evidential probabilities have been denoted with bold numbers.

It should be noted that firefighting response time is based on different actions required to perform the firefighting, including alerting, deploying onsite measures, providing required amount of water, etc.(31) The response time is thus a site-specific factor and needs to be assessed according to the characteristics of the site under consideration. Landucci *et al.*(16) have provided a simplified approach to estimate response time based on the type of target vessel, the fire mitigation strategy (suppression/cooling), and the facility location, which may take up to 50 minutes. The response times in Case 1 and Case 2 (Section 5.3.2) have been chosen only for illustrative purposes.

As can be seen from Table VII, a tank fire at T2 and T3 at t = 60 minutes will make fire propagate to T4 and T5 in the next time interval with the escalation probabilities of P(T4^{90} = Burning) = 0.996 and P(T5^{90} = Burning) = 0.938 (see the 4th row of Table VII). Thus, since the aim is to prevent fire from propagating to other vessels and then suppress the

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[1] Note that T1^0 = Burning has already been taken into account when modeling the domino effect in DBN.

fire, the optimal strategy would be to cool down T4 and T5 since otherwise they are very likely to catch fire in no time.

However, how about if one fire truck should supposedly suppress fire while the other is cooling down exposed vessels? Considering the fact that cooling an overly exposed target vessel is given priority over suppressing a burning vessel (due to the likelihood of an imminent fire in the former), the decision whether to cool down T4 or T5 cannot easily be made as updated escalation probabilities of T4 and T5 are very close. To determine which vessel is more critical as for facilitating fire propagation through the plant, the mutual information of T4 and T5, one at a time, with other not-burning tanks can be calculated using Equation (8). Accordingly, the criticality measure of T4 and T5 can be determined as:

$$\mathrm{Cr}\,(\mathrm{T4}) = \mathrm{I}\left(\mathrm{T4}^{90}, \mathrm{T5}^{120}\right) + \mathrm{I}\left(\mathrm{T4}^{90}, \mathrm{T6}^{120}\right) = 0.119 + 0.231 = 0.350$$

$$\mathrm{Cr}\,(\mathrm{T5}) = \mathrm{I}\left(\mathrm{T5}^{90}, \mathrm{T4}^{120}\right) + \mathrm{I}\left(\mathrm{T5}^{90}, \mathrm{T6}^{120}\right) = 0.141 + 0.260 = 0.401.$$

In other words, fire can better propagate to the other vessels through T5 than T4, although the updated probability of the latter (0.996) is slightly greater than that of the former (0.938).

Keeping T5 cool, T2 can be identified as the most critical burning vessel to suppress owing to the fact that T4 receives a larger amount of heat radiation from T2 (T2 → T4: 38 kW/m^2) than T3 (T3 → T4: 22 kW/m^2). It should be noted that yet the first strategy (cooling both T4 and T5) seems to outperform the second strategy (cooling T5 and suppressing T2) as in the second strategy there still is a chance for fire at T3 to propagate to T4 (and from T4 to T6 if not prevented).

5.3.2. *Case 2.*

As another example, this time assume the firefighting team arrives at the storage plant 90 minutes after the initiation of tank fire at T1 (with two fire trucks), seeing tanks T2 and T4 burning but T3, T5, and T6 not burning yet. Having this evidence (T2^{90} = Burning, T3^{90} = Not burning, T4^{90} = Burning, T5^{90} = Not burning, T6^{90} = Not burning), the updated escalation probabilities can be calculated using the DBN as partially reported in Table VIII, in which the evidential probabilities have been denoted with bold numbers.

Table VIII. Updated Escalation Probabilities Given (T2^{90} = Burning, T3^{90} = Not Burning, T4^{90} = Burning, T5^{90} = Not Burning, T6^{90} = Not Burning)

Time	T2	T3	T4	T5	T6
0	0.000	0.000	0.000	0.000	0.000
30	0.746	0.000	0.000	0.000	0.000
60	1.000	0.000	0.734	0.000	0.000
90	**1.000**	**0.000**	**1.000**	**0.000**	**0.000**
120	1.000	0.938	1.000	0.000	0.938
150	1.000	0.996	1.000	0.880	0.999

Note: Observation made by the firefighters (the evidence) has been identified with bold numbers.

Similar to the previous example, a tank fire at T2 and T4 at $t = 90$ minutes will escalate fire to T3 and T6 in the next time interval with the same escalation probabilities of P (T3^{120} = Burning) = P (T6^{120} = Burning) = 0.938 (see the 5th row of Table VIII). Thus, the optimal strategy would be to cool down both T3 and T6 since otherwise they are very likely to catch fire. Keeping T3 and T6 cool, the fire at T4 would not be able to escalate to T5 as, according to Table V, the amount of heat radiation T5 receives from T4 is below the credible threshold of 15 kW/m^2.

However, if like Case 1, one fire truck is supposed to suppress fire whereas the other truck should cool down an exposed vessel, the decision whether to cool down T3 or T6 can be made based on the vessels' criticality in form of mutual information. To determine which vessel is more critical as for facilitating fire propagation through the plant, the mutual information of T3 and T6, one at a time, with other tanks can be calculated using Equation (8) as:

$$\mathrm{Cr}\,(\mathrm{T3}) = \mathrm{I}\left(\mathrm{T3}^{120}, \mathrm{T5}^{150}\right) + \mathrm{I}\left(\mathrm{T3}^{120}, \mathrm{T6}^{150}\right) = 0.186 + 0.122 = 0.308$$

$$\mathrm{Cr}\,(\mathrm{T6}) = \mathrm{I}\left(\mathrm{T6}^{120}, \mathrm{T3}^{150}\right) + \mathrm{I}\left(\mathrm{T6}^{120}, \mathrm{T4}^{150}\right) = 0.046 + 0.079 = 0.125.$$

As a result, T3 is a more critical vessel for fire propagation than T6.

Keeping T3 cool, T4 can be identified as the most critical burning vessel to suppress owing to the fact that T4 is able to make fire propagate to T6 and thus to T5. It should be noted that the first strategy (cooling both T3 and T6) again outperforms the second strategy (cooling T3 and suppressing T4) based upon the assumption that cooling an exposed vessel would immediately reduce the likelihood of fire escalation ideally to zero, whereas suppressing a burning vessel would not reduce the emitting heat radiation as quickly to below the credible threshold, leaving some chance for fire escalation.

6. CONCLUSIONS

In the present study, we have developed a methodology based on DBN and information theory for optimal firefighting of domino effects especially in case of inadequate firefighting resources. In this work, DBN was employed to model temporal and spatial propagation of fire while accounting for availability and performance of fire protection systems in place (sprinkler systems in this study). DBN makes it possible to update escalation probabilities via insertion of evidence (e.g., observations of fire at process units) at certain time intervals, thus allowing for prediction of the most likely propagation pattern of fire in next time intervals.

We demonstrated how the mutual information scores calculated based on the updated escalation probabilities can be used to identify critical units to be included in optimal firefighting strategies. Among burning units and neighboring units, the ones with the highest sum of updated mutual information scores can be chosen as the units the suppression and cooling of which, respectively, would effectively reduce the propagation of domino effect.

The number of hazardous units that can contribute to fire domino scenarios and the number of firefighting trucks are usually fixed for a chemical plant. As such, the developed methodology can be computerized to set optimal firefighting strategies for a finite set of possible situations where fire may start at different units. As such, in case of major fires, the plant's firefighting team could intervene based on a preagreed optimal plan.

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