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A comprehensive study for probability prediction of domino effects considering synergistic effects

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ABSTRACT

Domino effects are a complex phenomenon of accident escalation with high uncertainty, which could lead to catastrophic consequences. Predicting the probability of domino effects presents a great challenge in the field of process safety. In multi-level domino chains, synergistic effects of accidents would further raise the complexity of probability prediction since escalation vectors emitted from those accidents may be coupled. In this paper, four categories of synergistic effects are classified according to the type of accidents and their place on the domino accident sequence. Subsequently, specific models for estimating escalation probability under different synergistic accident scenarios are proposed based on the widely-used probit models, allowing the analysis of the coupling effects of escalation vectors. A probability prediction method for domino chains is further developed using Bayesian Network. The application of the developed method is demonstrated by a case study, and the domino probability is estimated accounting for the synergistic effects and all possible accident scenarios. The key units for promoting accident propagation are further identified through posterior probability analysis. The method would be helpful for domino risk assessment and management of any chemical industrial area.

1. Introduction

The chemical industry made great contributions to human society, and many chemical industrial parks (CIPs) are established and planned worldwide [1–3]. However, the clustering of hazardous materials and chemical equipment in CIPs may serve fire or explosion accidents [1,4,5]. If a fire or an explosion occurs, it may propagate to the nearby units, which is so-called 'domino effect' [6]. For instance, on 21 March 2019, a fire caused a massive explosion in a CIP, Jiangsu Province, China, resulting in 78 fatalities and more than 1.986-billion-yuan loss [7]. Another typical domino accident occurred on March 23 2005, numerous fires and explosions following a vapor cloud explosion in the BP Texas City refinery, killed 15 people and injured 180, and caused significant economic loss [8]. Those disastrous accidents raise the urgent demand for the study of domino effects.

Over the past five decades, the significance of domino effects in the frame of all accidents has been emphasized in the field of process safety [1,6,9,10]. There are a number of definitions provided by different scholars to characterize domino effects, while the widely accepted one is given by Reniers and Cozzani [6], i.e., a primary unwanted event propagates within an equipment (temporally) and/or to nearby units (spatially), further triggering one or more secondary unwanted event(s), in turn possibly triggering higher order unwanted events, resulting in the more severe overall consequences rather than those of the primary event. The intensification of the overall consequences of an undesired event is so-called 'escalation'. Moreover, the term 'multi-level propagation' is employed to depict the phenomenon of the primary accident resulting in several simultaneous secondary scenarios and the secondary scenarios also trigger many higher-order scenarios, which is closer to the real domino scenarios [6]. To investigate the features of domino effects, some scholars made statistical analysis of domino accidents. For example, Darbra et al. [11] collected 225 domino accidents and categorized the general causes of primary accidents. Moreover, the materials most frequently involved and domino sequences are further analyzed

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based on past accident data [12–14]. Recently, Liang et al. [15] carried out a statistical analysis of 49 domino accidents in tank farms. The authors concluded that heat radiation and shock waves could exist simultaneously in one domino process, and the possibility of coupling effects of different accidents in multi-level propagation is highlighted. Based on those generic studies of domino effects, three key-points for domino research have been identified, including that: i) escalation and propagation are the typical features of domino effects; ii) the escalation probability is the fundament of quantifying the uncertainty in domino chains; and iii) the analysis of multi-level domino propagation should take into account the role of synergistic effects (i.e., several accidents act on one target unit) and parallel effects (i.e., one accident could trigger two or more accidents).

The simplified probit models for estimating the escalation probability due to heat radiation or overpressure were developed by Cozzani and coworkers [16–19], which have been widely used in the field of domino effects. It should be noted that there are some limitations of probit models, especially for the estimation of a key parameter (time to failure, *ttf*, of target unit) in the context of fire escalation. In the last few years, several scholars stated that the calculated value of *ttf* by the equations provided by Cozzani et al. [16–19] may be different from the actual *ttf,* resulting in the error of escalation probability prediction [20]. Many advanced works have been done to predict the *ttf* of target unit. Computational fluid dynamics (CFD) and finite element modelling (FEM) are employed in the literature to explore the structure response of a tank exposed to external fire, and the tank *ttf* can be estimated based on the temperature, pressure, stress profiles of tank [20–23]. In particular, Wu et al. [23] developed new equations for *ttf* estimation, while the intensity of heat radiation and filling level of target tank are considered. Some techniques, such as neural network [24], RADMOD simulations [25], etc., are further introduced into the *ttf* prediction, aiming to obtain more accurate results. Those studies certainly are of great significance in the improvement of probit model, but the advanced probit model is not presented in the literature. Therefore, the original probit models still are the conventional tools in most domino studies. Based on the probit models, various methods such as Bayesian network (BN) [26], mathematical programming [27], dynamic graph [28], Monte-Carlo simulation [29], Petri-net [30], hybrid model [31], etc., are further introduced for the modeling of accident propagation and the probability estimation of domino effects, which is helpful to enhance the understanding of the complex escalation phenomenon and to provide a scientific insight for managing related risk. Among those existing methods, BN is an effective graphical method for uncertainty reasoning of domino effects since its flexible structure could explicitly model the complex accident propagation [26,32,33]. However, the probit models [16–19] are focused on the escalation case triggered by one accident, the quantification of escalation probability considering synergistic effects still is a challenging work.

To address the difficulties and uncertainties related to synergistic effects, some studies have been conducted. In the earlier studies, the synergistic effects within the propagation of single-type accidents are simply investigated by the superposition of the strength of heat radiation or overpressure [1,6,34,35], then the probit model can be applied. In those studies, the change in time of the number of accident sources and the coupling case of multi-type accidents were neglected. In recent years, some scholars explored complex synergistic scenarios to obtain more accurate probability results. On the one hand, the temporal synergistic effects of multiple fires are studied. For example, Zeng et al. [36] proposed a dynamic modeling approach for fire-related domino effects and discussed the case of synergistic fires when the lower-order fire is burned out. Ding et al. [37] developed a fire synergistic effect model (FSEM) to support the calculation of escalation probability, in which the rise of wall temperature of target unit due to the former accidents is considered. Zhou et al. [38] defined the critical thermal dose for equipment failure and proposed an improved probit model to calculate the escalation probability under the dynamic evolution of fire-related domino effects. On the other hand, the synergistic effects of different types of accidents have raised attention in the research field. Ding et al. [39] analyzed the yield strength reduction of tank wall exposed to external fires and established the curve of escalation probability by probit fitting. Li et al. [40] developed an analytic method for the probability prediction of accident escalation due to the coupling effect of pre-fire load and subsequent explosion impulse, and a new probit model based on response number is established. However, the application of those methods is limited to some specific circumstances of synergistic effects. It is hard to integrate those different methods in a unified framework, raising great challenges for domino effect analysis.

The purpose of this paper is to make a comprehensive study for the probability prediction of domino effect accounting for all possible synergistic effects, which would contribute to the solution of uncertainty analysis in a real domino accident. The synergistic effects are discussed and classified according to the type and temporal difference of accident sources in domino effects. Then, the calculation models of escalation probability for different synergistic effects are proposed by advancing the original probit model, allowing the uncertainty assessment in a unified framework. A BN-based methodology is developed to simulate accident propagation and to evaluate the domino probability. Finally, the developed methodology is implemented in an industrial case and the future directions are discussed.

The rest of this paper is organized as follows. Section 2 classifies synergistic effects into four categories, and establishes the novel escalation probability model with respect to different synergistic effects. The basic procedure of developed methodology for the probability estimation of domino effects and the explanation of corresponding steps are presented in Section 3. Next, the developed methodology is illustrated by a case study in Section 4. Finally, Section 5 concludes this paper.

2. Synergistic effects in domino effects

2.1. Outline of domino effects and probit model

Five basic elements of domino effect are identified in the literature, including primary scenario, secondary scenario, propagation, escalation, and escalation vector [1,6,41]. Fire or explosion scenarios are the possible primary scenarios of domino effects, and the associated escalation vectors are heat radiation, overpressure, and fragments. However, fragment-driven escalation is excluded in most studies due to the damage process of fragment projection with high uncertainties [6,42–44]. In this paper, we also addressed only the accident escalation triggered by heat radiation and/or overpressure.

An illustrative domino chain within four tanks is depicted in Fig. 1. It is assumed that the domino propagation is initiated from the accident in T1 (primary accident). As shown in Fig. 1, T1 accident could trigger the secondary accidents in T2 and T3 (target unit) through the impact of escalation vector. The phenomenon is the so-called parallel effect, representing the escalation capacity of T1. The process from primary accident to secondary accident(s) is defined as the first-order domino effect. However, the intensity of escalation vector emitted from T1 accident is insufficient to trigger the T4 accident. After the secondary accidents occur, the tertiary accident would be triggered, forming the second-order domino effect. T4 as the target unit in this phase has received the coupled escalation vector emitted from T2 and T3 accidents. Moreover, the effect of T1 accident may also contribute to the damage of T4 if its escalation vector acted on T4 for a certain period. The superposition of those damage effects of former accidents are synergistic effect, resulting in the high vulnerability of target unit.

To quantify the uncertainty of accident escalation, the threshold and probit models are developed in the literature [1,6,16,45]. Some researchers stated that the equipment may be damaged when the strength of its received escalation vector exceeds the escalation threshold [4,26,35,45,46]. The escalation probability (P_e) under the impact of heat radiation or overpressure can be estimated by probit model, as follows [6,

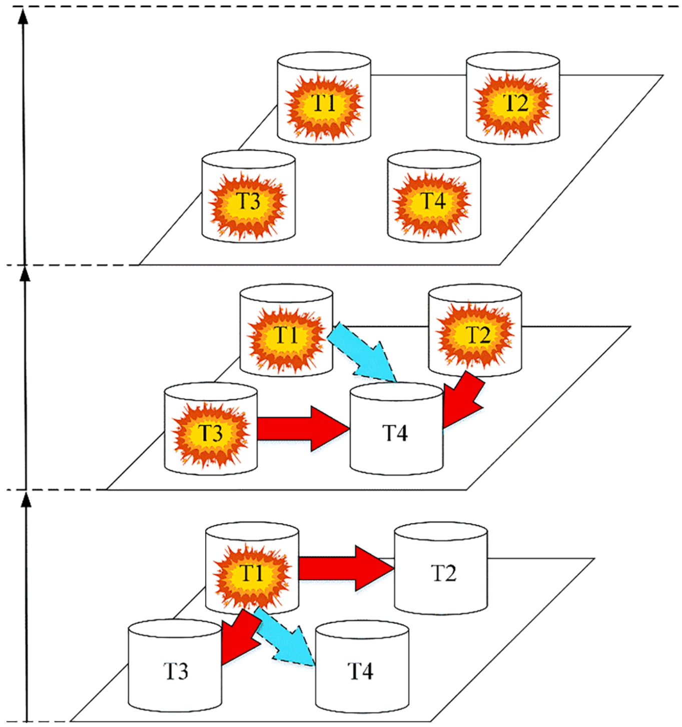


Fig. 1. An illustrative case of the evolution of domino effects.

16,45,47]:

$$P_e = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} \exp\left(-u^2/2\right) \mathrm{d}u \tag{1}$$

Where Y is the probit value, its determination depends on the escalation scenario. The threshold and the calculation method for Y are summarized in Table 1.

2.2. Classification of synergistic effects

In the case of multi-level propagation, several fires and explosions in different orders could cooperate and act on one target unit [6,15,35,39]. However, overpressure and heat radiation are mutually independent physical effects. The overpressure usually be deemed as the instantaneous loading with high-impact, and the elastic deformation of equipment due to overpressure could bounce back to the normal state [39,40]. Different from the explosion-related escalation scenario, the equipment exposed to external fire(s) may be damaged when the over-dose heat radiation lasts for a certain time (i.e., the *ttf* of the equipment). Therefore, the acting sequence and types of escalation vectors are key factors

Table 1
Summary of the threshold and the calculation method for probit value [6,16,45–47].

Escalation vector	Type of equipment	Threshold	Calculation method for probit value
Heat radiation	Atmospheric	15 kW/m^2	$Y = 9.261 - 1.85\ln(ttf)$, $ttf = 0.0167 \times \exp(-1.13\ln(I) - 2.667 \times 10^{-5}V + 9.877)$
	Pressurized	45 kW/m^2	$Y = 9.261 - 1.85\ln(ttf)$, $\ln(ttf) = -0.95\ln(I) + 8.845V^{0.032}$
Overpressure	Atmospheric	22 kPa	$Y = -18.96 + 2.44\ln(p^o)$
	Pressurized	16 kPa	$Y = -42.44 + 4.33\ln(p^o)$

ttf is the time to failure of the target equipment exposed to fire, min; I is intensity of heat radiation received by the target equipment, kW/m^2; V is the volume of the target equipment, m^3; p^o is the peak static overpressure on the target equipment, Pa.

for the analysis of synergistic effects. Four categories of synergistic effects are classified, as shown in Table 2.

The classification in Table 2 could support the detailed analysis for synergistic effects. In particular, heat radiation could be involved in all four categories of synergistic effects since the fire usually lasts for a longer period. Due to the features of overpressure, the explosions are not able to generate the DOST synergistic effect, and fire-explosion is the only accident sequence with respect to the DODT synergistic effect.

2.3. Novel calculation model of escalation probability

For SOST synergistic effects, the superposition method can be used to calculate the strength of coupling escalation vectors (S), as shown in Eq. (2):

$$S = \sum_{i=1}^{n} s_i \tag{2}$$

where s_i is the strength of escalation vector emitted from accident i. Next, the S is substituted in the original probit model, and the escalation probability ($P_{e\text{-SOST}}$) can be calculated.

For SODT synergistic effects, a conventional assumption in most of domino effect studies [6,26,35,39] is also adopted in this paper, i.e., the accidents located in the same order of domino effects occur simultaneously. The escalation probability in this case can be calculated by a logic OR gate, which can be expressed as:

$$P_{e-\mathrm{SODT}} = 1 - (1 - P_{e-\mathrm{F}}) \times (1 - P_{e-\mathrm{E}}) \tag{3}$$

where $P_{e\text{-F}}$ is the escalation probability due to external fire; and $P_{e\text{-E}}$ is the escalation probability due to external explosion. Those two probabilities can be calculated by the original probit model.

The DOST synergistic effect only could occur in fire-related domino effects. The original probit model for fire escalation could not be directly applied to the specific case, but it provides a physical value (D) to determine the failure criteria of a certain target unit [38,48]. If the volume of the target unit is given, D is a constant, as shown in Eq. (4):

$$D = \begin{cases} 0.0167 \times e^{9.877 - 2.667 \times 10^{-5} \times V} = I^{1.13} \times ttf, \text{atmosphericequipment} \\ 0.0167 \times e^{-8.845 \times V^{0.032}} = I^{0.95} \times ttf, \text{pressurizedequipment} \end{cases} \tag{4}$$

Table 2
The classification of synergistic effects in domino effects.

Category	Description	Example (based on the domino scenario in Fig. 1)
Same order same type (SOST) synergistic effect	The accident sources are located in the same order of domino effects, and the escalation vector emitted from each accident source are the same type.	Heat radiation released by two fires in T2 and T3 act on T4.
Same order different type (SODT) synergistic effect	The accident sources are located in the same order of domino effects, and the escalation vector emitted from each accident source are different type.	The accidents in T2 and T3 are fire and explosion, respectively. The heat radiation and overpressure act on T4.
Different order same type (DOST) synergistic effect	The accident sources are located in the different order of domino effects, and the escalation vector emitted from each accident source are the same type.	The accident in T1 and T2 both are fire. The heat radiation due to T1 fire is acted on T4 early, then the it works together with the heat radiation due to T2 fire.
Different order different type (DODT) synergistic effect	The accident sources are located in the different order of domino effects, and the escalation vector emitted from each accident source are different type.	The accident in T1 is fire while the accident in T2 is explosion. The heat radiation heated up T4 then the overpressure impact T4.

It can be inferred from Eq. (4) that the load of heat radiation is larger, the *ttf* of target unit is shorter, and vice versa. It is assumed that unit U is the target unit in the $m+1$-th order domino effect. The heating effect of lower-order fires (m order in total) can be deemed as the decrease of D value (D_{de}), which can be calculated by Eq. (5):

$$D_{de} = \begin{cases} \sum_{n=1}^{m} I_{order\ -n}^{1.13} \times \sum_{k=n}^{m} t_{order\ -k},\ atmosphericequipment \\ \sum_{n=1}^{m} I_{order\ -n}^{0.95} \times \sum_{k=n}^{m} t_{order\ -k},\ pressurizedequipment \end{cases} \tag{5}$$

where $I_{order\text{-}n}$ is unit U received heat radiation from the accident in n-th order; $t_{order\text{-}k}$ equals the time period of the k-th order domino accident, which can be evaluated using the *ttf* of the target unit in k-th order. the actual *ttf* of unit U can be calculated as follows:

$$ttf_U = \begin{cases} (D - D_{de}) \Big/ \left(\sum_{n=1}^{m+1} {I_{order-n}}^{1.13} \right), \text{atmosphericequipment} \\ (D - D_{de}) \Big/ \left(\sum_{n=1}^{m+1} {I_{order-n}}^{0.95} \right), \text{pressurizedequipment} \end{cases} \tag{6}$$

Then the probit value can be calculated and the escalation probability ($P_{e\text{-DOST}}$) of unit U can be obtained using Eq. (1).

In DODT synergistic effect, the heating up of target unit due to the lower-order fire would decrease the yield strength of target unit shell. The ratio (α) of the yield strength of heated unit to the normal one can be calculated by Eq. (7) [39,40,49]:

$$\alpha = \frac{\sigma_y(T_{surface})}{\sigma_y(20^\circ C)} = \begin{cases} 1 + \dfrac{T_{surface}}{767\ln(T_{surface}/1750)}, 0^\circ C \le T_{surface} \le 600^\circ C \\ 108 \times \dfrac{1 - T_{surface}/1000}{T_{surface} - 440}, 600^\circ C \le T_{surface} \end{cases} \tag{7}$$

where $\sigma_y(T_{surface})$ is the yield strength of unit shell surface at $T_{surface}$ (°C); $\sigma_y(20\ ^\circ C)$ is the yield strength of unit shell surface at the normal temperature (20 °C); and $T_{surface}$ is the temperature of unit shell surface, (°C).

The temperature of unit shell surface exposed to external heat radiation at time t ($T(t)_{surface}$) can be calculated by the following formula [39,50]:

$$\frac{dT(t)_{surface}}{dt} = \frac{q(t)_{absorbed}}{\rho_s \times c \times \delta} = \frac{I - \sigma \times \xi_{surface} \times {T(t)_{surface}}^4}{\rho_s \times c \times \delta} \tag{8}$$

where $q(t)_{absorbed}$ is the absorbed heat radiation of the target unit from external fire(s) at time t; ρ_s is the density of the target unit shell material, kg/m^3; σ is the Stefane-Boltzmann constant, 5.67×10^{-8} W/(m^2·K^4); $\xi_{surface}$ is the emissivity of the target unit, dimensionless number; c is specific heat of the target unit shell material, J/(kg·K); δ is the thickness of the target unit shell, m.

The failure criteria of target unit is that the stress produced by damage loading exceeds the yield strength [39,40], thus the decrease of the yield strength has a direct influence on escalation probability. To be on the safe side, it is conservatively assumed that the reciprocal of α (i.e., negative change of target unit's resisting ability) is the amplified coefficient of its escalation probability. Moreover, the probability value is not able to exceed 1. The escalation probability for DODT synergistic effects can be calculated by Eq. (9):

$$P_{e-\text{DODT}} = \min(1, P_e / \alpha) \tag{9}$$

3. General methodology

3.1. Basic procedure

A methodology including seven steps is developed for the quantitative assessment of domino probability accounting for different categories of synergistic effects, as shown in Fig. 2. In Step 1, all basic data for probability prediction are collected. In Step 2, the primary unit is selected and the primary accident scenario is analyzed. Next, the strength of escalation vector (damage loading) is estimated in Step 3. Step 4 determines the potential secondary unit(s) and corresponding escalation probability. The secondary accident scenario and corresponding escalation vector(s) are identified in Step 5. Possible synergistic effects are discussed in Step 6, supporting the assessment of damage loading driving next accident propagation. Based on the accident propagation pattern and escalation probability, the BN model is established to calculate the domino probability in Step 7.

The seven steps are explained hereafter.

Step 1: Basic information required for probability prediction can be obtained from the risk assessment report of chemical industrial area, including: i) the layout of investigated area with the location of hazardous sources; ii) characteristics of each chemical installation (e.g., dimensional parameters, the amount of involved hazardous materials, the unit type, etc.); iii) meteorological parameters to support the consequence assessment.

Step 2: As Khakzad et al. [26] pointed out that, the chemical installation with high failure probability and/or large inventory of hazardous material should be selected as the primary unit. According to the specific type of hazardous material, possible primary accident scenarios and corresponding probability can be analyzed by generic event trees, further details are provided elsewhere [51].

Step 3: Consequence assessment for each primary accident scenario is carried out to calculate the damage loading on surrounding units. The theoretical calculation models for heat radiation and overpressure can be found in some literature [6,39,40,48]. Implementing consequence assessment in professional software (e.g., DNV Phast, EFFECTS, etc.) is a convenient way due to the quick computation and visualization.

Step 4: The potential secondary unit(s) can be found if the damage loading exceeds the threshold in Table 1. The original Probit model is used to calculate the escalation probability in the first-order domino effect due to the single-source primary accident.

Step 5: Similar to Step 2, the possible accident scenario after the damage of each secondary unit can be analyzed. However, one secondary scenario may be the combination of several accidents due to the parallel effects, for which all emitted escalation vectors should be identified. If there is no chemical unit, the domino propagation is terminated, otherwise, the procedure enters to Step 6.

Step 6: Given the secondary accident(s) occur, possible synergistic effects are discussed according to the combination of all prior accidents. The damage loading on tertiary unit includes not only the escalation vectors emitted from secondary accident(s), but also the one from primary accident. The specific category of synergistic effect could be determined based on the accident type of those lower-order accidents, then Steps 3–5 are repeated until no other chemical units or the escalation vector is not enough to trigger next escalation. Notably, the assessment of damage loading in this step should consider the role of synergistic effects, and the escalation probability is calculated using the new model in Section 2.3.

Step 7: Based on the identified propagation pattern, the chemical units and related accidents are assigned as the nodes in BN, for which the nodes are connected by the directed arcs. Moreover, using the probabilities obtained from the above steps, the conditional probability table (CPT) for each node can be developed to explain the conditional dependence between itself and the connected nodes.

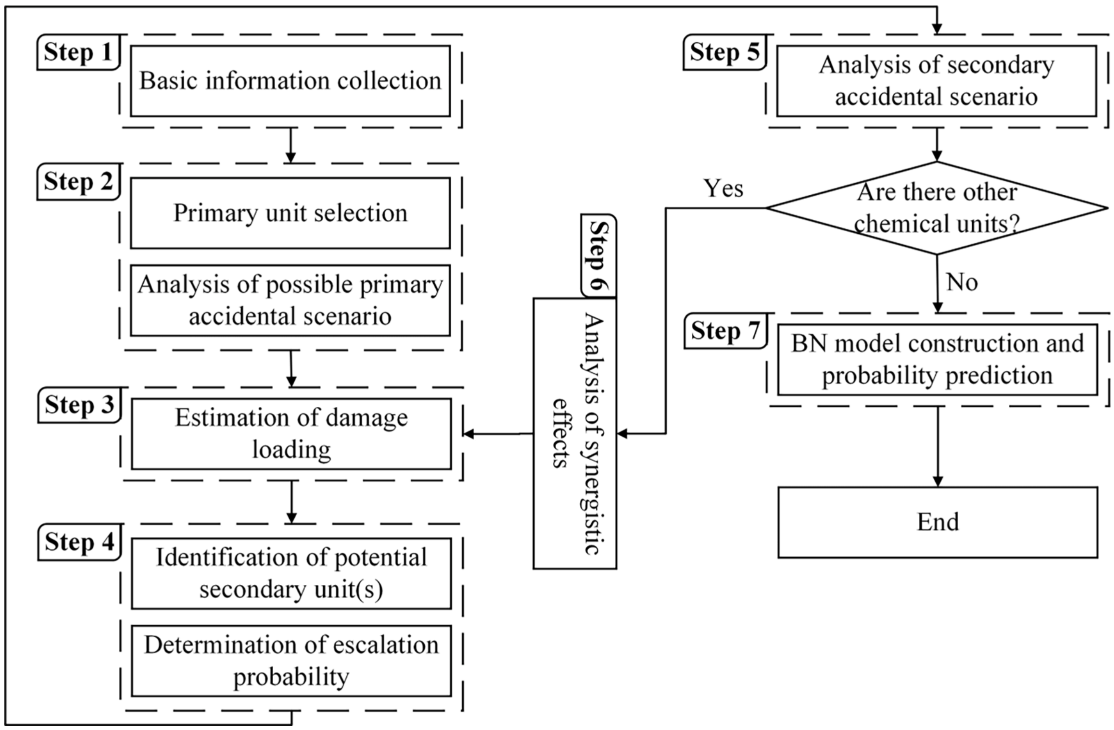


Fig. 2. Procedure for the developed methodology of domino probability prediction.

Through the computation of BN model, the domino probability can be obtained. The detailed modeling approach of BN is illustrated in Section 3.2.

3.2. Implementation of BN reasoning for domino effects

BN is a directed acyclic graph for probabilistic inference, which is widely used for uncertainty reasoning of domino effects [1,26,52]. For two linked nodes in BN, the node pointed to by the arc is 'child node', while the node from which the arc depart is 'parent node'. Using the chain rule and D-separation criteria, the joint probability distribution of a set (U) of nodes (X_1, X_2,…,X_n) can be calculated [26,53]:

$$P(U) = P(X_1, X_2, \cdots, X_n) = \prod_{i=1}^{n} P(X_i | Pa(X_i)) \tag{10}$$

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

In addition, BN also allows the backward inference if an evidence E is given, i.e., yielding the posterior probability, as shown in the following equation [26,35,54]:

$$P(U|E) = \frac{P(U) \times P(E|U)}{\sum_{U/E} P(U) \times P(E|U)} \tag{11}$$

For illustrative purposes, the propagation pattern in Fig. 1 is employed to explain the construction process of BN. The BN model is depicted in Fig. 3. T1 as the primary unit is assigned the first node in BN, which is linked to the primary accident node T1'. Unlike the simple assumption of direct accident propagation in the previous studies [5,34,35], the setting of T1' node could include the wide range of accident scenarios of T1 unit. The CPT of T1 and T1' are shown in Tables 3 and 4, respectively.

The arcs are drawn from the T1' node to T2 and T3 node, representing the damage effect on secondary units due to the escalation vector emitted from T1'. The CPT of T2/T3 is shown in Table 5. Then T2' and T3' nodes are added in the network, their CPTs setting could be referred to Table 4.

Subsequently, unit T4 is involved in the domino propagation, and its CPT is shown in Table 6. Furthermore, two nodes (D1 and D2) are added in BN to obtain the domino probabilities of the sequential orders. The CPTs of those two nodes are set according to the Boolean logistics within accident propagation. Taking D1 node as an example, the essential condition of its occurrence is 'T1' is fire/explosion state AND (T2' is fire/explosion state OR T3' is fire/explosion state)', as shown in Table 7.

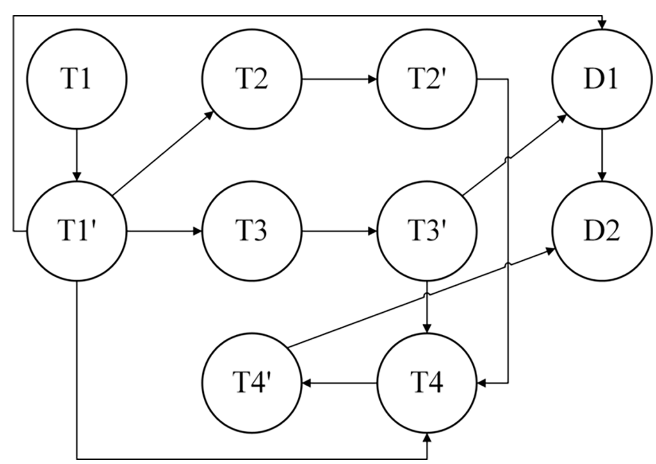


Fig. 3. BN model for the propagation pattern in Fig. 1.

Table 3
Conditional probability table for T1 node. (P_{LOC} is the LOC probability of T1, which can be obtained based on accident frequency or vulnerability model).

T1	Probability
Loss of containment (LOC)	P_{LOC}
Safety (S)	1- P_{LOC}

Table 4
Conditional probability table for T1' node. (P_F and P_E are the probability of fire or explosion scenario, respectively).

T1'↓T1→	LOC	S
Fire (F)	P_F	0
Explosion (E)	P_E	0
Other scenario without escalation vector (O)	$1-P_F-P_E$	0
No accident (N)	0	1

Table 5
Conditional probability table for T2/T3 node. ($P_{e\text{-}F}$ and $P_{e\text{-}E}$ are the escalation probability of T2/T3 due to T1's fire or explosion, respectively).

T2/T3↓T1'→	F	E	O	N
LOC	$P_{e\text{-}F}$	$P_{e\text{-}E}$	0	0
S	$1- P_{e\text{-}F}$	$1- P_{e\text{-}E}$	1	1

4. Case study

The proposed methodology is demonstrated via a tank farm that refers to the study of Huang et al. [55]. The tank farm consists of eight same-sized atmospheric tanks, for which each tank has a diameter of 38 m and a height of 8 m, with the inventory of 8000 m^3 gasoline. The density of the tank shell material is 7850 kg/m^3, the unit emissivity is 0.7, the specific heat of the tank shell material is 460 J/(kg·K), and shell thickness is 10 mm. The layout of the tank farm is shown in Fig. 4. The meteorological parameters are as follows: the wind speed is 2 m/s, stability class of B, relative humidity is 0.67, and the ambient temperature is 25 °C. The leakage hole is set as 200 mm and the possible accident scenario is pool fire and vapor cloud explosion. Huang et al. [55] also provided the estimated strength of heat radiation and overpressure, as shown in Table 8 and Table 9, respectively.

4.1. The application of developed model for escalation probability calculation

Since all tanks in the case study have uniform characteristics, the escalation probability of those tanks exposed to the same damage loading is the same. Take one tank as an example to illustrate the relationship between escalation probability and damage loading under a double-sources synergy accident. In the case of same-order synergistic effects, the strength of escalation vector emitted from each accident source is taken as two independent variables while the escalation probability is the dependent variable. For the different-order synergistic effects, the time difference between two accidents is added as an independent variable. Using a color bar to depict the range of escalation probability, the three-dimensional probability surfaces or four-dimensional probability cubes for different categories of synergistic effects can be drawn by employing corresponding novel models in Section 2.2, as shown in Fig. 5. Notably, there is a special situation in Fig. 5(d) and (e), i.e., the case of the time difference between two accidents equals 0, representing no different-order synergistic effect occurs. Except for the illustrative double-sources case, the developed ad-hoc models also allow the calculation of escalation probability exposed to multi-sources synergy accidents.

As shown in Fig. 5, the coupling damage loading leads to the non-linear increase of escalation probability. For the same-order synergistic effects, the coupling of low-intensity same-type escalation vectors may lead to the failure of target unit, whereas the coupling of different-type escalation vectors more easily damages the target unit. For the different-order synergistic effects, the preliminary acting time of lower-order heat radiation is a key parameter for the rise of escalation probability. With the acting time increased, the escalation probability is getting close to 1.

Table 6
Conditional probability table for T4 node. (P_1-P_{18} are the corresponding escalation probability under different scenario combinations, in which P13, P16-P18 can be calculated using the origin Probit model due to the only one accident source in those scenario combinations.).

T1'	F												E												O	N
T2'	F			E			O			N			F			E			O			N			…	…
T4↓T3'→	F	E	O/N	F	E	O/N	F	E	O/N	F	E	O/N	F	E	O/N	F	E	O/N	F	E	O/N	F	E	O/N	…	…
LOC	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	0	P_9	P_{10}	0	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}	P_{18}	0	P_{17}	P_{18}	0	0	0
S	$1-P_1$	$1-P_2$	$1-P_3$	$1-P_4$	$1-P_5$	$1-P_6$	$1-P_7$	$1-P_8$	1	$1-P_9$	$1-P_{10}$	1	$1-P_{11}$	$1-P_{12}$	$1-P_{13}$	$1-P_{14}$	$1-P_{15}$	$1-P_{16}$	$1-P_{17}$	$1-P_{18}$	1	$1-P_{17}$	$1-P_{18}$	1	1	1

O/N represent the state of T3 is 'only leakage' or 'no accident'.

Table 7
Conditional probability table for D1 node.

T1’	F																E																O	N
T2’	F				E				O				N				F				E				O				N				…	…
O1↓T3’→	F	E	O	N	F	E	O	N	F	E	O	N	F	E	O	N	F	E	O	N	F	E	O	N	F	E	O	N	F	E	O	N	…	…
Occur	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	0	0
Not occur	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	1

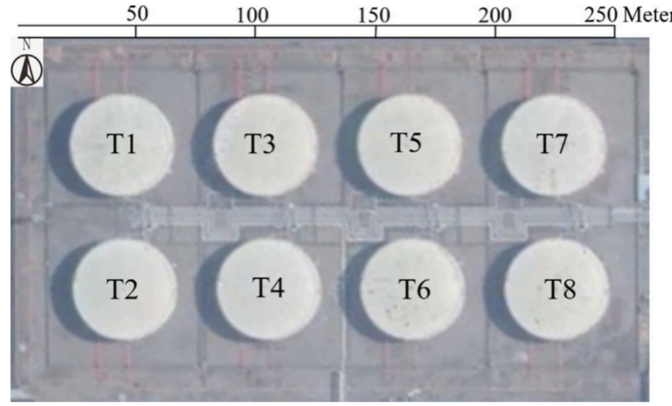


Fig. 4. The layout of the illustrative tank farm. (Referring to Huang et al. [55]).

Table 8
Heat radiation (kW/m^2) received by the different tank (Ti fire) [55].

Ti→/Tj↓	T1	T2	T3	T4	T5	T6	T7	T8
T1	/	11.1	11.1	5.2	3.2	0	0	0
T2	11.1	/	5.2	11.1	0	3.2	0	0
T3	11.1	5.2	/	11.1	11.1	5.2	3.2	0
T4	5.2	11.1	11.1	/	5.2	11.1	0	3.2
T5	3.2	0	11.1	5.2	/	11.1	11.1	5.2
T6	0	3.2	5.2	11.1	11.1	/	5.2	11.1
T7	0	0	3.2	0	11.1	5.2	/	11.1
T8	0	0	0	3.2	5.2	11.1	11.1	/

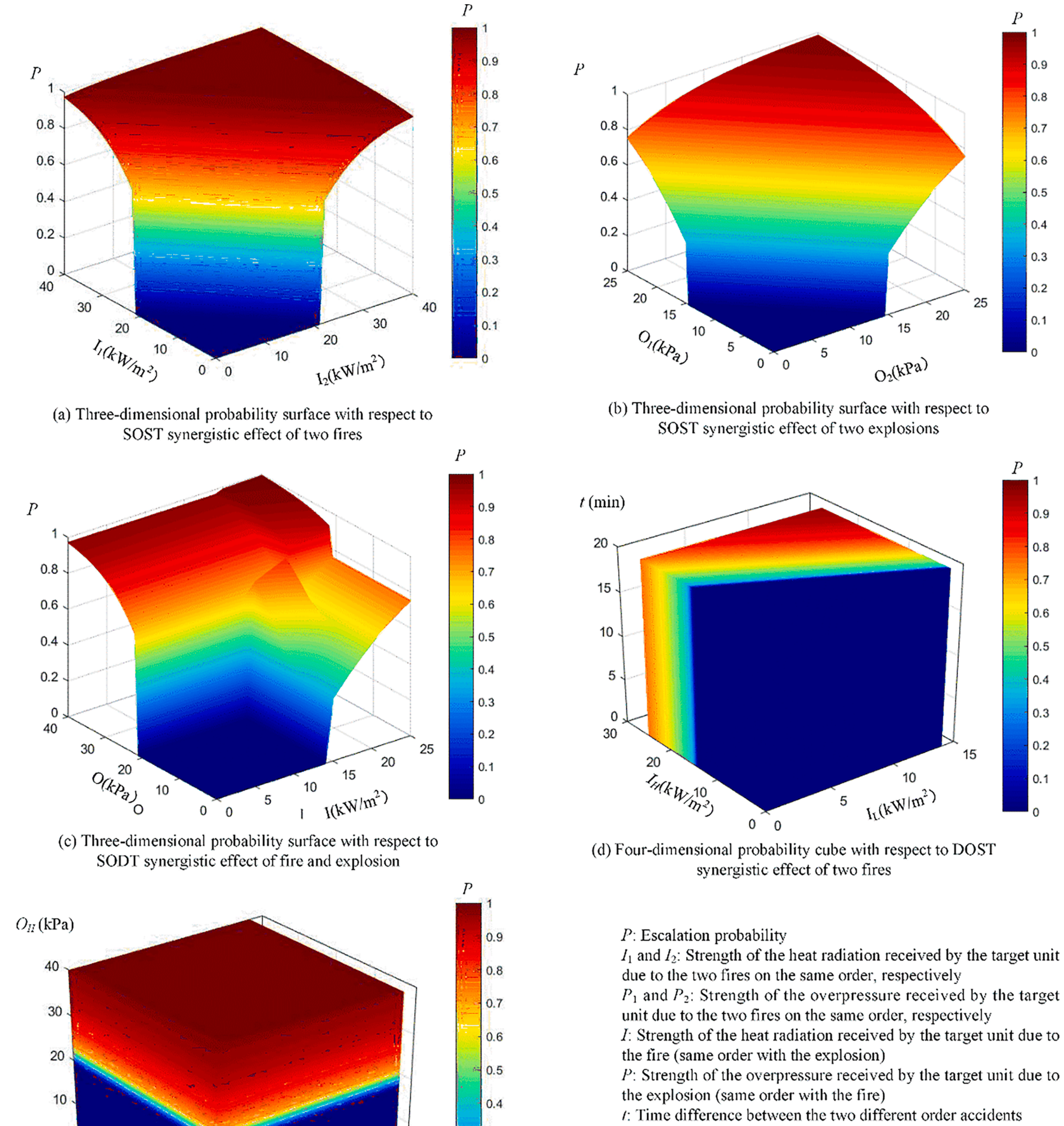
Table 9
Overpressure (kPa) received by the different tank (Ti explosion) [55].

Ti→/Tj↓	T1	T2	T3	T4	T5	T6	T7	T8
T1	/	22.8	22.8	9.7	0	0	0	0
T2	22.8	/	9.7	22.8	0	0	0	0
T3	22.8	9.7	/	22.8	22.8	9.7	0	0
T4	9.7	22.8	22.8	/	9.7	22.8	0	0
T5	0	0	22.8	9.7	/	22.8	22.8	9.7
T6	0	0	9.7	22.8	22.8	/	9.7	22.8
T7	0	0	0	0	22.8	9.7	/	22.8
T8	0	0	0	0	9.7	22.8	22.8	/

4.2. Domino probability results

It is assumed that T1 is the primary unit to start the domino propagation. To perform the analysis of accident scenarios, the pool fire probability of 0.065 and the explosion probability of 0.1122 [51,56] are applied to the case study. The BN model for the case study is developed as shown in Fig. 6. It should be noted that only the explosion of T1 could trigger the accident evolution according to the threshold model. Therefore, the arcs from T1’ to the tertiary units or higher-order units representing the related different-order synergistic effects could be neglected. The inference of prior probability and posterior probability is carried out by the BN software GeNIe [57]. The results are listed in Table 10.

It can be seen from the prior probability results that: i) there is a little difference between the probability of fire or explosion scenario for each unit, ii) the domino probability is gradually decreased with the accident order increased, and iii) the domino probability between two adjacent orders differ by 1 order of magnitude. Based on the results of posterior probability, it can be included that the explosion scenario plays a predominant role in accident propagation, while the probability of the fire scenario decreases with the occurrence of different orders of domino accidents. In addition, the analysis of posterior probability could guide the prevention and mitigation strategy of chemical industrial areas. For example, despite T2 and T3 having the same prior accident probability,



(a) Three-dimensional probability surface with respect to SOST synergistic effect of two fires

(b) Three-dimensional probability surface with respect to SOST synergistic effect of two explosions

(c) Three-dimensional probability surface with respect to SODT synergistic effect of fire and explosion

(d) Four-dimensional probability cube with respect to DOST synergistic effect of two fires

(e) Four-dimensional probability cube with respect to DODT synergistic effect of fire and explosion

P: Escalation probability
I_1 and I_2: Strength of the heat radiation received by the target unit due to the two fires on the same order, respectively
P_1 and P_2: Strength of the overpressure received by the target unit due to the two fires on the same order, respectively
I: Strength of the heat radiation received by the target unit due to the fire (same order with the explosion)
P: Strength of the overpressure received by the target unit due to the explosion (same order with the fire)
t: Time difference between the two different order accidents
I_L: Strength of the heat radiation received by the target unit due to the lower-order fire
I_H: Strength of the heat radiation received by the target unit due to the higher-order fire
O_H: Strength of the overpressure received by the target unit due to the higher-order explosion

Fig. 5. Three-dimensional probability surfaces or four-dimensional probability cubes with respect to different categories of synergistic effects.

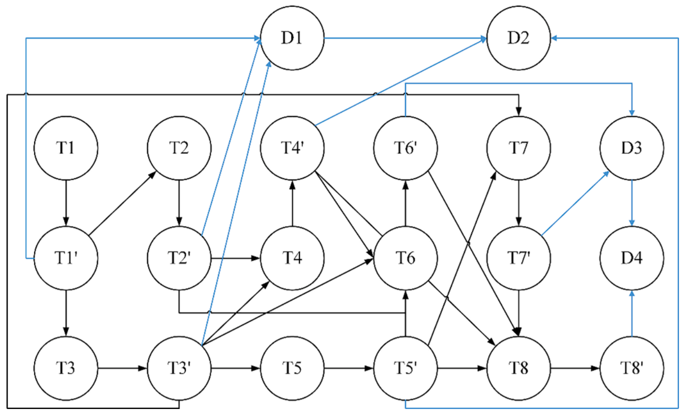


Fig. 6. BN model of domino effects in the case study.

allocating more prevention measures to T3 is advisable due to its higher posterior probability.

4.3. Discussion

The above case study shows how the developed methodology be implemented to calculate the domino probability accounting for the synergistic effects of multiple accident scenarios. On the one hand, the novel models could capture the characteristics of different coupling cases of escalation vectors and allow a straightforward probability calculation in a unified framework. On the other hand, compared to the complex and time-consuming CFD simulation-based method, the novel models in Section 2.3 provide a quick and effective way to model the accident scenario and obtain the escalation probability. Besides, most previous studies are carried out by neglecting the scenario evolution after the LOC event, the developed BN-based modeling approach could fill the gap. Specifically, the developed methodology could perform more accurate probability estimation since more information and details within accident evolution are taken into account. Moreover, the developed methodology has an extension application in domino effect quantitative risk assessment due to its rapidity and comprehensiveness advantages.

In the analyzed case, the explosion-related domino effects should be paid more attention. Some prevention and mitigation measures such as blast walls [58] and water spray curtains [59] could be employed to limit the explosion risk. In addition, as we discussed in Section 2, the lower-order fire may heat the target unit to make it more likely to fail. Table 10 shows that the fire in T2 plays a key role in domino propagation, thus some specific efforts for controlling the impact of T2 fire should be addressed in emergency management. The above safety recommendations are formulated based on the posterior probability analysis, for which the application of suggested measures is able to enhance the resisting ability of tank farm and decrease the time to recovery, i.e., increase the resilience of tank farm.

It is no doubt that the real domino accidents are more complicated than the case study. On the one hand, actual *ttf* of target unit depends on not only the intensity of received heat radiation, but also many other factors, e.g., the type of heat loading, the properties of stored materials, filling degree, the material and thickness of unit wall, the service time and the corrosion degree of chemical units [23–25]. The empirical formulas for *ttf* estimation [16–19] is an ideal function of the intensity of received heat radiation and the volume of target unit, neglecting the related uncertainty of other factors. Therefore, using the calculated *ttf* value may lead to inaccurate probability results. Recently, some efforts have been done to make an accurate estimation of *ttf* [20–25], the integration of those studies could further advance the proposed methodology. On the other hand, the ignition after a LOC event is a temporal stochastic process with high uncertainties, involving the uncertainty of ignition source, the uncertainty of delayed ignition time, etc. [56,60]. Moreover, the dynamic transition of unit state with the evolution of domino effects poses big challenges for the prediction of domino probabilities [36,61,62]. The application of Dynamic Bayesian Network (an inherent dynamic tool) is expected in future work to capture the temporal characteristics of domino effects and to facilitate the incorporation of those complicated uncertainties, which would be helpful for resilience assessment and management.

5. Conclusions

In this paper, a methodology to estimate the domino probability accounting for the role of synergistic effects is developed, allowing for the uncertainty modeling of multi-level domino propagation and facilitating the enhancement of safety and resilience of chemical industrial areas. The novel escalation probability model considering different categories of synergistic effects is derived from the original probit model, for which the acting mechanism and time-dependent behavior of coupled escalation vectors are studied. Then the BN tool is used for the modeling of accident propagation and the calculation of domino probabilities. The developed methodology is illustrated by a case study, the results showed the high-risk and complexity of accident escalation due to synergistic effects. Potential scenarios following the LOC of each unit are further modeled in BN to improve the accuracy of domino probability inference. Based on the analysis of posterior probability, the key unit for promoting accident propagation can be identified, offering valuable insights for safety management and emergency decision-making in chemical industrial areas. The proposed methodology can be further extended in the future to incorporate dynamic factors, such as the dynamic change of the strength of escalation vectors, dynamic

Table 10
Probability results obtained from BN analysis.

Node	P_F	P_E	P_F^{D1}	P_E^{D1}	P_F^{D2}	P_E^{D2}	P_F^{D3}	P_E^{D3}	P_F^{D4}	P_E^{D4}
T1	6.5E-2	1.1E-1	0	1	0	1	0	1	0	1
T2	5.1E-3	8.8E-3	2.0E-1	3.4E-1	3.9E-2	3.8E-1	4.7E-2	3.1E-1	4.3E-2	3.0E-1
T3	5.1E-3	8.8E-3	2.0E-1	3.4E-1	2.5E-2	6.7E-1	3.0E-2	7.4E-1	1.9E-2	7.6E-1
T4	7.9E-4	1.4E-3	3.0E-2	5.2E-2	2.5E-1	4.4E-1	3.9E-2	5.4E-1	3.7E-2	5.3E-1
T5	4.0E-4	6.9E-4	1.5E-2	2.7E-2	1.3E-1	2.2E-1	1.9E-2	4.9E-1	3.0E-2	5.0E-1
T6	9.5E-5	1.6E-4	3.6E-3	6.3E-3	3.0E-2	5.2E-2	2.8E-1	4.9E-1	2.8E-2	7.5E-1
T7	3.1E-5	5.4E-5	1.2E-3	2.1E-3	1.0E-2	1.7E-2	9.5E-2	1.6E-1	1.8E-2	2.6E-1
T8	9.9E-6	1.7E-5	3.8E-4	6.5E-4	3.2E-3	5.5E-3	3.0E-2	5.1E-2	3.7E-1	6.3E-1
D1	2.6E-2		1		1		1		1	
D2	3.1E-3		1.2E-1		1		1		1	
D3	3.3E-4		1.3E-2		1.1E-1		1		1	
D4	2.7E-5		1.0E-3		8.7E-3		8.1E-2		1	

P_F represents the prior probability of fire accident of T_i, P_E represents the prior probability of explosion accident of T_i, P_F^{Dj} represents the posterior probability of fire accident of T_i given the order-j domino accident occurred, and P_E^{Dj} represents the posterior probability of explosion accident of T_i given the order-j domino accident occurred.

transition of unit state, etc. Furthermore, the proposed methodology can be combined with a decision algorithm to determine the optimal allocation scheme for safety measures, which is another research direction for future work to increase chemical plant or cluster resilience.

CRediT authorship contribution statement

Tao Zeng: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Lijun Wei:** Writing – review & editing, Conceptualization, Supervision, Funding acquisition. **Genserik Reniers:** Writing – review & editing, Methodology, Conceptualization. **Guohua Chen:** Writing – review & editing, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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