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Chapter 1
Safety and Security of Domino Effects in the Process Industry: The State of the Art

1.1 Introduction

In the chemical process industry (CPI),[1] raw materials are processed into finished products by chemical and physical conversions while many hazardous materials are being stored, transferred, and processed in different facilities [3]. These facilities situated nearby one another pose a risk to each other due to possible major accident scenarios caused by the release of hazardous materials in any of the facilities. Once a major accident scenario occurs, it may sequentially or simultaneously propagate to nearby installations, leading to domino effects and possibly resulting in catastrophic consequences. Domino effects may be considered high-impact, low-frequency (HILF) events [4], a type II event [5], and they are responsible for several catastrophic disasters in the chemical industry [1, 6]. For instance, one of the most well-known domino effect accidents took place in Mexico City, in 1984, killing more than 500 people and injuring 7000 people [7]. Most recently, on March 21, 2019, an escalation accident occurred at Jiangsu Tianjiayi Chemical Company, China, resulting in at least 78 deaths, 617 injuries, and massive property loss [8].

In light of the severe consequences caused by domino effects, increasing attention has been paid to the prevention and mitigation of escalation effects since the 1990s [9, 10]. The early research work focused on the risk assessment and management of domino effects induced by accidental events [11–13]. In 2008, Reniers et al. [14] developed a methodology to manage domino effects caused by intentional attacks. Since then, intentional domino effects have also attracted attention in the scientific and technical domain [15, 16]. Since some years now, academic publications on domino effects triggered by natural disasters are available in the literature [17, 18]. These studies draw public concerns on preventing domino effects and promote the inclusion of domino effects into safety laws, regulations, and recommendations. In

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[1] This chapter is mainly based on two publications: Chen et al. [1], Chen [2].

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1996, the EU issued the "Seveso-II" Directive (Directive 96/82/EC) in which chemical companies are required to assess "domino" accident hazards inside and outside chemical industrial areas [19]. In 2012, the "Seveso-III" Directive emphasized the importance of exchanging information between chemical plants to prevent external domino effects in chemical clusters [20].

Besides, literature reviews related to past accident statistics [21–23], risk assessment of domino effects [4], escalation thresholds [24], bibliometric analysis [25], and historical summaries [26] are also available in the literature. However, intentional domino effects and escalation effects caused by natural disasters have almost been ignored in these reviews. Therefore, this chapter is to conduct a systematic review on domino effect assessment and management, obtaining insight into modeling approaches and protection strategies. Besides, the evolution of these models and methods are analyzed, and the main concerns for future needs are also discussed.

1.2 Method and Materials

This literature review focuses on the research issues and approaches related to risk assessment and management of domino effects in the chemical process industry. According to this study, we expect to achieve the following research objectives:

(1) A classification of current research literature
(2) A summary of the current classifications of domino effects
(3) The current models for risk assessment of domino effects
(4) The current management strategies and approaches used for decision-making on preventing and mitigating domino effects
(5) The research gaps related to domino effect assessment and management.

> To obtain the above research objectives, a four-step literature review method based on a systematic review and meta-synthesis techniques [27] is proposed.

Figure 1.1 shows the procedures of the proposed method. The review method consists of six steps. The first step is to search extensive literature from the online library of the Delft University of Technology. The literature is searched and collected from two databases: Core Collection of Web of Science (WoS) and ScienceDirect. The searching topics to serve as input in search engines are as follows:

Topic: domino effect OR knock-on event OR catastrophic effect, OR chain of accidents OR escalating event;

AND Topic: process industry OR chemical industry OR chemical plant OR chemical industrial cluster OR chemical industrial park OR oil OR gas OR petroleum OR LNG OR "LPG".

The literature collection date was on April 29th, 2019. A total of 284 publications were obtained. The title and abstract of each publication were examined thoroughly to further refine the publications, excluding the publications that were not closely related to domino effects. Finally, 127 journal papers were selected as the literature

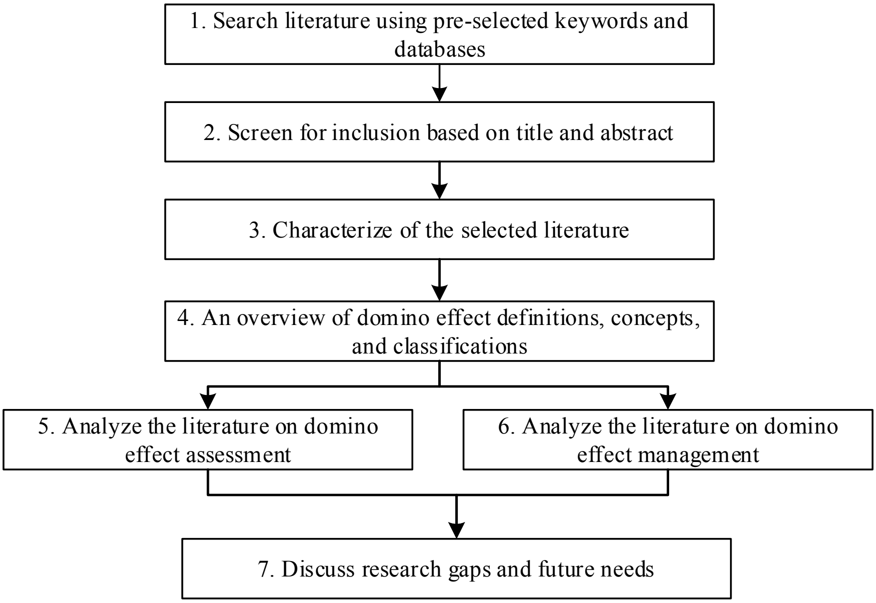


Fig. 1.1 Procedures of literature review

for analysis. These articles were from 32 international journals such as Journal of Loss Prevention in the Process Industries, Journal of Hazardous Materials, Process Safety and Environmental Protection, Reliability Engineering & System Safety, and Safety Science. Among these papers, 57 of them were published in the past five years (from 2015 to 2019) indicating that domino effects have obtained increasing attention in the scientific domain. The most productive authors in this domain include Valerio Cozzani, Genserik Reniers, Nima Khakzad, Gabriele Landucci, and Faisal Khan.

1.3 Characterization of Selected Publications

To analyze the research related to domino effects, the selected 139 journal papers are characterized by their research topics, research issues, and research approaches, as shown in Fig. 1.2.

The research topics are divided into two categories: domino effect assessment and domino effect management. The former consists of 2 research issues (e.g., vulnerability assessment and risk assessment), while the latter includes five research issues (e.g., inherent safety, safety barrier management, emergency management, cooperative management, security management). Research approaches used in each research issue are also identified. Based on the characterization, each paper can be identified

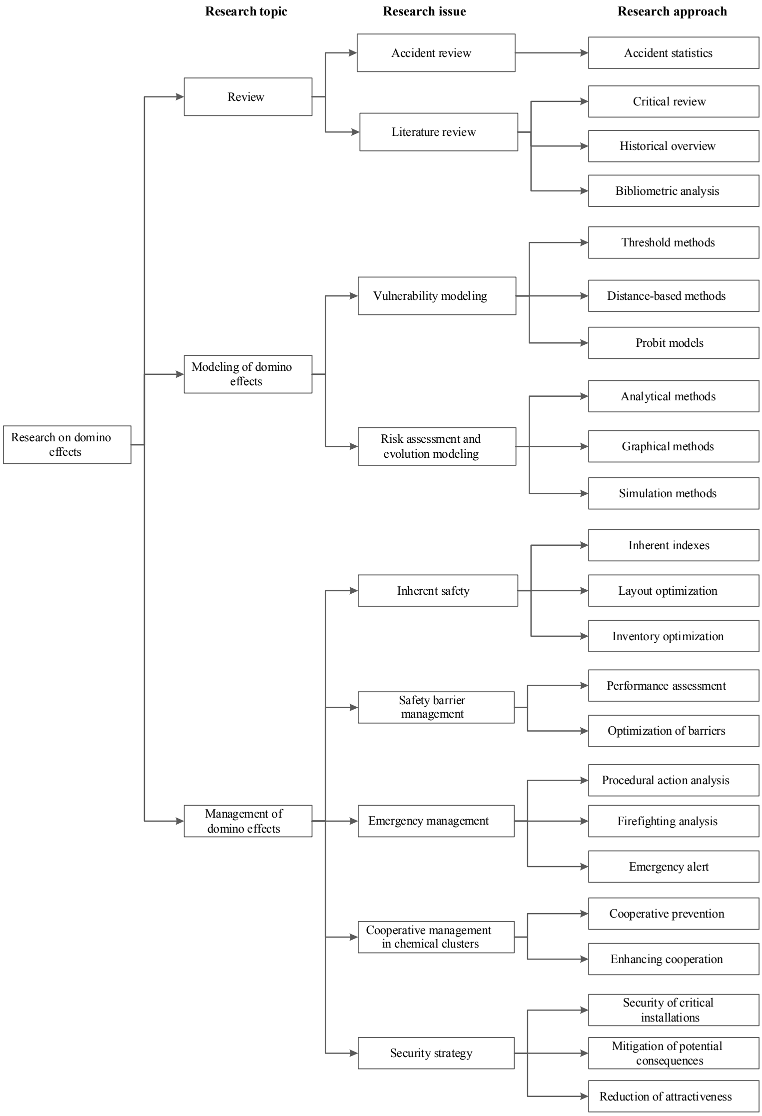


Fig. 1.2 Characterization of domino effect research (Chen et al. [1])

by its research topics (2), research issues (7), and research approaches (19). As a result, the selected 139 journal papers are divided into 23 categories, as shown in Table 1.1. The rest of this chapter will analyze and discuss research papers according to this classification.

Table 1.1 Characterization of current researches (Chen et al. [1])

Publication	Topic	Research issue	Research approach
Darbra et al. (2010)	Review	Accident	Accident statistics
Abdolhamidzadeh et al. (2011)	Review	Accident	Accident statistics
Hemmatian et al. (2014)	Review	Accident	Accident statistics
Alileche et al. (2015)	Review	Literature	Critical review
Necci et al. (2015)	Review	Literature	Critical review
Swuste et al. (2019)	Review	Literature	Historical overview
Li et al. (2017)	Review	Literature	bibliometric analysis
Alileche et al. (2015)	Modeling	Vulnerability	Threshold methods
Cozzani et al. (2006b)	Modeling	Vulnerability	Threshold methods
Salzano and Cozzani (2006)	Modeling	Vulnerability	Threshold methods
Cozzani and Salzano (2004c)	Modeling	Vulnerability	Probabilistic methods
Gubinelli et al. (2004)	Modeling	Vulnerability	Probabilistic methods
Gubinelli and Cozzani (2009b)	Modeling	Vulnerability	Probabilistic methods
Gubinelli and Cozzani (2009a)	Modeling	Vulnerability	Probabilistic methods
Hauptmanns (2001a)	Modeling	Vulnerability	Probabilistic methods
Hauptmanns (2001b)	Modeling	Vulnerability	Probabilistic methods
Jia et al. (2017)	Modeling	Vulnerability	Probabilistic methods
Jujuly et al. (2015)	Modeling	Vulnerability	Probabilistic methods
Landucci et al. (2009a)	Modeling	Vulnerability	Probabilistic methods
Landucci et al. (2015b)	Modeling	Vulnerability	Probabilistic methods
Lisi et al. (2014)	Modeling	Vulnerability	Probabilistic methods
Lisi et al. (2015)	Modeling	Vulnerability	Probabilistic methods
Mukhim et al. (2017)	Modeling	Vulnerability	Probabilistic methods
Pula et al. (2007)	Modeling	Vulnerability	Probabilistic methods
Salzano and Cozzani (2005)	Modeling	Vulnerability	Probabilistic methods
Salzano et al. (2014)	Modeling	Vulnerability	Probabilistic methods
Sun et al. (2012)	Modeling	Vulnerability	Probabilistic methods
Sun et al. (2013b)	Modeling	Vulnerability	Probabilistic methods
Sun et al. (2013a)	Modeling	Vulnerability	Probabilistic methods
Sun et al. (2016b)	Modeling	Vulnerability	Probabilistic methods
Sun et al. (2017)	Modeling	Vulnerability	Probabilistic methods
Tugnoli et al. (2014b)	Modeling	Vulnerability	Probabilistic methods
Tugnoli et al. (2014a)	Modeling	Vulnerability	Probabilistic methods
Zhang and Jiang (2008)	Modeling	Vulnerability	Probabilistic methods

(continued)

Table 1.1 (continued)

Publication	Topic	Research issue	Research approach
Zhang and Chen (2009)	Modeling	Vulnerability	Probabilistic methods
Ahmadi et al. (2019)	Modeling	Vulnerability	CFD/FEM methods
Argentia et al. (2014)	Modeling	Vulnerability	CFD/FEM methods
Landucci et al. (2009b)	Modeling	Vulnerability	CFD/FEM methods
Landucci et al. (2016b)	Modeling	Vulnerability	CFD/FEM methods
Rum et al. (2018)	Modeling	Vulnerability	CFD/FEM methods
Antonioni et al. (2009)	Modeling	Risk assessment	Analytical method
Antonioni et al. (2015)	Modeling	Risk assessment	Analytical method
Baesi et al. (2013)	Modeling	Risk assessment	Analytical method
Bagster and Pitblado (1991)	Modeling	Risk assessment	Analytical method
Cozzani et al. (2006a)	Modeling	Risk assessment	Analytical method
Cozzani et al. (2005)	Modeling	Risk assessment	Analytical method
Cozzani and Salzano (2004b)	Modeling	Risk assessment	Analytical method
Cozzani and Salzano (2004a)	Modeling	Risk assessment	Analytical method
Cozzani et al. (2014)	Modeling	Risk assessment	Analytical method
Kadri et al. (2013)	Modeling	Risk assessment	Analytical method
Khan and Abbasi (1998a)	Modeling	Risk assessment	Analytical method
Khan and Abbasi (2001)	Modeling	Risk assessment	Analytical method
Khan and Abbasi (1996)	Modeling	Risk assessment	Analytical method
Khan and Abbasi (1998b)	Modeling	Risk assessment	Analytical method
Khan and Abbasi (2000)	Modeling	Risk assessment	Analytical method
Khan et al. (2001a)	Modeling	Risk assessment	Analytical method
Khan et al. (2001b)	Modeling	Risk assessment	Analytical method
Ramirez-Camacho et al. (2015)	Modeling	Risk assessment	Analytical method
Silva et al. (2016)	Modeling	Risk assessment	Analytical method
van der Voort et al. (2007)	Modeling	Risk assessment	Analytical method
Zhang and Chen (2013)	Modeling	Risk assessment	Analytical method
Zhou and Reniers (2018a)	Modeling	Risk assessment	Analytical method
Alileche et al. (2017)	Modeling	Risk assessment	Graphical method
Chen et al. (2018)	Modeling	Risk assessment	Graphical method
Dai et al. (2019)	Modeling	Risk assessment	Graphical method
Ji et al. (2018)	Modeling	Risk assessment	Graphical method
Kamil et al. (2019)	Modeling	Risk assessment	Graphical method
Khakzad (2015)	Modeling	Risk assessment	Graphical method
Khakzad (2018b)	Modeling	Risk assessment	Graphical method

(continued)

Table 1.1 (continued)

Publication	Topic	Research issue	Research approach
Khakzad (2019)	Modeling	Risk assessment	Graphical method
Khakzad et al. (2018a)	Modeling	Risk assessment	Graphical method
Khakzad et al. (2018b)	Modeling	Risk assessment	Graphical method
Khakzad et al. (2013)	Modeling	Risk assessment	Graphical method
Khakzad and Reniers (2015b)	Modeling	Risk assessment	Graphical method
Khakzad et al. (2016)	Modeling	Risk assessment	Graphical method
Reniers and Dullaert (2007)	Modeling	Risk assessment	Graphical method
Yuan et al. (2016)	Modeling	Risk assessment	Graphical method
Yang et al. (2018)	Modeling	Risk assessment	Graphical method
Zhou and Reniers (2017b)	Modeling	Risk assessment	Graphical method
Abdolhamidzadeh et al. (2010)	Modeling	Risk assessment	Simulation method
Ahmed et al. (2012)	Modeling	Risk assessment	Simulation method
Rad et al. (2014)	Modeling	Risk assessment	Simulation method
Zhang et al. (2018)	Modeling	Risk assessment	Simulation method
Cozzani et al. (2007)	Management	Inherent safety	Inherent safety indexes
Cozzani et al. (2009)	Management	Inherent safety	Inherent safety indexes
Landucci et al. (2008)	Management	Inherent safety	Inherent safety indexes
Tugnoli et al. (2008b)	Management	Inherent safety	Inherent safety indexes
Tugnoli et al. (2008a)	Management	Inherent safety	Inherent safety indexes
Bernechea and Arnaldos (2014)	Management	Inherent safety	Layout optimization
Dan et al. (2015)	Management	Inherent safety	Layout optimization
de Lira-Flores et al. (2014)	Management	Inherent safety	Layout optimization
de Lira-Flores et al. (2018)	Management	Inherent safety	Layout optimization
Jung et al. (2011)	Management	Inherent safety	Layout optimization
Khakzad and Reniers (2015a)	Management	Inherent safety	Layout optimization
Latifi et al. (2017)	Management	Inherent safety	Layout optimization
Lee et al. (2005)	Management	Inherent safety	Layout optimization
Lee et al. (2006)	Management	Inherent safety	Layout optimization
López-Molina et al. (2013)	Management	Inherent safety	Layout optimization
Nomen et al. (2014)	Management	Inherent safety	Layout optimization
So et al. (2011)	Management	Inherent safety	Layout optimization
Khakzad et al. (2014)	Management	Inherent safety	Inventory optimization

(continued)

Table 1.1 (continued)

Publication	Topic	Research issue	Research approach
Bucelli et al. (2018)	Management	Safety barriers	Performance assessment
Janssens et al. (2015)	Management	Safety barriers	Performance assessment
Khakzad et al. (2017a)	Management	Safety barriers	Performance assessment
Khakzad et al. (2017c)	Management	Safety barriers	Performance assessment
Landucci et al. (2015a)	Management	Safety barriers	Performance assessment
Landucci et al. (2016a)	Management	Safety barriers	Performance assessment
Landucci et al. (2017a)	Management	Safety barriers	Performance assessment
Landucci et al. (2017b)	Management	Safety barriers	Performance assessment
Sun et al. (2016a)	Management	Safety barriers	Performance assessment
Tugnoli et al. (2012)	Management	Safety barriers	Performance assessment
Tugnoli et al. (2013)	Management	Safety barriers	Performance assessment
Ghasemi and Nourai (2017)	Management	Safety barriers	Optimization of barriers
Khakzad and Reniers (2017)	Management	Safety barriers	Optimization of barriers
Khakzad et al. (2017b)	Management	Safety barriers	Optimization of barriers
Khakzad et al. (2018c)	Management	Safety barriers	Optimization of barriers
Tsai et al. (2018)	Management	Emergency	Procedural action analysis
Zhou et al. (2016)	Management	Emergency	Procedural action analysis
Zhou and Reniers (2016)	Management	Emergency	Procedural action analysis
Zhou and Reniers (2017a)	Management	Emergency	Procedural action analysis
Zhou and Reniers (2018b)	Management	Emergency	Procedural action analysis
Cincotta et al. (2019)	Management	Emergency	Firefighting analysis

(continued)

Table 1.1 (continued)

Publication	Topic	Research issue	Research approach
Khakzad (2018a)	Management	Emergency	Firefighting analysis
Khakzad (2018d)	Management	Emergency	Firefighting analysis
Hosseinnia et al. (2018)	Management	Emergency	Emergency alert
Reniers et al. (2005a)	Management	Cooperative	Cooperative prevention
Reniers et al. (2005b)	Management	Cooperative	Cooperative prevention
Reniers et al. (2009)	Management	Cooperative	Cooperative prevention
Reniers and Soudan (2010)	Management	Cooperative	Cooperative prevention
Pavlova and Reniers (2011)	Management	Cooperative	Enhancing cooperation
Reniers (2010)	Management	Cooperative	Enhancing cooperation
Reniers et al. (2012)	Management	Cooperative	Enhancing cooperation
Reniers et al. (2008)	Management	Security	Security of critical installations
Reniers et al. (2014)	Management	Security	Security of critical installations
Khakzad and Reniers (2019)	Management	Security	Mitigation of consequences
Reniers and Audenaert (2014)	Management	Security	Mitigation of consequences
Srivastava and Gupta (2010)	Management	Security	Mitigation of consequences
Chen et al. (2019)	Management	Security	Reduction of attractiveness
Khakzad (2018c)	Management	Security	Reduction of attractiveness

1.4 An Overview of Domino Effect Definitions, Characteristics and Classifications

Based on the review papers on domino effects, this section illustrates domino effect definitions, characteristics, and classifications.

1.4.1 Domino Effect Definitions

In the Collins dictionary, the item "domino effect" refers to the phenomenon that one event causes another similar event, which in turn causes another event, and so on. In the broad definition, the event can be desired or undesired while the event is specially defined as an undesired event in the safety and security domain. In terms of process safety, many definitions of "domino effects" are provided in the review literature [1, 4, 26]. Table 1.2 lists several definitions of "domino effects".

Each definition provided in Table 1.2 summarizes one or more characteristics of domino effects. For example, the definition provided by Lees [28] describes the spatial propagation of domino effects (from one unit to another unit) while Khan and Abbasi [30] highlights that the primary accident may cause accidents in multiple units. Due to the propagation, the consequences of domino effects are more severe than those of the primary event, which is characterized by the definitions provided by Council Directive 96/82/EC [29], Reniers et al. [31], Darbra et al. [21], etc. Reniers and Cozzani [6] developed a more comprehensive definition, covering five main characteristics of domino effects:

(i) A "primary event," initiating the domino effect;
(ii) Escalation vectors responsible for possible accident propagation;
(iii) One or more secondary accident events;

Table 1.2 A list of the definitions of "domino effects"

Sources	Definitions
Lees [28]	An event in one unit that causes a follow-up event in another unit
Council Directive 96/82/EC [29]	Stablishments are sited in such a way or so close together as to increase the probability and possibility of major accidents or aggravate their consequences
Khan and Abbasi [30]	An accident in one unit causes accidents in one or more other units
Reniers et al. [31]	A cascade of events in which the consequences of a previous accident are increased by following one(s), spatially as well as temporally, leading to a major accident
Khan and Abbasi [30]	A chain of accidents that a fire/explosion/missile/toxic load generated by an accident in one unit in an industry causes secondary and higher-order accidents in other units
Darbra et al. [21]	A relatively minor accident can initiate a sequence of events that cause damage over a much larger area and lead to far more severe consequences
Abdolhamidzadeh et al. [23]	A loss of containment accident in a process unit becomes the trigger of one or more loss of containment accidents in one or more other process units
Reniers and Cozzani [6]	A primary unintentional or intentional event propagates within an equipment ('temporally'), or/and to nearby equipment ('spatially'), sequentially or simultaneously, triggering one or more secondary unwanted events, in turn possibly triggering (higher-order) unwanted events, resulting in overall consequences more severe than those of the primary event

(iv) The overall consequences are more severe than those of the primary event;
(v) The primary event can be intentional or unintentional.

Since this work concerns both intentional domino effects and unintentional domino effects, the comprehensive definition provided by Reniers and Cozzani [6] is adopted in the book.

1.4.2 Domino Effect Characteristics

Domino effect characteristics can be analyzed and summarized from past domino effect accidents [22, 23]. Abdolhamidzadeh et al. [23] analyzed 224 domino effect accidents between 1910 to 2008 in the process industry. They demonstrated that 43% of the recorded domino accidents were induced by fires, and 53% of those were triggered by explosions. Although the most common major accident scenarios in the process industry include fire, explosion, and toxic cloud dispersion, the last scenario is always neglected since they do not directly lead to damage to secondary installations [32]. Among the domino events triggered by fires, pool fire (80%) was the most frequent starting scenario [23]. Among explosions, VCE (vapor cloud explosion) was the most frequent scenario. Besides, long-lasting stationary fires (i.e., pool fires and jet fires) are responsible for most of the escalation events in industrial accidents [33]. The analysis further indicated that 44% of jet fire accidents occurred in transportation, 36% in process plants, 11% during loading/unloading operations, and 9% in storage plants. According to the analysis, primary events of domino effects can be divided into three categories: fires, explosions. The physical effects induced by primary events are called escalation vectors responsible for possible hazardous scenario propagations [11]. The escalation vectors induced explosions mainly consist of overpressure and fragment projection, while these induced by fires include heat radiation, fire, and impingement. Possible primary scenarios and escalation vectors derived from past domino accident analyses [10, 34] are shown in Table 1.3.

Table 1.3 Possible escalation vectors of different primary scenarios (Chen et al. [1])

Primary scenario	Escalation vector
Pool fire	Heat radiation, fire impingement
Jet fire	Heat radiation, fire impingement
Fireball	Heat radiation, fire impingement
Flash fire	Fire impingement
BLEVE	Overpressure, fragment projection
Confined explosion	Overpressure, fragment projection
Mechanical explosion	Overpressure, fragment projection
VCE	Overpressure

BLEVE: Boing Liquid Expanding Vapor Explosion; VCE: Vapor Cloud Explosion

Hemmatian et al. [22] conducted a historical survey on 330 accidents related to domino effects in process/storage plants and hazardous material transportations. This study indicates that process plants (39%) and storage areas (33%) are the most common locations for domino effects. The causes of domino effects involve mechanical failure, external events, human factors, etc. The distribution of domino effect causes is shown in Fig. 1.3 [22].

According to Fig. 1.3, the most frequent cause is mechanical failure (35.2%), followed by external events (29.4%), human error (24.6%), and impact failure (16.7). External events include Natech events (6.1%) and sabotage events (0.6%). The Natech events include 14 lightning events, 3 extreme temperature events, 2 earthquakes, and 2 floodings. Sabotage events are intentional, while other causes are unintentional. As a result, domino effects can be divided into two categories: unintentional domino effects (the causes include mechanical failure, human error, aging, natural disasters, etc.) and intentional domino effects (the causes involve terrorist attacks, sabotage, criminal actions, etc.). A comparison between intentional domino effects and unintentional domino effects is provided in Table 1.4.

In the process industry, major accidents may be triggered by natural disasters, resulting in the damage of installations and the loss of containment (LOC) of hazardous substances, which are called Natechs [35]. If we consider the LOC as a secondary event, Natechs may be regarded as a special domino effect triggered by natural events such as lightning, earthquakes, floods, and hurricanes. In this book, domino effects triggered by Natech events are narrowly tailored as Natech events in which the damaged equipment furtherly causes escalation and results in major accident scenarios at other hazardous installations [18].

The frequencies of domino effects caused by intentional attacks are much less than those triggered by accidental events and natural disasters, but the overall consequences may be more severe due to simultaneous damage of installations induced by multiple-target attacks [15, 16]. Besides, safety barriers may also be attacked,

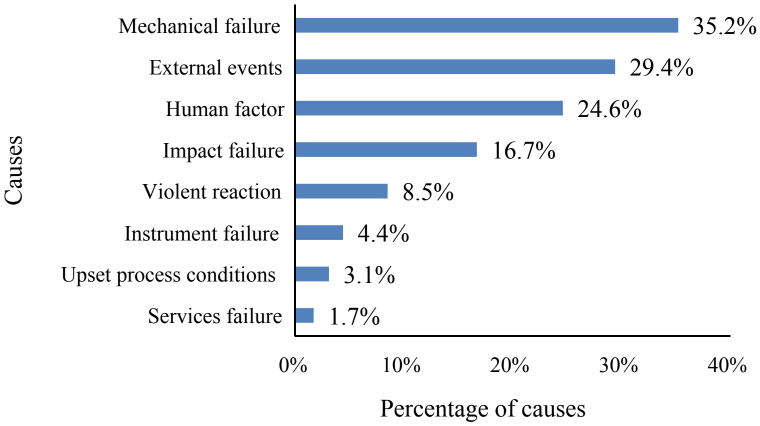


Fig. 1.3 The distribution of domino effect causes

Table 1.4 Comparison between unintentional and intentional domino effects (Chen et al. [1])

Types	Unintentional domino effects	Intentional domino effects
Definition	Domino effects triggered by unintentional events	Domino effects triggered by intentional events
Positions of primary events	Usually occurring at installations	Any positions within chemical plants or outside the area nearby
Sources of hazards	Hazardous materials in chemical installations and hazardous materials form loading and unloading vehicles	Hazardous materials in chemical installations, and external hazardous materials carried by attackers such as explosive devices
Main escalation vectors	Heat radiation, fire impingement, overpressure, and fragments	Heat radiation, fire impingement, overpressure, and fragments
Simultaneous primary scenarios	Usually involving a single installation	Multiple installations can be involved due to multiple target attacks
Protection measures	Safety barriers	Security countermeasures and safety barriers

resulting in unpreventable propagation of major accident scenarios. For instance, water supply infrastructures, power supply systems, communication, and medical facilities may be simultaneously or sequentially attacked by an adversary that has a good knowledge of safety and security in the process industry. Compared with unintentional domino effects, intentional domino effects may be more challenging to prevent since intelligent and strategic adversaries can aim to damage security and security measures. Moreover, adversaries can deliberately induce domino effects by attacking the installations has a high probability of initiating domino effects. Thus both intentional and unintentional domino effects can not be ignored for chemical industrial areas.

According to the failure sequences of installations in domino effects, the initiating events or the primary events are characterized by cardinality 0, whereas cardinality 1 refers to secondary domino events, and cardinality 2 to tertiary domino events, etc. [6]. The propagation from the primary scenario to the secondary scenario may be called first-level propagation, while from a secondary scenario to a tertiary scenario may be called second-level propagation [1]. All the major hazards of fire, explosion, and toxic cloud dispersion can be simultaneously or sequentially present in one disaster due to the propagation of hazardous scenarios. For example, 81% of explosions triggered fires among 330 domino effect accidents [22].

1.4.3 Domino Effect Classifications

In light of these features, domino effects can be classified into several categories according to different criteria. Following the research by Reniers [36], domino effects are divided by eight different criteria, as shown in Table 1.5. These classifications are based on one feature of domino effects. For instance, domino effects can be divided into external domino effects and internal domino effects according to the damaged area of domino effects. External domino effects can only occur in a chemical cluster when multiple chemical plants are involved in a domino effect accident. Besides, A domino effect can belong to different types. If a domino effect accident damages

Table 1.5 Categories of domino events (excluding toxic domino effects) (Chen et al. [1])

Type	categories	Definition
1	Unintentional	Domino effects induced by accidents or natural disasters
	Intentional	Domino effects caused by intentional attacks
2	Fire-induced	The primary event is a fire
	Explosion-induced	The primary event is an explosion
3	Internal	The start and end of the escalation vector characterizing the domino event are situated inside the boundaries of the same chemical plant
	External	The start and end of the escalation vector characterizing the domino event are not situated inside the boundaries of the same chemical plant
4	Direct	Domino events occur as a direct consequence of the previous domino event
	Indirect	Domino events occur as an indirect consequence of a preceding domino event, not being the previous one
5	Temporal	Domino events occur within the same area as the preceding event, but with a delay
	Spatial	Domino events occur outside the area where the preceding event took place
6	Serial	Domino events occur as a consequent link of the only accident chain caused by the preceding event
	Parallel	Domino events occur as one of several simultaneous consequent links of accident chains caused by the preceding event
7	Heat radiation-induced	Domino effects caused by heat radiation
	Overpressure-induced	Domino effect caused by overpressure
	Fragment-induced	Domino effects caused by fragmentation impact
	Coupled	Multiple kinds of escalation vectors are present during the evolution of the domino effect
8	First-level	The highest propagation is first-level order
	Second-level	The highest propagation is second-level order
	Nth-level	The highest propagation is Nth-level order

multiple chemical plants and involves several hazardous scenarios, it can be called an external domino effect or a coupled domino effect.

1.5 Vulnerability Assessment of Installations

Vulnerability assessment can provide reliable models to estimate damage possibility and probability of an asset or a human exposed to an undesired event, which is critical for safety and security risk assessment. The vulnerability assessment for domino effects is to assess the inability of a hazardous installation to withstand the failure induced by escalation vectors. An accident scenario propagates when the generated escalation vectors lead to the failure of hazardous installations. As a result, a vulnerability assessment is essential for assessing the escalation of potential cascading effects. The vulnerability assessment methods in literature can be divided into three categories: deterministic methods, probabilistic methods, and CFD/FEM methods.

1.5.1 Deterministic Methods

Deterministic methods based on propagation thresholds are the earliest vulnerability analysis approaches for assessing the failure of installations exposed to hazardous scenarios. These thresholds can be obtained by experiments and accident analysis [37]. An escalation threshold represents the minimum intensity of physical effects able to cause a propagation, which can be used to develop "rules of thumb" or as a screening tool for the preliminary assessment of possible escalation scenarios [6]. The required minimum distance between two hazardous installations to avoid propagation events is usually called "safety distance" or "effect distance" [4, 13]. Table 1.6 lists escalation thresholds of escalation vectors and safety distances between installations for different equipment.

Escalation thresholds can be transferred to safety distances by consequence analysis [38, 39]. According to escalation thresholds and safety distances, domino effects can be easily assessed while the escalation uncertainties are not considered. The vulnerability of installations depends on the complexity of escalation vectors and the features of target installations. Many uncertainties exist in domino effect escalation since a threshold value derived from a special condition may not suitable for other conditions. As a result, different or contradictory threshold values for domino effect assessment can be observed in the literature and technical specifications [10, 38]. For example, the recommended threshold values and safety distances span over an order of magnitude among different countries in the EU due to the lack of a harmonized approach to assessing major accident hazards in the European countries [24]. Besides, the safety distance obtained by comparing the consequence analysis results of hazardous scenarios with the escalation threshold values may not be conservative.

Table 1.6 A list of escalation thresholds and safety distances (Alileche et al. [24])

Scenario	Escalation vector	Modality	Target category	Escalation threshold	Safety distance
Flash fire	Heat radiation	Fire impingement	Floating roof tanks	Flame envelope	Max. flame distance
–			All other units	Escalation unlikely	–
Fireball	Heat radiation	Flame engulfment	Atmospheric	$H > 100$ kW/m^2	Maximum flame distance
			Pressurized	Escalation unlikely	–
		Distant radiation	Atmospheric	$H > 100$ kW/m^2	Maximum flame distance
			Pressurized	Escalation unlikely	–
Jet fire	Heat radiation	Fire impingement	All	Flame envelope	–
		Stationary radiation	Atmospheric	$H > 15$ kW/m^2	50 m from flame envelope
			Pressurized	$H > 45$ kW/m^2	25 m from flame envelope
Pool fire	Heat radiation	Flame engulfment	All	Flame envelope	–
		Stationary radiation	Atmospheric	$H > 15$ kW/m^2	50 m from flame envelope
			Pressurized	$H > 45$ kW/m^2	25 m from flame envelope
VCE	Overpressure	Blast wave interaction	Atmospheric	$P_S > 22$ kPa	R = 1.75 (ME); 1.50 (BS)
			Pressurized	$P_S > 20$ kPa	R = 2.10 (ME); 1.80 (BS)
			Elongated (toxic)	$P_S > 20$ kPa	R = 2.10 (ME); 1.80 (BS)
			Elongated (flammable)	$P_S > 31$ kPa	R = 1.35 (ME); 0.85 (BS)

(continued)

Table 1.6 (continued)

Scenario	Escalation vector	Modality	Target category	Escalation threshold	Safety distance
	Heat radiation	Fire impingement	Floating roof tanks	Flame envelope	Max. flame distance
			All other units	Escalation unlikely	–
Confined explosion	Overpressure	Blast wave interaction	Atmospheric	$P_S > 22$ kPa	20 m from vent
			Pressurized	$P_S > 20$ kPa	20 m from vent
			Elongated (toxic)	$P_S > 20$ kPa	20 m from vent
			Elongated (flammable)	$P_S > 31$ kPa	20 m from vent
Mechanical explosion	Overpressure	Blast wave interaction	Atmospheric	$P_S > 22$ kPa	R = 1.80
			Pressurized	$P_S > 20$ kPa	R = 2.00
			Elongated (toxic)	$P_S > 20$ kPa	R = 2.00
			Elongated (flammable)	$P_S > 31$ kPa	R = 1.20
	Missile projection		All	Fragment impact	300 m (prob. < 0.05)
BLEVE	Overpressure	Blast wave interaction	Atmospheric	$P_S > 22$ kPa	R = 1.80
			Pressurized	$P_S > 20$ kPa	R = 2.00
			Elongated (toxic)	$P_S > 20$ kPa	R = 2.00
			Elongated (flammable)	$P_S > 31$ kPa	R = 1.20
	Missile projection		All	Fragment impact	300 m ($p <$ 5%)
Point-source explosion		Blast wave interaction	Atmospheric	$P_S > 22$ kPa	–
			Pressurized	$P_S > 20$ kPa	–
			Elongated (toxic)	$P_S > 20$ kPa	–
			Elongated (flammable)	$P_S > 31$ kPa	–

H: heat radiation intensity; P_S: static peak overpressure; *R*: energy scaled distance; ME: Multi Energy method; BS: Baker-Sthrelow method; *p*: probability

Although the uncertainty of safety distances derived from thresholds and primary scenarios is inevitable, it is also adopted in inherent safety design [40] and technical specifications [39] due to the simplicity and transparency of the approach.

1.5.2 Probabilistic Methods

To model escalation uncertainties and support quantitative risk assessment (QRA) of domino effects, probabilistic methods are developed to assess the vulnerability of installations. According to probability theory, the vulnerability of an installation exposed to an escalation vector can be modeled by a distribution function such as a probit function and normal distribution. Probit analysis is a well-known method to evaluate the dose–effect relationship for human responses to toxic substances, thermal radiation, and overpressure [41], as shown in Eq. (1.1):

$$Y = a + b\ln(D) \tag{1.1}$$

D denotes the "dose" and Y is the probit value representing the "response". a and b are constant parameters, depending on the type of dose and response. Y characterizes the vulnerability of humans exposed to toxic substances. Then the death or injury probability can be obtained using a cumulative standard normal distribution, as shown in Eq. (1.2) [11].

$$P_r = \Phi(Y - 5) \tag{1.2}$$

Φ is the function of a cumulative standard normal distribution, P_r is the death or injury probability. The probit model (Eqs. (1.1) and (1.2)) can also be extended to assess the vulnerability of installations exposed to the most common escalation vectors in domino effects: overpressure, heat radiation, and fragments.

(1) **Overpressure**

Overpressure and fragments are the two main escalation vectors induced by explosions. Bagster and Pitblado [10] proposed a probability approach defining a damage probability function based on the distance from the center of the primary scenario and the safety distance. Khan and Abbasi [34] adopted a probit function approach to model the damage probability caused by overpressure, considering peak overpressure (static pressure) and dynamic pressure. The probit function for overpressure is obtained by using overpressure as a substitute for the dose D in Eq. (1.1). However, using a general probit model for assessing the vulnerability of all vessels exposed to overpressure may lead to large deviations. Cozzani and Salzano [42] thus developed a probit model for each type of vessel to improve the performance of the probit model. The vessels are divided into four categories: atmospheric, pressurized, elongated, and small. The equipment-specific models can significantly reduce the errors caused by the general probit model, presenting an important difference between the damage probabilities and the damage threshold of different categories of vessels.

To reduce the regression errors of probit models, the equipment-specific models were improved by distinguishing the extent of damage and assigning a linear relationship between the probit value and the observed thresholds for each type of damage [43]. In that case, a series of more accurate models were obtained, decreasing the errors between observed data and predicted data. Besides, Mukhim et al. [3] further improved the work of Zhang and Jiang [43] by classifying the equipment into 11 categories and developing a probit model for each category of equipment. These vulnerability models for overpressure can also be applied to vulnerability assessment for installations subject to explosives [44]. Furthermore, the probit models were coupled to simplified calculation models for peak overpressure to develop a straightforward approach for estimating safety distances caused by blast waves and damage probability as a function of the scaled distance. Besides, Salzano and Cozzani [45] studied the intensity of the loss of containment following overpressure wave interaction with process equipment using fuzzy set analysis, which may be used to assess second-level escalation. Although these probit models can address the uncertainties in the escalation caused by overpressure, some important parameters that have essential impacts on vulnerability are neglected, such as the thickness of the vessel wall and vessel materials.

(2) **Fragments**

Fragments and missile hazards may be induced by several accident scenarios such as BLEVE, physical explosions, confined explosions and runaway reactions, etc. Among these accident scenarios, the BLEVE is responsible for most industrial accidents involving fragment projection and usually leads to severe consequences [46]. Gubinelli et al. [47] proposed a probabilistic model according to the event sequence to assess the damage probability induced by fragments. In the model, the damage process caused by fragments are divided into four independent events, and the damage probability can be obtained by multiplying the probability of each event:

$$f_{d,F} = f_p \times P_{gen,F} \times P_{imp,F} \times P_{dam,F} \tag{1.3}$$

$f_{d,F}$ denotes the damage probability induced by a fragment F; f_p represents the probability of primary event; $P_{gen,F}$ denotes the probability of the fragment to be generated in the primary event; $P_{imp,F}$ represents the probability of impact between the fragment and a target installation; $P_{dam,F}$ represents the probability of target damage given the impact with the fragment. As a result, the total damage probability can be represented as the sum of the probability caused by each fragment [47]. This model characterizes the impact of the likelihood of sequential events (where regarded as independent events) on the damage of an installation caused by fragments, while simultaneous damages induced by multiple fragments on one installation are ignored. Besides, the dependencies among the sequential events are not considered. Projected fragments can generate secondary accidents at relevant distances from the primary scenario due to possible large projection distances. The hazards associated with projected fragments are related to the number of fragments, fragment mass, and velocity. To assess the vulnerability of installations subject to fragments, the following steps are usually adopted: (i) calculation of explosion energy, (ii) estimation of the number of fragments, (iii) calculation of initial velocity, (iv) calculation of the angle of departure, and (v) calculation of trajectory [48]. Because it is very difficult to accurately obtain the initial velocity and the departure angle, thus thresholds for fragments are rare in the literature. To reduce the complexity of probability calculation and consider more uncertainties, Monte Carlo simulation and probability density functions are always used to simulate the damage process of fragment projection [46, 48]. Zhang and Chen [49] derived a formula for the initial projection velocity of fragments by taking the explosion moment as a polytropic process and solving the energy transformation equation.

(3) **Heat radiation**

Different from the damage caused by an explosion, the damage mechanism of fire is a dynamic process, i.e., installations exposed to heat radiation do not fail immediately. As time goes by, the vulnerability of exposed vessels increases due to the build-up of temperature/pressure inside the vessel. The vessel fails when a loss of containment emerges. The delay time between the start of the fire and the failure of the target equipment is named "time to failure" (*ttf*) [37]. The concept of *ttf* is derived for assessing first-level domino effects, neglecting the time-lapse in higher-level escalations. To apply it in higher-level propagations, the concept of "residual time to failure" (RTF) is proposed by Chen et al. [15]. The vulnerability of a vessel can be dynamically assessed by updating RTF when the received heat radiation changes in higher-level propagations. In terms of a special industrial area, the two assumptions may be adjusted to obtain more accurate results. Therefore, emergency response has a huge impact on the vulnerability of installations besides heat radiation intensity (threshold). In this context, Landucci et al. [50] developed a probit model for estimating the damage probability of storage tanks exposed to fire based on the *ttf* obtained via empirical formulas. The probit model is based on three assumptions: (i) 10% probability of failure for $ttf = 5$ min, which is equal to the minimum time required to start on-site emergency response operations; (ii) 90% probability of failure for $ttf = 20$ min, which is equal to the minimum time required to start the mitigation actions. Chen et al. [9] extended this work to overcome the limitation of the "probit model" approach in higher-level propagations, modeling the uncertainty of emergency response using a normal distribution.

1.5.3 CFD/FEM Methods

In recent years, more attention has been paid to advanced numerical methods such as Computational Fluid Dynamics (CFD) and the Finite Element Method (FEM) due to their strengths in physical effect simulation. These advanced methods are considered to be a promising tool to support the assessment of complex accidental scenarios, such as three-dimensional pool fire and vapor cloud dispersion [51]. Landucci et al. [50] modeled the failure of storage tanks exposed to fire using a commercial FEM code. The FEM model can simulate the thermal and mechanical parameters of vessel shells under heat radiation, such as heat radiation, wall temperature, and stress. A storage vessel is assumed to fail when the equivalent intensity of combined stress becomes greater than the maximum allowable stress. This work was extended to model the performance of different materials proposed for the passive fire protection of tanks [52]. Jujuly et al. [53] developed a three-dimensional computational fluid dynamics (CFD) simulation of a liquefied natural gas (LNG) pool fire using ANSYS CFX. In this study, shell temperature and heat radiation thresholds were used to determine the failure of storage vessels. The results show that wind speed has a significant contribution to the behavior of a pool fire and its possible accompanying domino effects. Besides, ANSYS FLUENT was also used to model the heat transfer and pressure build-up in LPG vessels exposed to fires [51]. FLACS software developed by Gexcon AS was also be used to model flammable cloud dispersion and VCE explosion, supporting domino effect assessment [54]. These studies indicate that using advanced simulation tools can obtain a more precise assessment of failure conditions of vessels engulfed in fires, thus supporting the development of vulnerability models for process equipment exposed to fire. More recently, the Fire Dynamics Simulator (FDS) is adopted to simulate tank and dike pool fires in a tank farm [55]. CFD simulation may obtain more accurate results of physical effects and thus facilitate vulnerability assessment of installations exposed to escalation vectors, but it is very complex, time-consuming, and costly [56]. With the rapid development of computer science, applying CFD methods in vulnerability assessment may become more accessible and acceptable for researchers and engineers in the future.

1.6 Risk Assessment of Domino Effects

Based on the vulnerability assessment methods reviewed in Sect. 1.5, a domino effect assessment can be conducted to obtain the likelihoods and consequences of domino effect scenarios. This section reviews past research on the risk assessment of domino effects. The risk assessment methods used for domino effects are divided into three categories: analytical methods, graphical methods, and simulation methods.

1.6.1 Analytical Methods

Analytic methods refer to the methods using exact theorems to present formulas that can be used to obtain domino effect risks without using graphic and numerical methods. Bagster and Pitblado [10] developed a program based on a squared decay function, considering higher-level escalations and multi-vector. In this study, the differences of physical mechanisms among different escalation scenarios were not fully addressed since safety distance was used for all escalation scenarios.

Different from the safety distance-based approach, probabilistic methods can be more suitable to model uncertainties. Khan and Abbasi [57] established a probabilistic method to assess domino effects and developed a software package called MAXCRED based on the assessment method. In this study, a maximum credible accident analysis is conducted to assess the potential consequences of a chemical plant, and Probit models were used to assess the vulnerability of installations exposed to different escalation scenarios. The results show that a confined vapor cloud explosion followed by a pool fire would be the worst scenario with the maximum likelihood of triggering domino effects. Khan and Abbasi [30] updated the work and developed a new user-friendly software (DOMIFFECT). This software adopted an analytical approach to model different escalation scenarios (i.e., fire, explosion, and toxic release) and the interactive impacts between fire and explosion. The updated software was used to estimate possible hazards from loss of containment to explosions, deal with interactions among different escalation scenarios, assess the probability of domino effect scenarios, and estimate the potential consequences. Furtherly, Khan et al. [58] the DOMIFFECT software was regarded as a consequence analysis module of a risk analysis methodology called Optimal Risk Analysis (ORA).

Cozzani and Salzano [42] established a quantitative assessment methodology for overpressure-induced domino effects using equipment-specific probit models. This study demonstrated that individual risk increases up to an order of magnitude by considering domino effects. Following this work, Cozzani et al. [11] developed a systematic quantitative risk assessment method for domino effects. In this QRA method, the vulnerability of installations exposed to escalation vectors of heat radiation and overpressure were modeled by probit models, while that of fragment projection is characterized by a probabilistic model. According to the methodology, the individual risk, societal risk can be obtained considering all the credible combinations of secondary events. Besides, the QRA methodology was integrated with GIS software called Aripar-GIS [59]. By applying this software in chemical plants, possible escalation targets can be automatically identified, determining individual and societal risk induced by possible domino effects. Combining the vulnerability assessment methods for installations subject to natural disasters, the QRA framework was extended to assess domino effects caused by natural disasters [17].

Besides, TNO (Netherlands Organization for applied scientific research) developed a QRA tool for industrial plants with respect to dust explosion hazards, considering the first-level escalation based on safety distances [60]. To quantify domino effect risk, Zhang and Chen [61] proposed a QRA method based on failure mechanism analysis using a visualized risk cloud figure. Kadri et al. [62] established a QRA method for domino effect induced by fire and explosion in hazardous material storage areas by defining a concept of “domino system”. Zhou and Reniers [63] introduced a matrix-based approach for quantitative risk assessment of fire-induced domino effects, considering possible synergistic effects. Besides, commercial QRA or consequence software may also facilitate domino effect assessment, such as FLACS developed by Gexcon AS, Shepherd and FRED developed by Shell as well as EFFECTS and RISKCURVES developed by TNO [1].

With the construction of parallel pipelines, increasing attention in the scientific literature has been paid to domino effects induced by parallel pipelines [64]. Compared with domino effects in industrial plants, domino effect management with respect to parallel pipelines may be more difficult since they are over long distances [1]. Ramirez-Camacho et al. [64] established an analytical model to assess the likelihood of domino effects in parallel pipelines. The likelihood was a function of the location of the hole, the jet direction and solid angle, the diameters of pipelines, and the distance between pipelines. In terms of underground parallel pipelines, Silva et al. [65] developed an analytical model based on historical accident data and pipeline crater models, indicating that a separation distance of 10 m would be sufficient to prevent domino effects caused by parallel pipelines.

1.6.2 Graphical Methods

Chemical industrial areas consist of various hazardous installations with different domino effect potentials. Some installations exhibit a high probability of initiating domino accidents, while other installations are more likely to propagate domino events. These installations can be regarded as nodes. The quantitative possibility of accident propagation may be represented by the weight of the links between nodes in a network or graph [9, 13, 66]. Compared with analytical methods, graphical models may provide a framework for the evolution of domino effects, tackling complex domino scenarios and higher-order propagations.

(1) **Graph/network models**

Reniers and Dullaert [13] proposed a domino effect assessment method in chemical industrial plants based on graph theory. In a graph, nodes represent chemical installations, and arcs between each pair of nodes denote escalation vectors. The weight of each arc denotes the escalation likelihood from a tail installation to a head installation. In this study, a distance-based matrix called Domino Danger Unites Matrix (DDU) was defined as the weight of arcs, characterizing possible accident scenarios from one installation to another [13]. By the graphic approach, hazardous installations in an industrial area can be modeled as a whole in terms of the danger they pose to each other. As a result, the developed algorithm and software critical installations with a high probability of initiating or propagating domino effects can be identified, supporting escalation prevention decision-making [13].

(2) **Graph metrics**

Khakzad and Reniers [66] analyzed the vulnerability of process plants in the context of domino effects using graph metrics such as betweenness, out-closeness, and in-closeness of directed graphs, and closeness of undirected graphs. The betweenness of a node represents the fraction of geodesic distances or the weights of edges between all pairs of nodes that traverse the node of interest. As a result, the betweenness can represent both the escalation likelihood and the damage likelihood of installations. The out-closeness of a node represents the number of steps needed to reach every other node of the graph, indicating the escalation potential of the node (installation). Finally, the in-closeness of a node denotes the number of steps needed to reach the node from every other node of the graph, reflecting the likelihood of nodes (installations) being damaged by domino effects. Applying these metrics, critical installations or the most vulnerable installations in an industrial area can be quickly identified [66].

(3) Bayesian network

In risk assessment and artificial intelligence, Bayesian network (BN) is a widely used probabilistic graphical tool to model uncertain knowledge and dependency in probabilistic systems [67, 68]. Khakzad et al. [69] firstly introduced a BN to model the domino effect and estimate the domino effect probability at different escalation levels. By the structure of the network, possible synergistic effects can be considered, considering the complex interaction and conditional dependencies among the units involved in the domino effects. In that case, limited assumptions such as independent events or random or binomial selection of target units can be relaxed [69]. A Bayesian network represents one evolution path of domino effects, while the evolution path is uncertain at the beginning of domino effects. Similar to the approach based on graph metrics, the Bayesian network approach may be used to model the conditional dependencies of a critical evolution path. If the uncertainties of evolution paths need to be considered, multiple Bayesian networks need to be developed [70]. Figure 1.4 is a case of a dynamic network for domino effect assessment. In this network, the modeled evolution path is determined (T1 → T3 → T2 and T4 → T5).

Based on the ordinary Bayesian network approach [69], Khakzad [71] developed a dynamic Bayesian network (DBN) model considering both the spatial and temporal escalation of domino effects. The DBN explicitly models time dependencies and identifies the most probable sequence of accidents. Compared to the ordinary BN, this method can reflect the characteristics of a domino effect much better than the

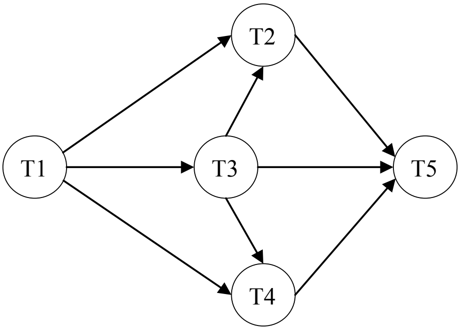
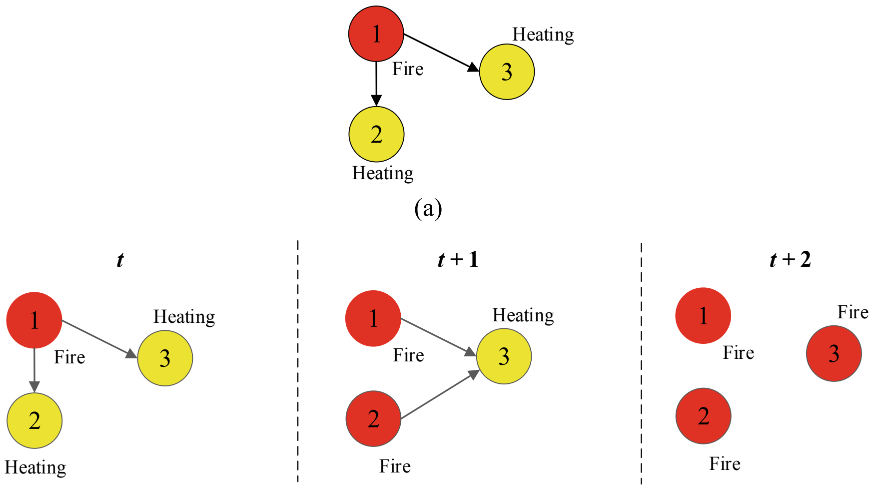


Fig. 1.4 A possible propagation pattern of the domino effect represented by BN (Chen et al. [1])

most probable combination of accidents. Similar to the ordinary BN approach, only the most probable sequence of accidents is considered to determine the structure of BN. Besides, DBN was employed to analyze domino effect escalation in wildland-industrial interfaces [72] and the escalation effects caused by intentional attacks [16]. Graph metrics can rapidly identify the critical installations and support the establishment of a critical evolution path, while BN can be used to calculate domino effect probabilities based on the critical evolution path.

(4) Dynamic graphs

Graph metrics is a threshold-based approach that neglects the uncertainties and time-dependencies in escalation assessment. To overcome these limitations and quantify domino effect risks, Chen et al. [9] developed an approach based on dynamic graphs to model the spatial–temporal evolution of domino accidents. This approach models the uncertainties and time-dependencies in escalation assessment and overcomes the limitation of the "probit model" w.r.t higher-level escalation. Complex spatial evolutions such as synergistic effects and parallel effects and the superimposed effects in spatial evolution are considered in this approach. Different from static graph models, a dynamic graph consists of sequential static graphs, and each static graph represents an escalation status at a specific time. Therefore, a dynamic graph is updated with the evolution of domino effects. Compared to the static graph, which provides merely a snapshot of the whole process at once, dynamic graphs seem to be able to model the dynamic evolution of domino effects (escalation sequence) [15]. Figure 1.5 shows a comparison between a static graph and a dynamic graph. The static graph (a) only provides one snapshot of the entire evolution process, while the dynamic graph (b) models the dynamic evolution process. By the application of the dynamic



(a)

(b)

Fig. 1.5 The structure of (**a**) a static graph model and (**b**) a dynamic graph model of domino effects graph method, we can rapidly obtain the evolution time, evolution paths, the status of installations, the failure probabilities of installations. Besides, possible multiple failures of installations within a primary scenario caused by intentional attacks or natural disasters can also be addressed using the dynamic graph approach. Furthermore, combining this approach with Monte Carlo simulation, the uncertainties in scenario evolution and escalation assessment can also be addressed [73].

(5) Petri-net models

Petri-nets are graphic tools that are widely used to analyze and simulate concurrent systems [74]. A Petri-met consists of two sets of nodes: the set of places representing system objects, and the set of events or transitions denotes the dynamics of the system. Zhou and Reniers [75] proposed a Petri-net model to analyze domino effect evolution induced by overpressure. The probabilistic dependencies in different events were modeled by the token of a place with a probability value. Similar to the BN method, the structure of the Petri-net is developed based on threshold values. Then the probability calculation is performed according to the developed network [75]. Besides, Petri-nets were applied to model the complex interaction and time dependencies among installations during the evolution of fire-induced domino effects [76].

(6) Event tree method

Event tree analysis is a forward, top-down, logical modeling technique using dichotomous conditions to model the propagation of events by different branches of the tree [77]. It is widely used to analyze the sequential events following an initial event. Alileche et al. [78] developed a methodology based on event tree analysis to model the propagation of domino effects. By applying the event tree analysis, different accident scenarios caused by a loss of containment can be identified to support propagation analysis.

1.6.3 Simulation Methods

Simulation methods are used to generate possible scenarios and then obtain the probabilities by the statistics of each scenario. It can simplify the complexity of analytical techniques and thus improve the efficiency of tracking complex accident evolutions. Abdolhamidzadeh et al. [23] proposed a Monte Carlo method for assessing the probability of domino effects and the failure frequency of installations. Then, this simulation method was extended to model multi-scenario and higher-level escalations [79]. The Monte Carlo-based simulation approach can successfully model the spatial evolution of domino accidents while it may be time-consuming. Similar to the BN approaches, it is a purely probabilistic tool based on randomly generated numbers, lacking actual accident propagation mechanisms. Besides, Zhang et al. [80] proposed an agent-based simulation tool considering installations' states that was developed to analyze the second or higher-level propagations and temporal dependencies. An algorithm based on Monte Carlo simulation is used to solve the model. As a result, it takes enormous computation time for realistic chemical clusters with many installations.

1.7 Safety and Security Management of Domino Effects

Safety and security management in the chemical and process industry reduces the hazard of a process, the likelihood of accidents, and the consequences. A wide variety of strategies, techniques, procedures, policies and systems are used to this end [81]. Since domino effects can be triggered by both intentional and unintentional events, Reniers et al. [14] deemed that both safety and security are important for domino effect management. Therefore, a wide variety of safety and security measures are needed to prevent or mitigate possible intentional domino effects and unintentional domino effects. According to Bollinger and Crowl [81], risk reduction strategies can be divided into four categories: inherent, passive, active, and procedural. In this review, strategies for managing domino effects are divided into four categories: inherent safety, safety barrier management, cooperative prevention strategies, and security strategies for intentional domino effects.

1.7.1 Inherent Safety

Inherent safety aims to remove the hazard at the source rather than to accept the hazard by attempting to mitigate the effects. Inherent safety is a practical and straightforward approach that has received the most attention in the prior development of assessment tools [82]. Kletz [83] proposed five inherent safety principles: intensification or minimization, substitution, moderation by attenuation, simplification, and moderation by limitation of effects, as shown in Table 1.7.

Some of the principles may be difficult to implement in practice, and not all these principles can be used in domino effect management. These principles can always be used to identify inherent safety measures for escalation prevention if they are considered in an assessment. Inherent safety strategies can prevent the initiation of the accident, decrease the potential of domino effects or terminate the accident sequence. Past domino effect management work related to inherent safety, includes developing inherent safety indexes, optimizing layout, and optimizing inventories.

(1) **Inherent safety indexes**

Cozzani et al. [84] analyzed possible escalation scenarios to identify inherent safety measures related to the prevention and mitigation of domino effects. This study shows that the principle of "limitation of effects" is more effective, and integrating inherent safety criteria with passive or active protections may be a promising route for domino

Table 1.7 Inherently safer principles (Chen et al. [1])

Inherently safer principles	Description
Intensification or minimization	Using so little of the hazardous material that there is no significant risk if it all leaks out
Substitution	using a less hazardous material or a process that is less likely to develop into an accident scenario (e.g., a runaway reaction)
Moderation by attenuation	Using the hazardous material in the least hazardous form (under the least hazardous condition)
Simplification	Using simpler plants that provide fewer opportunities for error and less equipment that can fail
Moderation by limitation of effects	Duplicate or separate processes, critical activities, installations, to limit the possibility of severe effects

effect management in chemical and process plants. According to these inherent safety principles, Cozzani et al. [40] defined a set of inherent safety indexes to identify process and layout hazards related to escalation events. The hazard indexes can be used to identify inherent measures for domino effect management, such as measures in layout design. Tugnoli et al. [85] examined the five inherent safety principles and demonstrated that the principles of "attenuation", "simplification", and "limitation of effects" are practical for layout design. According to these principles, they established indexes for plant layout design, considering possible escalation scenarios [86]. To compare different technologies for hydrogen storage, Landucci et al. [87] developed a set of inherent safety key performance indicators according to consequence assessment and credit factors of possible LOC events. These studies evidence that the application of inherent safety principles in domino effect management can effectively prevent and mitigate domino effects.

(2) **Layout optimization**

A widely used inherent safety practice in domino effect management is layout optimization for chemical plant layout design. Lee et al. [88] proposed a nonlinear program to optimize the distribution of explosive facilities, considering possible escalation effects caused by fire, overpressure, and fragments. The optimization can minimize the total escalation probabilities caused by different escalation scenarios, ignoring the difference of likelihoods of different primary scenarios. The developed computer-aided module (MiniFFECT) sequentially allocates hazardous installations in a limited land [89]. This optimization approach was further improved to obtain the optimal plant layout minimizing the total weighted consequences of different escalation scenarios [90]. Besides, the research was also extended to minimize the total construction costs, including pipeline connection cost, protection cost, and land-use cost [91].

Jung et al. [92] developed an optimization approach for facility siting and layout decision-making using a mixed-integer nonlinear program (MINLP). MINLP is a widely used algorithm used for optimization problems with continuous and discrete variables and nonlinear functions in the objective function and/or the constraints. This study aimed at minimizing the overall cost, including land costs, interconnection costs between facilities, and risk costs derived from possible structural damage caused by overpressures). The optimization results can be used to safely and economically determine the location of new facilities. Based on probit models and consequence indexes, the MINLP approach was also used to optimize chemical plant layout and thus to reduce domino effects [93]. Besides, Latifi et al. [94] proposed an MINLP formulation to optimize process plant layout, considering major accidents such as toxic release, fire, explosion, and possible domino effects induced by them.

Bernechea and Arnaldos [95] proposed a multi-objective optimization method to optimize the design of storage facilities based on inherent safety design and quantitative risk assessment. Multi-objective optimization is a decision-making tool using multiple criteria in which two or more objectives subjected to different restrictions are simultaneously optimized. Consequently, it can be used to balance the conflict between domino effect management and the reduction of investment costs [95]. Nomen et al. [96] proposed a plant layout design method based on QRA results. In this approach, a simple criterion based on the surface enclosed in isorisk curves is used for comparing different QRA results. Khakzad and Reniers [97] developed a multi-criteria decision analysis (MCDA) tool using an analytic hierarchical process (AHP) to support chemical plant design. In this study, BN is combined with MCDA techniques for layout optimization, considering a variety of hazardous installations and multiple accident scenarios.

(3) Inventory optimization

Besides plant layout, domino effects also depend on the distribution of hazardous substances. Thus optimization of the distribution of chemical inventories is a practical option when reducing the total mass of hazardous substances is impossible. Khakzad et al. [98] proposed an approach based on DBN to optimize the chemical plant inventory, minimizing domino effect risk. This study indicated that optimization of the distribution of hazardous inventories is essential for process plants with fixed safety distances.

1.7.2 Management of Safety Barriers

Passive barriers in process safety management refer to any measures that can reduce either the frequency or consequence of the hazard without the active functioning of any device, such as dikes, firewalls, and fireproofing coatings. Active barriers are any measures that can detect and respond to process deviation from normal operation using controls, alarms, safety instrumented systems or functions, and mitigation systems, such as water deluge systems (WDS), emergency shutdown systems (ESD), and emergency depressurization systems (EDP) [1, 15]. Previous work on safety barriers related to domino effects is divided into three categories: barrier performance assessment, barrier optimization, and emergency response.

(1) Safety barrier performance

The performance of a safety barrier for preventing escalation prevention depends on the "availability" and "effectiveness" of the barrier. The availability represents the complement of the probability of failure on demand (PFD) of the safety barrier, and the effectiveness refers to the conditional probability of the escalation being prevented given the barrier is activated. Landucci et al. [99] proposed a quantitative method for assessing the performance of safety barriers. A fault tree was used to quantitatively assess the PFD of safety barriers, and an event tree is adopted to analyze domino effects, considering the function of relevant safety barriers. The performance of different barriers can be obtained by combining the quantitative method with key performance indicator analysis [100]. Table 1.8 lists the PFD values of the common-used safety barriers in the chemical and process industry.

The performance of safety barriers strongly depends on external factors such as external temperature, wind and wave height, etc. [101]. Consequently, harsh environments possibly reduce the performance of safety barriers and the availability of emergency resources [101]. Harsh environments refer to those climatic conditions that may be difficult for people to work and for equipment to be normal operation [102]. For instance, the reliability of emergency response procedures may be decreased due to harsh environments, resulting in the delay of escalation control and the non-achievement of the optimal rescue time. To address the uncertainty

Table 1.8 PFD values of common-used safety barriers (Chen et al. [1])

Safety barrier	Actuation type	Proportioning method	PFD
Foam-water sprinkler system	Pneumatic	In-line educator[a]	5.43×10^{-3}
		Metering proportioning[b]	5.01×10^{-3}
		Bladder tank[c]	3.76×10^{-3}
	Electric	In-line educator	5.39×10^{-3}
		Metering proportioning	4.96×10^{-3}
		Bladder tank	3.72×10^{-3}
WDS for LPG vessels protection	Pneumatic	–	1.89×10^{-2}
	Electric	–	4.33×10^{-2}
WDS for horizontal separator protection	Pneumatic	–	2.24×10^{-2}
	Electric	–	2.24×10^{-2}
ESD system	–	–	3.72×10^{-4}
Pressure Safety Valve (PSV)	–	–	1.00×10^{-2}
Fireproofing coating	–	–	1.00×10^{-3}
Emergency intervention	–	–	1.00×10^{-1}

[a] In line educator has an inlet pressure which can be brought a significant distance from the engine

[b] Metering proportioning is located in line to the front brakes to allow pressure to cause the valve to open allowing pressurized brake fluid to flow to the caliper

[c] Bladder tank includes a pressure-rated tank with an internal elastomeric bladder for foam concentrate storage

and complexity induced by harsh environments, Landucci et al. [101] developed an event tree approach to address the influence of harsh environmental conditions on the performance of hardware safety barriers. Besides, Khakzad et al. [103] established a dynamic Bayesian network to address the degradation of safety barriers during domino events. In this study, an exponential probability distribution was used to model the availability of safety barriers and time-dependent fragility models were adopted to assess the failure probability of installations exposed to fire.

(2) Optimization of safety barriers

Performance assessment can identify effective safety barriers for preventing and mitigating escalation effects such as fireproof coatings and WDS. However, these safety barriers may not be implemented for all equipment in a chemical industrial area due to the safety budget. Therefore, a risk-based methodology is developed to identify fireproofing zones in the initial phases of layout definition, considering domino effects caused by both pool fire and jet fire [104]. This study used a risk matrix to rank the severity of different LOC scenarios and thus identify the reference scenarios. Then, plotted envelopes corresponding to the reference LOCs were used to identify the fireproof zones [104]. Besides, Ghasemi and Nourai [105] developed an approach to determine the water application rate for protecting storage tanks from an external non-contacting fire. The optimization can lead to at least 25% saving in a tank farm area by calculating the water application rate to reduce the separation distance between adjacent tanks.

Janssens et al. [106] developed an optimization method to allocate safety barriers to mitigate the consequences of possible fire-induced domino effects. The optimization aimed to maximize the total failure time associated with a domino effect given a limited budget. This study considered the decision-making on the allocation of safety barriers a knapsack problem and proposed a metaheuristic algorithm to obtain the optimal allocation strategy. This approach can support the allocation of safety barriers under a limited budget. Khakzad et al. [107] applied a cost-effective analysis for decision-making on the allocation of safety barriers. Cost-effectiveness analysis does not strictly require the monetization of protection benefits while always needs to compute cost-effectiveness ratios (CERs). CERs are used to select the most effective protection strategies between two options [5]. The cost-effective analysis based on the limited memory influence diagram can identify the most cost-effective strategy for the allocation of safety barriers.

(3) Emergency response

In the process and chemical industry, emergency response actions are essential for protecting installations, the public, workers, and the environment [1]. Besides, emergency response actions also impact the evolution of accidents and thus play an important role in domino effect management. However, the performance of emergency response is difficult to assess due to the uncertainties related to emergency response procedures [15]. For instance, the performance of firefighting depends on the skills and preparedness of emergency responders, the number of firefighting trucks, the distance between the water resources and the chemical plant, and the time required to start the emergency operations [108]. In terms of intentional attacks on chemical facilities, more than one fire may co-occur, and these fires may lead to domino effects at different locations in a chemical industrial area. In that case, emergency management may be challenging since it is challenging to allocate limited emergency resources to multiple locations. In light of these challenges, much work on emergency management has been done in recent years.

Zhou and Reniers [109] studied the emergency response against simultaneous large-scale fires using a Petri-net simulation method. The simulation analyzed the executing actions and the system status during an emergency response process to obtain the optimal strategy for the allocation of firefighters. The study shows that the allocation of firefighters should be based on fire severity rather than average distribution; the effects of backups on firefighters depend on particular fire scenarios; thus it is not always necessary to improve the backups [109]. A further analysis based on timed colored hybrid Petri-net (TCHPN) indicates that cooling adjacent tanks is more important for preventing fire-induced domino effects [110]. This work was improved to deduce the consequence-antecedent relationship between an accident and the emergency response actions using a fuzzy Petri-net [111]. Besides, an approach combining an event sequence diagram and Monte Carlo simulation was developed to assess emergency response actions considering sequence, duration, correctness, and mutual interaction [112].

Khakzad [113] developed a risk-informed approach based on DBN for emergency response analysis in oil terminals. This study can identify optimal firefighting strategies, especially when the number of fire trucks is insufficient to handle all the vessels exposed to fires. The study shows that cooling an exposed vessel can immediately reduce the likelihood of fire escalation, while suppressing a burning vessel can not quickly reduce the emitting heat radiation. The results from a graph-based approach indicate that suppression and cooling of tanks with the highest out-closeness index is an optimum firefighting strategy [114]. Besides the firefighting optimization based on risk reduction, Cincotta et al. [108] proposed a new optimization based on the resilience concept. This study is used to optimize firefighting strategies, maximizing the resilience of process plants. The failure probability of installations was considered in the developed resilience metrics, whereas the recovery ability was ignored. Hosseinnia et al. [115] developed an emergency response decision matrix to tackle domino effects in chemical clusters. A decision tree of emergency levels and an alert notification system based on a decision matrix are used in the methodology. Compared with unintentional domino effects, the emergency management for intentional domino effects needs to consider the security forces. In target identification, the attractiveness of installations to adversaries should be addressed. Also, the consequence analysis should consider the vulnerability of installations exposed to intentional attacks and the vulnerability of installations subject to escalation effects [115].

1.7.3 Cooperative Prevention

A chemical industrial park or so-called chemical cluster always consists of multiple chemical plants belonging to different companies. The implementation of safety and security resources in one chemical plant may benefit nearby plants due to the prevention and mitigation of possible external domino effects. From a safety viewpoint, domino effect scenarios in the cluster are unknown to other plants if there is no collaboration. Moreover, security measures may increase the (security) risk of nearby plants since the attractiveness of the chemical plants for possible common adversaries may decrease with the implementation of protection measures. As a result, cooperative prevention is thus needed to prevent and mitigate domino effects in chemical clusters.

(1) **Cooperative prevention of external domino effects**

In a chemical cluster, a domino effect can be an internal domino effect or an external domino effect. Internal domino effects refer to the escalation effects occurring within the boundaries of the plant, while external domino effects are the escalation effects that propagate outside the boundaries of the plant [12]. Due to possible external domino effects, a terrorist attack on chemical plant A may have an impact on company B, resulting in a major catastrophic disaster in the cluster. These scenarios may be more likely to unfold if the terrorist has access to sufficient and accurate information about domino effects. These catastrophes may damage multiple plants in a chemical cluster, and it is therefore important to involve all plants in the chemical cluster to collaborate in cross-plant safety [116]. Even if a company invested in preventing domino effects while its neighbors have not, the company might suffer from major accidents triggered by an initial event in an adjacent chemical enterprise in the chemical cluster. Besides, the neighboring company may become more attractive for terrorists since its attractiveness increases if no security investments are implemented [116].

To manage possible external domino effects, Reniers et al. [31] examined risk analysis tools used by 24 chemical plants in Belgium. This work identified the at the time of the study used practices in the chemical industry subject to European Seveso legislation and examined how the risk analysis approaches may be integrated to improve the safety policy. The survey shows that the exchange of expertise and cooperation can lead to a safer working environment. Three risk analysis tools (HAZOP, what-if analysis, and the risk matrix method) are identified as promising tools for stimulating inter-company cooperation. Based on the investigation, an external domino effect management framework (Hazwim) based on identified risk analysis methods was established. The Hazwim framework consists of a process scheme and an organized schedule, which is very useful for decision-making to prevent external domino effects [12]. Besides, Reniers et al. [117] applied a cooperative game to model the decision-making of different plants within a chemical cluster on prevention investments.

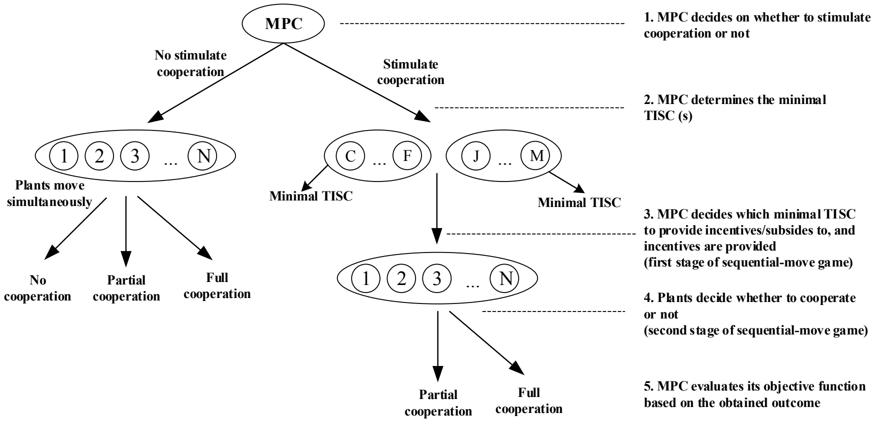


Fig. 1.6 The decision procedures of a two-stage sequential move game (Pavlova and Reniers [118])

According to the approach, a win–win strategy or so-called Nash equilibrium where all the players (companies) can obtain benefits from the investment in prevention measures.

(2) Enhancing safety and security cooperation

Due to the extremely low probabilities of external domino effects, trust and confidentiality concerns, it may be difficult to obtain an agreement among companies in the investment in cross-plant preventive measures [36]. Pavlova and Reniers [118] thus developed a sequential-move game to enhance safety and security cooperation within chemical clusters dealing with domino effects, as shown in Fig. 1.6.

As shown in Fig. 1.6, an institution called Multi-Plant Council (MPC) could be established to stimulate the prevention cooperation in a chemical cluster [118]. The MPC would be responsible for a continuous follow-up of safety and security improvements at different companies in the cluster. In the two-stage game, the MPC is a leader who aims at achieving full cooperation among players by developing a system of incentives at minimum expense. After the leader makes a decision, the followers (different companies) may decide about investment, in cooperative prevention of domino accidents.

1.7.4 Security of Intentional Domino Effects

Reniers et al. [14] proposed to prevent intentional domino effects in chemical clusters in light of possible intentional attacks on chemical infrastructures. Unlike other critical infrastructures, an intentional attack on one or more hazardous installations in chemical industrial areas may trigger escalation effects, resulting in severe consequences. In addition to securing chemical plants, some attempts have been done in the literature. These attempts can be divided into three categories: security of critical installations, mitigation of potential consequences, and reduction of attractiveness.

(1) Security of critical installations

The domino effect potential of hazardous installations depends on the amount of substances present, the physical and toxic properties of the substances, and the specific process conditions, etc. Critical installations refer to the installations with a high likelihood of initiating or propagating accidents. These critical installations are more attractive for adversaries that aim to trigger catastrophic disasters. As a result, the security of critical installations can maximize the benefits of limited protection resources. The strategy of securing critical installations was proposed to address security-related issues in domino effect management [14]. This study indicates that enhancing the security of critical infrastructure can improve the overall security of the chemical industrial area. From the perspective of resilience, Reniers et al. [119] proved that the layout of a chemical industrial area follows a power-law distribution. In other words, only a few installations exhibit very high escalation potential, and securing those installations with high domino effect potential can decrease the possible consequences of an attack. Bubbico and Mazzarotta [120] explored the role of plant layout on security risk in chemical industrial areas, highlighting the role of planning plant layout from a security perspective. According to this study, the most critical zones should be preliminarily identified when planning a plant layout, including process areas, control room(s), storage areas for hazardous materials, loading and unloading facilities, and fire equipment. Based on the concept of the rings of protection, critical facilities should be set in the middle to provide concentric levels of security and increase the number and complexity of the barriers moving toward the center [120].

(2) Mitigation of potential consequences

If the prevention of intentional attacks seems impossible, mitigating the potential consequences by safety measures may be considered an effective approach for protecting chemical industrial plants against domino effects. Safety measures can not only mitigate the potential consequences of intentional attacks but also contribute to the prevention of unintentional domino effects. Therefore, the protection strategy may result in a safer and more secure chemical plant. Based on the protection strategy, Srivastava and Gupta [121] developed a Stepped Matrix Procedure (SMP) method to deal with domino effects by using safety barriers. Reniers and Audenaert [122] proposed to minimize the potential consequences of intentional domino effects based on vulnerability assessment. The approach proposed in the study may also be used to develop an inherent security plant by identifying the most vulnerable installations or to solve layout or site location problems in the early design phase. Khakzad and Reniers [16] proposed a cost-robust mitigation strategy to keep some of the storage tanks empty in the case of imminent terrorist attacks. The robustness of the plant against intentional attacks can be temporarily increased by using this strategy. Consequently, any safety measures for escalation prevention may be used to mitigate the potential consequence of intentional attacks and thus prevent intentional domino effects.

(3) **Reduction of attractiveness**

The attractiveness of hazardous facilities to adversaries depends on many factors: access, security, visibility, opacity, secondary hazard, robustness, law enforcement response, victim profile, and political value [123]. Attractiveness analysis should assess the perceived value of a target to adversaries and the adversaries' choice of targets [124]. Since adversaries usually launch attacks to lead to as many losses as possible [122, 125], both the strategies of security of critical installations and mitigation of potential consequences can lead to a reduction of the attractiveness to adversaries. Therefore, using both safety and security resources to protect chemical industrial areas against intentional domino effects is considered a strategy to reduce attractiveness. Khakzad [125] highlighted the role of reducing the attractiveness of chemical plants to terrorist attacks and recommended using safety concepts such as inherently safer design and land use planning to improve the security of chemical plants. These safety concepts can reduce both the attractiveness of the chemical plant and the consequences of attack scenarios. Chen et al. [15] proposed an integrated approach to prevent and mitigate intentional domino effects, considering the vulnerability of installations exposed to intentional attacks as well as the vulnerability of installations against subsequent domino effects. The developed resource allocation method in this study can effectively reduce a chemical cluster's attractiveness as well as the potential consequences of attacks.

1.8 Research Trends and Future Needs

1.8.1 A Summarization of Current Research

(1) **Risk assessment of domino effects**

Early quantitative research on domino effect assessment mainly forced on the first-level escalations to obtain the likelihood of domino effects in a chemical industrial area [11, 126]. However, only modeling the first-level escalation may underestimate the consequences of escalations while considering second and higher-level escalations is challenging due to the uncertainties associated with higher-level propagations, such as failure types, failure sequences, and intensity of escalation vector. Besides, complex propagations such as synergistic effects and parallel effects may occur at higher-level propagations. In recent years, attempts have been made for modeling higher-level propagations [9, 79]. Graphic methods such as graph metrics and dynamic graphs provide a visible framework for the evolution of domino effects and thus have advantages in modeling higher-level propagation. Graph structures in previous research are mainly based on threshold values, which may only represent one possible evolution sequence of domino effects. Multiple graphs or a more complex structure should be established if the uncertainty of evolution paths is considered. Monte Carlo simulation is a widely used method to deal with propagation uncertainty while the technique may take more computation time than graphic and analytical methods.

Bagster and Pitblado [10] regarded a domino effect accident as a spatial escalation triggered by a loss of containment. Since then, the main task of domino effect risk assessment is modeling the spatial evolution of domino effects, obtaining the likelihood of domino effects and the failure probability of installations [10, 34, 69]. Reniers and Cozzani [6] defined domino effects as a chain of accidents that may occur simultaneously or sequentially, so the evolution of domino effects may be a dynamic process such as the propagation caused by heat radiation (time to failure). Modeling the temporal evolution of domino effects required dynamic tools such as dynamic Bayesian network (DBN) [71], agent-based modeling [80], dynamic graphs [9], and Petri-nets [76]. These dynamic tools were widely used to model superimposed effects in which the heat radiation received by an installation varies in different stages. In terms of domino effects induced by overpressure or fragments, temporal evolution is ignored since the failure caused by these escalation vectors is considered almost instantaneous.

(2) Domino effect management

In a chemical cluster, due to possible external escalation effects, the risk of a chemical company depends on the company's safety and security strategies and the decisions of other chemical plants nearby in the chemical cluster. As a result, cooperation management of domino effects is undoubtedly a good choice in a chemical cluster [12, 117]. However, achieving cooperation among different companies is challenging since it is related to technical and organizational problems. To achieve prevention corporation in a chemical cluster, a Multi-Plant Council (MPC) may be recommended to prompt the cooperation [117]. Besides, the decision-making on alert levels in a chemical cluster was also developed to avoid external domino effects [115]. To promote cooperation in a real chemical cluster, more strategic and proactive cooperation should be explored by addressing more organizational issues.

Previous research on domino effect management mainly focused on accidental domino effects using inherent safety [40, 84, 97], safety barriers [99], and emergency response [110, 112, 113]. Little attention has been paid to Natech domino effects and intentional domino effects. Although these protection strategies for accidental domino effects may also be applied to manage domino effects triggered by natural disasters or intentional attacks, special characteristics of these domino effects are not fully addressed. For instance, active protection measures have a high probability of being damaged by natural disasters. Besides, emergency response actions may also be impossible due to the inaccessibility of other critical infrastructures nearby. In terms of intentional domino effects, past management attempts include security of critical installations using security measures [14], mitigation of potential consequences using safety measures [16, 121] and reduction of attractiveness using both safety and security resources [122, 125]. However, adversaries' strategies were almost ignored. For example, multiple-target attacks may lead to multiple fires, resulting in unpreventable escalations.

Based on protection principles, decision-making tools are needed to identify the best strategy according to decision criteria. Decision-making for inherent safety strategies has drawn much attention, including comparative analysis [86, 87], layout optimization [88, 90, 91], and inventory optimization [98]. The decision-making on safety barriers includes optimization of the allocation of safety barriers [104, 105], cost-effective analysis [107] of the influence of costs on decision-making for safety barriers. Besides, game theory is also used to support the decision-making among different plants in a chemical industrial cluster [118]. However, current research mainly focuses on one kind of protection measure or one protection principle, and decision-making based on multiple protection principles which can be used in different stages of chemical plants is lacking. Besides protection costs, the protection benefits may also be interesting for safety and/or security managers since they are important for a company's long-term profitability.

1.8.2 Comparison of Different Modeling Approaches and Protection Strategies

(1) **Comparison of different domino risk assessment approaches**

Many approaches have been proposed for risk assessment and management of domino effects in the process and chemical industry. Different stakeholders related to the process and chemical industry can select different approaches according to their various and different interests and concerns. Consequently, a comparison among different approaches is conducted based on six criteria [1], as follows:

(1) the source of the approach;
(2) the category of the approach;
(3) the vulnerability models used in the approach;
(4) the escalation vector considered in the approach;
(5) the evolution considered in the approach;
(6) the computation cost needed for the implementation of the approach.

According to the analysis in Sect. 1.6, 11 main approaches for modeling domino effects are selected and analyzed based on the six foregoing criteria, as shown in Table 1.9.

(2) **Comparison of different domino management approaches**

Domino effect research aims to prevent and mitigate domino effects in the process and chemical industry. Different protection approaches are available, including inherent safety, safety barriers, emergency response, cooperative prevention in chemical industrial clusters, and security of domino effects. To prevent domino effects, the possible causes of domino effects should be analyzed since different areas may face

Table 1.9 Comparison among different modeling approaches (Chen et al. [1])

Source	Category	Vulnerability basis	Escalation vector	Evolution	Computation cost
Bagster and Pitblado [10]	Analytical method	Safety distances	Multiple	Higher-level	High in large scale case
Khan and Abbasi [34]	Analytical method	Probabilistic models	Multiple	First-level	Low
Cozzani et al. [11, 17]	Analytical method	Probit models	Multiple	First-level Extend to higher levels	Low High in large scale case
Reniers and Dullaert [13]	Network method	Safety distances	Multiple	Higher-level	low
Abdolhamidzadeh et al. [79, 126]	Model-Carlo simulation	Probit models	Multiple	First-level Extend to higher levels	high
Khakzad et al. [69]	Bayesian network	Probit models and thresholds	Multiple	Higher-level	High in large scale case
Khakzad [71]	Dynamic Bayesian network	Probit models and thresholds	Heat radiation	Higher-level Temporal evolution	High in large scale case
Khakzad and Reniers [66]	Graph metrics	thresholds	Multiple	Higher-level	Low
Kamil et al. [76] Zhou and Reniers [75]	Petri-net	Probit models	Multiple	Higher-level	Low High
Zhang et al. [80]	Agent-based simulation	Probit models	Heat radiation	Higher-level Temporal evolution	High
Chen et al. [15]	Dynamic graph model	Residual time to failure	Heat radiation	Higher-level Temporal evolution	Low

different threats. For accidental domino effects, hazards are mainly located within a chemical industrial area, while in the case of intentional domino effects, from outside the chemical industrial park threats may be involved. Safety measures for escalation prevention (i.e., inherent safety, safety barriers, and emergency response) can reduce the risk of domino effects caused by intentional attacks, accidental events, and natural disasters. Security measures are mainly for preventing intentional attacks and thus reduce the probability of intentional domino effects. Besides, cooperative prevention strategies are proposed to prevent possible external domino effects, enhancing the safety and security of chemical industrial clusters. Therefore, stakeholders should choose protection strategies according to their threats, concerns, and preferences, as shown in Fig. 1.7.

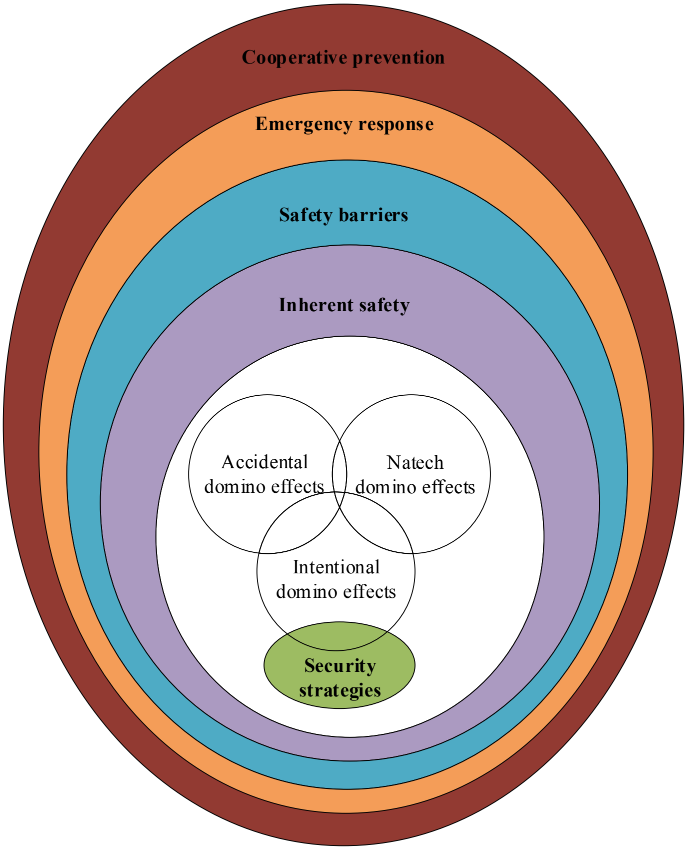


Fig. 1.7 Protection strategies for preventing and mitigating domino effects

1.8.3 Research Gaps

According to the review of past work on risk assessment and management of domino effects in the process and chemical industry, research gaps are identified.

(1) **Dynamic risk assessment of fire-induced domino effects**

The propagation of fire scenarios depends on the time to failure (ttf) of installations exposed to fire. As a result, fire-induced escalation may be regarded as a spatial–temporal evolution process. During the evolution, one installation may receive heat radiation from multiple fires (synergistic effects), and the received heat radiation may change over time. The effects of heat radiation in different stages should be superimposed when determining the ttf (superimposed effects). Besides, the time-lapse in the second or higher-level escalation should be considered in probit models. In light of these research gaps, Chap. 2 develops a dynamic graph approach to model fire-induced domino effects.

(2) Dynamic risk assessment of VCE-induced domino effects

Compared with fire scenarios, vapor cloud explosion (VCE) is more difficult to assess due to the uncertainty of ignition position, the uncertainty of delayed ignition time (DIT), and the complexity of overpressure intensity calculation. The VCE induced by the release of hazardous substances in chemical plants is a dynamic process along with the vapor cloud dispersion. However, previous risk analysis methods for VCE always assume that the explosion occurs immediately at the release place [75, 126], which is inconsistent with the observations from large VCEs in recent years. As a result, a dynamic tool is established in Chap. 3 to address the vapor cloud dispersion and delayed ignition in the assessment of VCE-induced domino effects.

(3) Dynamic risk assessment of coupled domino effects

If a loss of containment occurs in a chemical industrial area, accident scenarios such as a toxic release, a VCE, and a fire may simultaneously or sequentially occur, and the generated hazards can evolve spatially and result in a cascading disaster. Consequently, all the major hazards (fire, explosion, and toxic release) can simultaneously or sequentially be present in a domino effect. Neglecting any known hazard may underestimate the risk of domino effects and result in more severe consequences. Therefore, modeling the spatial–temporal evolution of hazards originating from the release of hazardous materials in industrial areas is essential for protecting staff, nearby residents, and emergency rescuers. As a result, a dynamic method is developed in Chap. 4 to model coupled domino effects.

(4) Integrated management of domino effects

Domino effects can be triggered by intentional or unintentional events. Safety barriers can reduce the likelihood and consequences of accidental domino effects, Natech domino effects, and intentional domino effects. Security resources are essential to prevent intentional attacks and also decrease the attractiveness of a possible target. Past research on domino effect management mainly concerned unintentional domino effects, neglecting intentional domino effects, which may result in even more severe consequences. Thus safety and security resources may be integrated to manage different kinds of domino effects from a systemic perspective. Therefore, Chap. 5 establishes an integrated management framework to prevent and mitigate domino effects.

(5) Economic approach to manage domino effects

Many safety and security measures can be used for managing domino effects, while not all of these measures can be implemented due to the safety and security budget. Chemical companies have to consider the costs of protection measures since the budget is not infinite, evidentially. Consequently, the economic issues of safety and security play an indispensable role in the decision-making on the allocation of safety and security measures. In decision-making on the investment in the prevention and mitigation of domino effects, economic approaches may be used to address these economic issues and make the protection more profitable. Chapter 6 thus introduces an economic approach to manage domino effects, considering both the costs of protection measures and domino effect events.

(6) **Resilience approach to manage domino effects**

Disruptions that may trigger domino effects such as intentional attacks may be difficult to predict and prevent, thus safety and security measures may be insufficient for preventing domino effects. Once a domino effect occurs, an adaptation operation or a quick restoration can reduce the loss and thus mitigate the consequences of domino effects. Resilience refers to the capability of a chemical plant to resist, mitigate, adapt, and recover from undesired events, to maintain its desired performance. As a result, developing a resilient chemical plant may be a practical and effective way to deal with these disruptions. A resilience-based approach is proposed in Chap. 7 to prepare a chemical plant to anticipate, absorb, adapt to, and restore from domino accidents.

1.9 Conclusions

In recent decades, the importance of domino effect management has been recognized by researchers and practitioners in the process and chemical industries. More and more efforts have been put into assessing the possibility of domino effects, modeling the evolution of domino effects, and preventing or mitigating domino effects. This chapter reviews the research issues and methods in domino effect risk assessment and management and their development in the literature. The available methods for simulating the domino effect are roughly divided into three categories: analytical methods, graphical methods, and simulation methods. The current management strategies are divided into five types: inherent security, security barrier management, emergency response, cooperative prevention, and security strategies. It provides a very clear picture of the development of research issues and the methods used to assess and manage possible domino effects. Besides, according to several standards, different types of modeling methods and management strategies are further compared to locate their applications and promote future research directions. Finally, we obtain research gaps, which are also the motivations for the following chapters.

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