Dynamic Assessment of VCE-Induced Domino Effects

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Chapter 8
Conclusions and Future Research

This book introduces three domino effect models that can be used for risk assessment of both intentional domino effects and unintentional domino effects. Based on these risk assessment models, three chapters on domino effect management are provided to prevent and mitigate domino effects triggered by unintentional events or intentional attacks.

When a hazardous scenario (toxic release, fire, and explosion) occurs in a chemical industrial area, many hazardous installations are mutually linked via escalation vectors (e.g., heat radiation, overpressure), forming a system [1]. The spatial–temporal evolution of hazardous scenarios within the system may lead to domino effects. In light of the characteristics, a dynamic tool is better to model the temporal evolution and a graph/network-based approach is suitable to model the spatial escalation. As a result, a domino evolution graph (DEG) model based on dynamic graphs is proposed in Chap. 2 to model the spatial–temporal evolution of fire-induced domino effects. In Chap. 3, a dynamic event tree is used to model the dynamic evolution of vapor cloud explosion. Besides, Monte Carlo method is integrated into the dynamic graph model (called "Dynamic Graph Monte Carlo" (DGMC)) in Chap. 4 to tackle the evolution uncertainties in domino effects. In the DGMC model, hazardous installations, humans, and ignition sources are modeled as graph nodes and the physical effects between different nodes are modeled as graph edges. The Monte Carlo method is employed to automatically update graphs and deal with uncertainties, obtaining numerical evolution results.

In terms of domino effect management, not only safety barriers but also security measures should be considered due to possible catastrophic consequences caused by intentional attacks. In decision-making on prevention and mitigation of domino effects, economic issues need to be considered because chemical companies usually face budget limitations and pursue more profit. As a result, safety and security resources are integrated into domino effect management in Chap. 5, and a cost–benefit analysis is conducted in Chap. 6 to obtain the optimal protection strategy. Besides safety and security measures, adaptation and restoration should also be considered

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to deal with unpredicted and unpreventable domino effects. Therefore, a resilience-based approach is developed in Chap. 7 in which the roles of resistance, mitigation, adaptation, and restoration in domino effect management are quantified.

8.1 Main Conclusions

(1) Conclusions on the state-of-the-art of domino effect research

Since the 1990s, increasing attention has been paid to domino effects in the process industry. In the past three decades, various methods have been developed to model and manage domino effects in the process industry. The modeling methods were divided into three categories: analytical approaches, graphical approaches, and simulation approaches. Some analytical methods-based software was developed in early research of domino effects to quantify the likelihood of domino effects. Graphical approaches, such as Bayesian network and Petri-net obtain increasing attention in recent years and can be used to map higher-order escalation of domino effects and thus estimate the probability of domino effects and the vulnerability of installations. Simulation approaches based on the Monte Carlo method can simplify probability calculation and may be used to deal with complex escalations while requiring longer calculation time. Although current methods have contributed enormously to modeling domino effects, many challenges still exist. The problems include modeling the spatial–temporal evolution of domino effects involving higher-order escalations, modeling the VCE-induced domino effects, and modeling the evolution of multi-hazardous scenarios in one domino effect. In terms of the prevention and mitigation of domino effects, various management strategies were proposed: inherent safety, management of safety barriers, emergency response, cooperative prevention, and security strategies. Safety managers may select one protection strategy or a combination of multiple strategies. These strategies with different performances and costs may be used in different stages of the entire operating life. Thus, both the protection costs and financial implications related to potential avoided losses should be considered since protection resources are always limited and essential for the company's profitability in the long term. Besides, both safety and security measures should be used to deal with intentional domino effects in which multiple failures of installations are possible. Once domino effects are inevitable, a quick repair or reconstruction may reduce the consequences of domino effects. As a result, the adaptation and restoration of chemical plants should also be considered in the whole to deal with unpredictable or unpreventable domino effects.

(2) Conclusions on risk assessment of fire-induced domino effects

In this book, a domino evolution graph (DEG) model based on dynamic graphs is developed in Chap. 2. In the model, hazardous installations are modeled as graph nodes and the escalation vectors are modeled as graph edges. The graph structure can model possible complex phenomena in spatial evolution, such as synergistic effects and parallel effects. Besides, graph updates can model the time dependencies in temporal evolution such as superimposed effects. Moreover, the model can also overcome the limitation of the probit model in higher-level escalation and rapidly obtain the evolution paths, evolution time, and the failure probabilities of installations. An illustrated case study demonstrates that the synergistic effects and the superimposed effects considered in the DEG play a vital role in domino effect evolution. The domino effect risk may be underestimated if they are ignored in domino effect modeling. The primary scenario involving the failure of multiple installations that are more likely to occur in intentional domino effects can speed up the escalation of domino effects, leading to the prevention of domino effects more difficult and more severe consequences. Since the evolution process and the damage probability of installations can be rapidly obtained using the dynamic graph approach, the developed model can be applied to realistic chemical clusters with a large number of installations, significantly supporting the decision-making on the allocation of safety and security resources.

(3) Conclusions on risk assessment of VCE-induced domino effects

Chapter 3 establishes a dynamic VCE evolution assessment (DVEA) model based on a dynamic event tree. The DVEA model integrates the dispersion process of vapor cloud and ignition uncertainty into a stochastic simulation engine (a dynamic event tree) to assess the vapor cloud explosion risk in chemical industrial areas and obtain the damage probabilities of installations exposed to VCEs and the likelihood of domino effects. Both the time dependencies in vapor cloud dispersion and the uncertainty of delayed ignitions are addressed in the DVEA model. Applying the DVEA model in a real case shows that both the time dependencies in vapor cloud dispersion and the uncertainty of delayed ignition are crucial for reflecting the characteristics of possible large VCEs and avoiding underestimating consequences. The vulnerability of installations to VCEs depends on the congestion of the plant layout and delayed ignition time (DIT). A long-delayed explosion may result in multiple-failure of installations, resulting in catastrophic disasters. The influence factors of DIT include the distance between the release position and the ignition sources, the type of ignition sources, and the ignition control measures in place. Ignition control measures in a chemical plant can decrease the ignition probability of single sources while may lead to a larger VCE and more severe consequences if the vapor cloud disperses outside the plant in which ignition sources are not fully eliminated. As a result, ignition control may be regarded as a delay measure but not as a preventive measure. Combining ignition control measures with emergency response actions may be an effective way to prevent VCEs since ignition control might provide enough time for emergency response actions to prevent VCEs.

(4) Conclusions on multiple accident scenarios in a domino effect

Based on the research of the DEG model of fire-induced domino effects in Chap. 2 and the DVEA model of VCE-induced domino effects in Chap. 3, a dynamic model called "Dynamic Graph Monte Carlo" (DGMC) is developed to model the evolution of multi-hazardous scenarios and assess the vulnerability of humans and installations exposed to such hazards. Since the DGMC model integrates dynamic graphs and Monte Carlo method, it has the advantages of both methods: graphs can provide a structure for model spatial evolution, graph update can model temporal evolution, and the random number generator in Monte Carlo simulation can deal with uncertainties in domino effect evolution. Therefore, the DGMC model can effectively model multiple hazardous scenarios that may simultaneously or sequentially occur in one domino effect. Neglecting any hazardous scenarios may underestimate the consequences of domino effects, resulting in an unreasonable allocation of safety barriers and personal protection equipment (PPE). The study results show that humans in different locations may be threatened by different hazards, thus different protection measures may be formulated for different people. A long-delayed ignition can damage multiple installations and acute toxicity of people around the release source. As a result, VCE-induced domino effects may result in more severe consequences than fire-induced domino effects. The safety distances based on fire hazards are not sufficient for the prevention of VCE-induced domino effects. People close to the release source are prone to the threat of multi-hazardous scenarios, while the distant deaths are mainly induced by acute toxicity and overpressure.

(5) Conclusions on integrated safety and security management of domino effects

Intentional attacks may lead to simultaneous accident scenarios, resulting in synergistic effects and making the prevention of domino effects more difficult than unintentional domino effects. As a result, an integrated safety and security management framework is developed in Chap. 5, considering the performance of both safety measures and security measures. This framework includes six steps: chemical plant description, threat, and hazard identification, the vulnerability of installations subject to hazards and threats, the vulnerability of installations exposed to domino effects, consequence analysis, risk treatment, and risk reduction. These measures are divided into three categories: detection measures, delay measures, and response measures. According to the functions of each protection measure and domino effect models proposed in this book, the performance of a protection strategy on domino effect risk reduction can be obtained, considering fatalities, property loss, environmental impacts, business loss, and reputation or negative publicity. Finally, the domino effect risk can be calculated and evaluated to determine whether the risk is acceptable. If the risk is unacceptable, additional protection measures should be taken until the risk is lower than the pre-defined risk tolerability criteria. According to this framework, decision-making approaches can be developed to obtain an optimal protection strategy.

(6) Conclusions on cost–benefit management of domino effects

According to the integrated management framework developed in Chap. 5, a cost–benefit management approach is established to support decision-making on protection measures. The performance of a protection strategy (a combination of different protection measures) is quantified and monetized in the cost–benefit analysis. The expected avoided loss caused by a protection strategy is considered the benefit while the investment related to the protection strategy is regarded as the cost. As a result. the disproportion factor (DF) is employed in the cost–benefit analysis to determine whether a protection strategy is recommended. Besides, an optimization algorithm called "PROTOPT" is developed to achieve the optimal strategy. The study demonstrates that multiple kinds of protection measures should be employed in chemical industrial areas since they follow the law of diminishing returns. The likelihood of threats plays a critical role in a protection strategy's benefits. Therefore the optimal protection strategy varies with different plants and different threats. The protection is profitable only when the threat likelihood is no less than the threat probability at the break-even point. At the break-even point, the protection benefit is equal to the protection cost.

(7) Conclusions on resilience management of domino effects

Domino effects may be unpreventable such as the escalation caused by simultaneous attacks or natural disasters. In that case, protection measures may not prevent domino effects. A feasible way to deal with these unpreventable domino effects is to reduce the effects on the operation of companies by adjusting operation strategies and rapidly restoring the damaged installations. Resilience is the ability of a system to resist, mitigate, adapt and recover from disruptions. As a result, enhancing the resilience of a chemical plant can promote to prevent and mitigate domino effects, adapt, and recover from the damaged situation. A resilience-based approach is thus proposed in Chap. 7 to deal with domino effects. In this chapter, a dynamic stochastic model is developed to quantify the resilience of chemical plants. A resilience evolution scenario is modeled as a dynamic process that consists of four stages: disruption, escalation, adaptation, and restoration stages. A simulation algorithm is developed to generate possible resilience evolution scenarios for obtaining chemical plant resilience. Besides safety and security measures, the developed resilience approach highlights the roles of adaptation and restoration in dealing with domino effects, which is more suitable for tackling unpredictable and unpreventable disruptions. Chemical plant resilience depends on resistance capability, mitigation capability, adaption capability, and restoration capability. Improving any of these capabilities can contribute to the prevention and mitigation of domino effects. Various resilience measures such as safety barriers in the escalation stage, speeding inventory turnover in the adaptation stage, and shortening restoration time in the restoration stage are effective for developing a more resilient chemical plant and thus reducing the likelihood and consequences of domino effects.

8.2 Recommendations for Future Research

(1) Recommendations on probit models

Probit models are used in this study for the risk assessment of domino effects and significantly impact the reasonable risk assessment results. The probit models for assessing fire-induced domino effects depend on the time to failure (TTF) of vessels exposed to fire. The common-used calculation method for TTF is developed for small vessels (atmospheric vessels: 25–17,500 m^3; pressurized vessels: 5–250 m^3). However, using large storage vessels for hazardous materials is a development trend in the process industry [2]. Besides vessel types, volumes considered in probit models, other vessel parameters such as wall thickness and wall material may also impact the vessel vulnerability. To extend the application of probit models and this study, vulnerability experiments may be used to improve the probit models. But experiments of large vessels may be expensive and dangerous, numerical simulations may be conducted using advanced consequence simulation software, such as ANSYS, FLUENT, FLACS, FDS, etc.

(2) Recommendation on uncertainty modeling in domino effects

This study develops graphical-based models for modeling the spatial–temporal evolution of domino effects, addressing the time-dependencies, ignition uncertainty, and possible multiple hazardous scenarios in domino effects. However, accurately modeling domino effects is still challenging due to the uncertainty involved in the evolution of domino effects. The uncertainty can be divided into two parts, the intensity uncertainty of hazardous scenarios and the uncertainty of propagation. The former refers to heat radiation intensity, overpressure value, and the number, weight, and velocity of fragments. The latter involves the failure likelihood of installations subject to hazardous scenarios, failure types, and the subsequent scenarios. These uncertainties may be tackled in future research to support domino effect risk assessment and management.

(3) Recommendation on modeling VCE-induced domino effects

In this study, vapor cloud dispersion is considered in VCE-induced domino effects. However, the vapor cloud dispersion model based on empirical formulas may not extend to model all possible release scenarios. Besides, the empirical model neglects VCE dilution with distance, the influences of wind velocity, and the effects of obstacles on dispersion. Thus, dynamic CFD methods may be integrated into domino effect risk assessment to obtain more accurate results in future studies. With the rapid improvement of computational resources, applying dynamic CFD methods in risk assessment may become easier and acceptable for researchers and practitioners in the future.

(4) Recommendation on domino effect management

In Chap. 6, a management approach is established to prevent and mitigate domino effects in chemical plants. However, there may be multiple chemical plants belonging to different companies in a chemical cluster. In terms of the cross-plant areas, safety and security resources allocated in one chemical plant has a benefit for nearby plants due to the mitigation of possible external domino effects while it may also relatively increase the security risk of nearby plants because of the change of attractiveness for possible common adversaries. To get the optimal strategy in a chemical plant, the protection strategies of other plants should be considered. Hence, the cost–benefit management may be extended to support decision-making on domino effects in chemical luster. Besides, the management approach proposed in this study neglects inherent safety design. Future research may consider inherent safety measures in a protection strategy to develop a life cycle management tool.

(5) Recommendations on economic aspects of safety and security

In this study, cost–benefit analysis is used to support decision-making on protection strategies. The reliability of the optimal protection obtained by economic approaches depends on the monetization of costs. However, economic data is difficult to collect and a database for economic values of accident costs and the costs of safety measures may be developed in the future. Besides, some costs are difficult to be monetized or unethical to be monetized, such as the value of human life, reputational costs, and psychological costs. Therefore, other economic approaches such as cost-effectiveness analysis may be used to reduce the monetization work. Moreover, multiple-criteria decision (MCD) may be developed to deal with these costs and multi-objective optimization may be used to obtain the optimal protection strategy.

(6) Recommendations on resilience-based approach

Chapter 7 develops a resilience-based approach for tackling domino effects, considering safety measures, security measures, adaptation measures, and restoration measures. Besides these measures, more design and operation options may be identified and quantified in the future to improve chemical plant resilience. Furthermore, the costs of different resilience measures are not considered and the benefits of resilience are not monetized. To support decision-making on resilience investment, resilience management approaches may be developed by combining the resilience quantification method developed in this study with economic tools such as cost–benefit analysis and cost-effectiveness analysis. Furthermore, the resilience quantification method developed for chemical plants may be applied to other interdependent infrastructure systems such as water supply systems and energy transportation systems. In recent decades, domino effect accidents in the process industry have raised an increasing concern in scientific and technical domains. Domino effects such as the Buncefield accident in 2005 can lead to a chain of accidents and result in more severe consequences than the primary event. The primary event can be an accident, a natural disaster, or an intentional attack. To prevent and mitigate domino effects, growing research on risk assessment and management of domino effects has been conducted in recent decades such as quantitative risk assessment of domino effects and safety barrier management for preventing domino effects. However, little attention has been paid to domino effects triggered by intentional events (intentional domino effects) such as terrorist attacks. This book thus aims to introduce advanced approaches that can model and manage both intentional and unintentional domino effects, developing a safer, securer, and more resilient process plant.

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