Samenvatting proefschrift

A Dynamic and Integrated Approach for Modeling and Managing Domino-effects (DIAMOND)

Chao Chen[1]

Summary of the dissertation

In light of the catastrophic consequences of past escalation accidents in the process industry, domino effects have raised an increasing concern in the scientific and technical domains. To prevent and mitigate domino effects, growing research on modeling and managing domino effects was conducted in recent decades. However, modeling and managing domino effects are still challenging concerning the time-dependencies and evolution uncertainties. As a result, this dissertation aims to deal with these limitations, supporting decision-making on preventing and mitigating domino effects. The contributions of this study are summarized as follows:

(1) Insights into modeling and managing domino effects in the process industry

A systematic literature review is conducted to summarize and classify the methods used for modeling and managing domino effects, analyze current research trends, and discuss future research needs. The models are divided into three categories (analytical methods, graphical methods, and simulation methods) and the management strategies are grouped into five types (inherent safety, management of safety barriers, emergency response, cooperative prevention, and security strategies). Graphical methods such as Bayesian network and graph theory are increasingly used to model domino effects. Increasing attention is paid to managing intentional domino effects and Natech domino effects. Although past work has contributed a lot to modeling and managing domino effects, many challenges are still left, such as modeling the evolution of coupled domino effects, management of domino effects in extreme conditions, integrating safety and security resources to prevent domino effects, decision-making on managing domino effects in chemical clusters.

(2) A spatial-temporal evolution model of fire-induced domino effects

A domino evolution graph (DEG) model based on dynamic graphs is established to model the spatial-temporal evolution of domino accidents triggered by fire. The proposed model extends the TTF (time to failure) to RTF (residual time to failure) to dynamically model the higher-level escalation of domino effects, considering synergistic effects, parallel effects, and superimposed effects. Ignoring these physical effects may underestimate domino effect risk because they can speed up fire escalations and thus make the control of domino effects more difficult. Compared with previous probabilistic models, the DEG model concerns more physical mechanisms and it is more flexible and visible to model the dynamic escalation process. The Minimum Evolution Time (MET) algorithm proposed for the DEG model can rapidly obtain the evolution paths, evolution time, and the failure probability of installations. Therefore, the model can be used to assess domino effects in chemical industrial areas with a large number of hazardous installations.

(3) A dynamic evolution model of VCE induced domino effects

Past risk assessment methods on VCEs ignore the effects of vapor cloud dispersion and delayed ignitions on the vulnerability of installations. In light of this limitation, a dynamic VCE evolution assessment (DVEA) model is developed based on a dynamic event tree, considering the spatial-temporal evolution of VCEs and the uncertainty of delayed ignition time (DIT). Multiple ignition sources can be considered in this model, addressing the uncertainties of ignition time and ignition position. The study shows that a long-delayed explosion may lead to multi-failure of installations, resulting in catastrophic disasters. The result is consistent with past VCE-induced domino accidents. It indicates that the DVEA model can reflect the characteristics of possible large VCEs and avoid underestimating the consequences. Besides, this study demonstrates that only using ignition control measures in chemical plants is not enough for preventing VCEs and may aggravate the consequences. Combining ignition control measures with emergency response actions (e.g., diluting oil vapor by water vapor) may be an effective way to prevent VCEs.

(4) A multi-agent evolution model of coupling domino effects

Accident analysis indicates that major accident scenarios such as acute toxicity, fire, and explosion may simultaneously or sequentially occur in a domino effect event. However, most of the previous domino effect models

[1] *Doctor of Philisophy, promotion institute: Delft University of Technology, Safety and Security Science; promotion date: May 27, 2021*

only concern one hazardous scenario in domino effects, neglecting the evolution between different hazardous scenarios. Therefore, a multi-agent approach called "Dynamic Graph Monte Carlo" (DGMC) is developed based on dynamic graphs and the Monte Carlo method to model the evolution of multi-hazardous scenarios in domino effects. In the model, chemical plants are regarded as a multi-agent system with three kinds of agents: hazardous installations, ignition sources, and humans. Hazardous effects caused by domino effects are modeled as the dependencies of agents and the evolution of domino effects is determined by the behavior of agents. This study demonstrates that the model can avoid underestimating domino effect risk since the spatial-temporal evolution of multi-hazard scenarios is addressed. The hazardous effect of VCE may be more severe than that of fire, and the safety distance designed based on fire hazard may not be sufficient to prevent domino effects triggered by VCEs.

(5) An approach for decision-making on preventing and mitigating domino effects

Previous research on managing domino effects mainly focused on the performance of safety barriers, neglecting the role of security measures in intentional domino effects. Besides, the financial issues related to the investment of safety and security measures are always ignored while the protection budget is always limited. As a result, a cost-benefit management approach is proposed to support the decision-making on the investment and allocation of domino effects. This method considers the costs of protection measures and the expected benefits obtained from the protection investment. This study finds that investment in safety and security measures follows the law of diminishing returns. The protection strategies including multiple kinds of protection measures are recommended in terms of preventing and mitigating domino effects. The likelihood of threats plays a critical role in a protection strategy's profitability, so different companies should formulate their optimal strategies based on their threats.

(6) A resilience strategy for the prevention and mitigation of domino effects

Safety barriers can be used to prevent and mitigate accidental domino effects and intentional domino effects. Security measures can be used to prevent intentional attacks and thus prevent intentional domino effects. As a result, protection strategies based on safety and security measures are always recommended for preventing and mitigating domino effects. Limited attention has been paid to mitigating the consequences of domino effects after the events. Therefore, a resilience-based approach is developed to prevent and mitigate domino effects. Besides safety and security measures, adaptation and restoration are considered for mitigating the consequences of domino effects on the operation of the companies. To support the decision-making on resilience measures, a chemical resilience indicator is developed, considering the capabilities of resistance, mitigation, adaptation, and restoration. A sensitive analysis for the indicator demonstrates that adaptation and restoration measures can effectively enhance the resilience of chemical plants, mitigating the consequences of domino effects.

In summary, this study establishes evolution models for assessing domino effects and proposes two protection strategies based on the developed models for preventing and mitigating domino effects. The developed domino effect models can contribute to a better understanding of the evolution of domino effects and the protection strategies can support the decision-making on the investment and allocation of protection measures.

The doctoral dissertation will be defended publicly on Thursday, 27 May 2021. For access to the dissertation, you can have a look in TU Delft Repository (the digital storage of publications of TU Delft): https://repository.tudelft.nl/islandora/search/?collection=research.