An Economic Approach for Domino Effect Management

Chen, Chao; Reniers, Genserik; Yang, Ming

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Chapter 6
An Economic Approach for Domino Effect Management

6.1 Introduction

Domino effects are responsible for many catastrophic disasters in the chemical and process industry,[1] such as the Buncefield accident in 2005 [3] and the Jaipur disaster in 2009 [4]. Both unintentional (safety-related) events (e.g., mechanical failure, human error, and natural disasters) and intentional (security-related) events (e.g., terrorist attacks) can lead to a domino effect.

In light of possible intentional and unintentional escalation events, Reniers and Soudan [5] proposed setting up a Multi-Plant Council (MPC) to stimulate the prevention cooperation, thus preventing and mitigating domino effects from a chemical cluster-level perspective. Reniers and Audenaert [6] provided a systematic method to reduce the potential consequences of domino effects triggered by intentional attacks. Janssens et al. [7] developed a mathematical model to optimize the allocation of safety barriers for mitigating domino effects. Landucci et al. [8] developed a model to assess the vulnerability of industrial installations and possible escalation effects triggered by homemade explosives. Zhou and Reniers [9] optimized emergency response strategies for tackling domino effects caused by multiple simultaneous fires. Hosseinnia et al. [10] proposed a matrix for decision-making on emergency response. Khakzad and Reniers [11] proposed to make some of the storage tanks empty to prevent the escalation of domino effects. Although the previous work for domino effect management has made significant progress in preventing and mitigating domino effects, economic issues are very often, if not always neglected in decision-making. Economic aspects of safety and security nonetheless play an indispensable role in the decision-making of protection strategies because companies usually have a budget for safety and security. Besides, the limited safety and security resources need to be optimized since resources allocated to one target are not available for others, which is referred to in economic literature as the "opportunity cost"

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

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[12–14]. In other words, economic issues greatly impact the effectiveness of prevention strategies and the profitability of a company in the long term [15]. Therefore, operational safety economics needs to be applied in decision-making on safety and security strategies [15]. Safety economics may be defined as a transdisciplinary and interdisciplinary field of academic research focusing on the interdependencies and coevolution of economics and safety for the trade-off between safety and economics [1]. Safety economics aims to support decision-making on safety investments to make decisions more profitable under the premise of safety criteria. It may be interpreted as balancing the costs of risks and economic benefits or balancing the costs for decreasing risks and safety benefits.

However, there is a research gap between safety economics and domino effect management due to the complexity and uncertainty of domino effect evolution, the monetization of protection costs and benefits, and insufficient information about the intelligent and strategic adversaries. Thus, this chapter develops a cost–benefit approach based on safety economics to manage domino effects in the chemical and process industry. First, safety economics is introduced in Sect. 6.2. Based on safety economics, a commonly used approach (cost–benefit analysis) is selected as a decision-making tool for managing domino effects. A cost–benefit management approach is developed in Sect. 6.3, and an optimization algorithm is presented in Sect. 6.4. The conclusions are drawn in Sect. 6.5.

6.2 Safety Economics

Safety economics can be traced back to the 1960s when economics was considered in safety [16]. From an economic perspective, safety is regarded as a resource-absorbing product or service. The objective of safety economics is to produce safety in a suitable amount and as cheaply as possible [16]. Safety economics is used to obtain a balance between safety and the cost of safety measures as well as develop an optimal combination of rewards and penalties to balance the costs of safety measures under the framework of competition and bargaining [16]. Therefore, an optimal safety strategy should minimize the sum of potential accident costs and the accident prevention costs rather than reduce the frequency and consequences of accidents to be as low as possible [17]. Besides, operational safety economics can be regarded as a decision-making tool for the safety and security of organizations [15]. According to past research, the contributions of economics on safety may be divided into three categories: (i) identifying and measuring the costs of accidents, (ii) understanding the relationship between business and safety, and (iii) achieving a trade-off between safety and other goals of an organization. Besides the economic perspective of safety, safety should also be considered in economic activities since safety risk plays a vital role in developing a sustainable economic organization [15, 18]. In terms of the feasibility of a new economic project or product, safety can be a non-negligible factor. For instance, the paradigm "safety at all costs" was proposed for nuclear plant safety in the 1980s, but it may increase questionable back fitting measures and production costs [19, 20]. As a result, safety economics may be defined as:

> A transdisciplinary and interdisciplinary field of academic research focusing on the interdependencies and coevolution of economics and safety for the decision-making between safety and economics [1].

Some approaches used in safety economics can be discussed such as risk-based optimization, minimal total safety cost approach, cost–benefit analysis, cost-effectiveness analysis, multi-objective optimization, and the game-theoretical approach.

6.2.1 Risk-Based Optimization

Risk-based optimization is a widely used approach in safety economics, considering both the costs of safety measures and risk tolerability criteria. This approach consists of three steps: risk assessment, risk management, and economic analysis, as shown in Fig. 6.1. According to this approach, the first step is to describe the system (e.g., individual and industrial company). Besides, risk acceptance criteria are determined

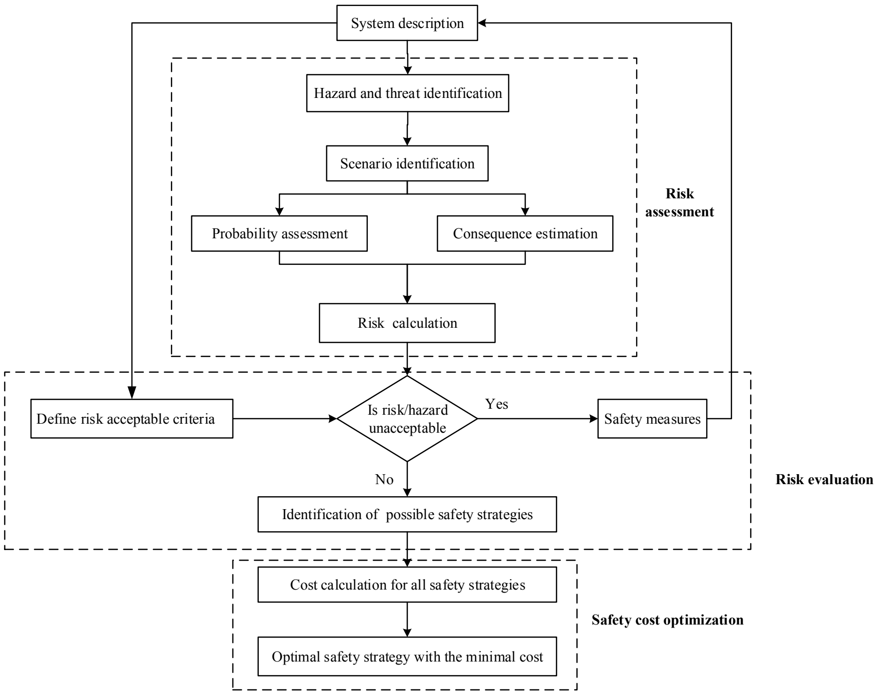

Fig. 6.1 Flowchart of risk-based optimization (Chen et al. [1])

and used to judge whether the risk of the system is acceptable. If the risk is unacceptable, additional protection measures should be implemented to make the risk following the criteria. The second step is hazard identification which is used to identify possible hazards. Many hazard identification methods are available in literature, such as HAZOP, LOPA, Checklists, and What-If analysis [21]. In terms of security risk, possible threats should also be identified in this step. Following the hazard and threat identification, possible undesired scenarios caused by these hazards and threats can be determined in the third step. Next, probabilities and consequences of each scenario need to be estimated. Some analysis methods can support the probability calculation, such as fault tree analysis, Bayesian network, and Monte Carlo simulation. Risk can be regarded as a function of the likelihood and consequence of undesired scenarios. Following the likelihood estimation and consequence analysis, the risk can be calculated. Subsequently, the risk should be evaluated based on the selected risk tolerability criteria.

The risk tolerability criteria may vary with different systems, decision-makers, or jurisdictions and may be determined by experience, standards, laws, etc. [22]. As a result, different risk criteria are available for decision-makers. For example, individual risk or societal risk criteria may be used if decision-makers are concerned more about possible fatalities than other consequences. Individual risk represents the likelihood of death if an individual is exposed to hazards. In contrast, societal risk means the cumulative probability of N fatalities (using F-N curves) given a population (a group of people) is exposed to risks [23]. Besides the individual and societal risk criteria, risk-based economic losses and environmental damage can also be applied [24]. For each risk criterion, a risk threshold may be defined to determine if the risk is acceptable. If the calculated risk is below the threshold, it is acceptable. If the calculated risk is higher than the threshold, risk reduction measures should be taken to decrease the risk under the condition of the maximum protection budget. If required protection measures are neither available nor feasible (cost-wise, operation-wise, etc.), the system may need to be discontinued.

Safety cost optimization aims to determine the optimal safety strategy with minimal costs from all the possible protection strategies obtained in a risk evaluation. The main task of this step is to calculate the costs of protection strategies. According to previous studies [15, 25], the costs may be divided into two types: direct cost and indirect cost.

The direct cost represents the investment for implementing protection measures, involving initial cost and recurring cost. The initial cost is a one-off expense that only occurs at the initial stage before implementation of the safety measures. It can be divided into two categories: initiation cost (e.g., material and design) and installation cost (e.g., labor cost and equipment cost). The recurring cost represents the ongoing expenses for operating the protection measures, including operation cost, maintenance cost, and inspection cost, etc. The initial cost and the recurring safety cost should not be directly summed since they do not simultaneously occur. To deal with this problem, a discount rate can convert the initial cost to an equivalent annual cost (EAC) or discount the recurring cost to the net present value (NPV).

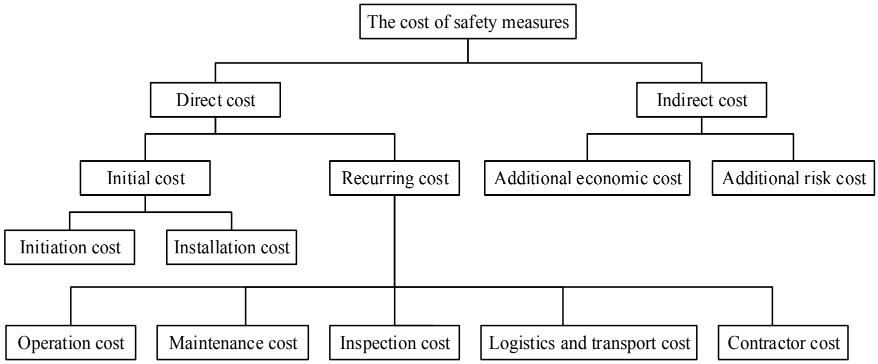

Fig. 6.2 The components of the costs of safety measures (Chen et al. [1])

The indirect cost refers to the additional economic loss and additional risk caused by protection measures. It may play a leading role in protection costs. For example, the additional economic cost (e.g., economic recession and high unemployment rate) of protection measures (e.g., social distance and face mask) for preventing Covid-19 is much higher than the direct costs for implementing these measures. Besides, these protection measures may also bring additional risks. For instance, taking a face mask may increase transportation accidents due to foggy glasses caused by the mask. In terms of a specific case, some types of costs listed in Fig. 6.2 may be neglected if they are much lower than others. According to the costs of all protection strategies, the optimal protection strategy that has the minimum cost can be obtained.

6.2.2 Minimum Total Cost Approach

In the risk-based approaches, risk acceptance criteria are used to select viable protection strategies that can make the actual risk lower than a risk threshold. Cost analysis is used to obtain the optimal protection strategy with the minimum implementation cost. In the minimum cost approach, not only the implementation cost but also the potential accident cost are considered [26]. This approach is to obtain the optimal safety strategy with the minimum total cost (the sum of the implementation cost and the accident cost). As shown in Fig. 6.3, this approach also involves hazard identification, scenario identification, probability assessment, and consequence estimation. Based on the above steps, a cost analysis can be conducted to obtain both the potential accident costs and the implementation cost of protection strategies. The total cost is obtained by summing the implementation cost of the protection strategy and the expected value of potential accident cost (based on the calculated risk) after implementing the protection strategy. As a result, the protection strategy with the minimum total cost should be selected as the optimal strategy.

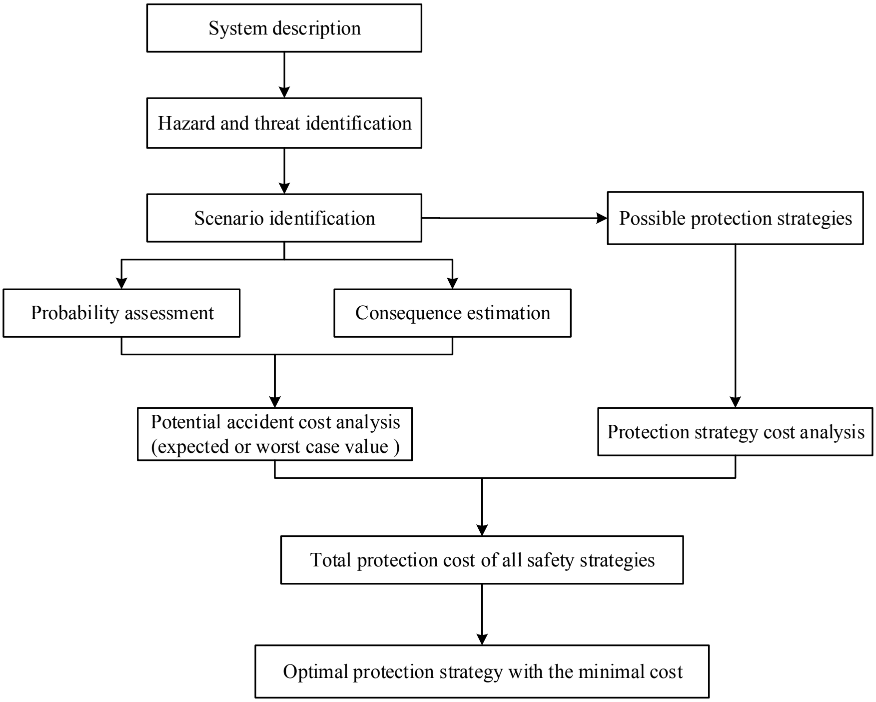

Fig. 6.3 Flowchart of the minimal total safety cost approach (Chen et al. [1])

The cost analysis for implementing a protection strategy in this approach is identical to that in the risk criteria-based approach (see Sect. 6.2.1). Thus the calculation and monetization of accident costs is the most important task in the minimum total cost approach. Many accident consequence cost calculation methods are available in literature. For instance, Sun et al. [27] divided accident costs into two categories: insured costs and uninsured costs. Besides, Gavious et al. [28] demonstrated that accident costs should consist of four sub-categories: direct costs, indirect costs, payment (the increased payment to employees), and immeasurable costs. Moreover, Reniers and Van Erp [15] divided accident costs into ten categories, as shown in Fig. 6.4.

Among the ten categories of accident costs, the cost of human loss has obtained the most attention since the value of human life is an ethical issue and thus not so easy to monetize. Since it is difficult to directly obtain the monetary value of human life, it can be indirectly monetized via those that can be directly quantified. For example, the willingness to pay (WTP) method uses the money that a company is willing to pay to reduce the risk of human loss to indirectly obtain the value of human life. Besides, the WTPs of a group of humans can be used to calculate the average individual value called the Value of a Statistical Life (VSL) [29]. The VSL is a location-based value that depends on the region (varies in 1–10 million Euros) and that may vary with

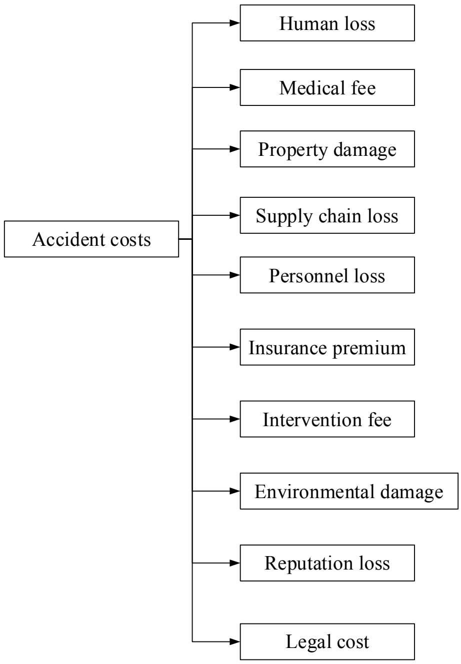

Fig. 6.4 The components of accident costs (Chen et al. [1])

time [30]. Other widely used methods include the human capital method and the Quality-Adjusted Life Years (QALY) [31].

6.2.3 Cost–Benefit Analysis

Cost–benefit analysis (CBA) is a widely used approach for decision-making on prevention strategies [13]. Figure 6.5 shows the procedure of a cost–benefit analysis approach for decision-making about protection strategies.

In a cost–benefit analysis, costs and benefits are usually represented by money to compare different options [32]. In the safety, security, and health domain, it is used to value costs and benefits and enable a broad comparison among difficult risk reduction measures, obtaining the optimal protection strategies. As a result, all costs related to the implementation of an intervention must be identified and monetarized. Similarly, all relevant benefits (usually avoided costs) caused by the intervention need to be identified and represented in monetary terms. The implementation cost of protection measures may be regarded as a sunk cost for avoiding and mitigating potential costs of undesired events. The avoided costs thus can be considered as the expected benefits of the investment in protection measures. To calculate the expected benefit of protection investments, a baseline protection strategy needs to be defined, such as the strategy “without any additional protection investment” (the so-called

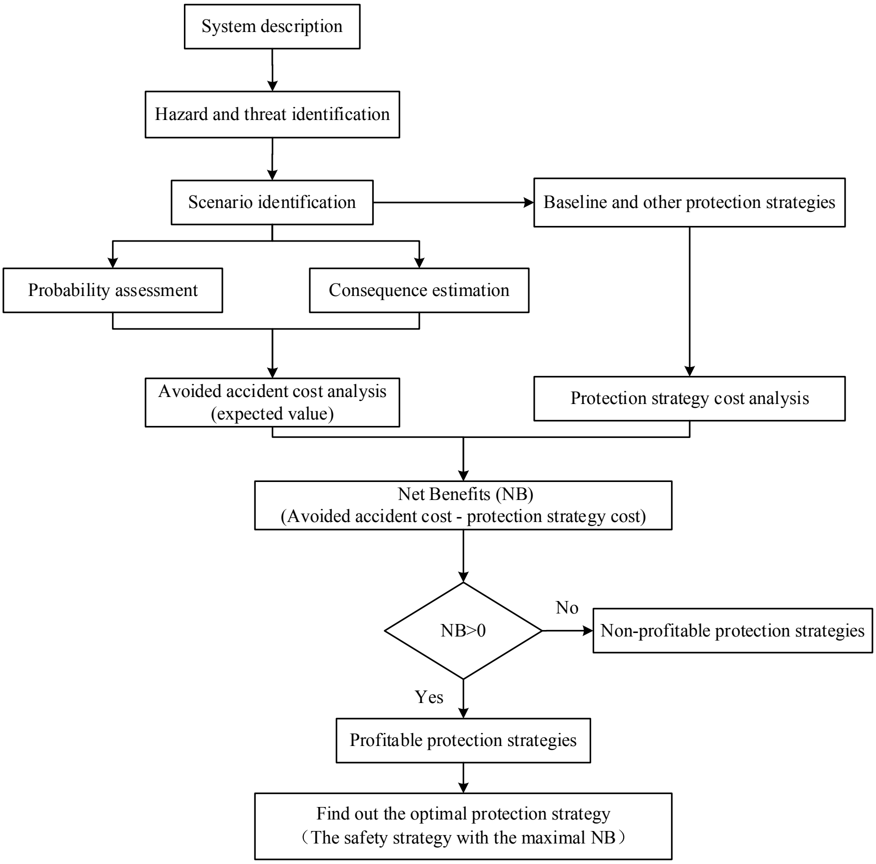

Fig. 6.5 Flowchart of cost–benefit analysis approach (Chen et al. [1])

"naked option"). As a result, the hypothetical benefit of a protection strategy can be expressed as the difference between the undesired event cost of the baseline strategy minus the undesired event cost of the protection. The net benefit of a protection strategy can be easily represented as the difference between the expected benefit of a protection strategy and the equivalent annual cost of the protection strategy. A protection strategy is profitable and may be adopted if the net benefit is larger than zero; otherwise, the protection strategy is non-profitable and may be abandoned if more profitable strategies are available. In other words, the protection strategy that has the maximum net benefit is the optimal protection strategy.

6.2.4 Cost-Effectiveness Analysis

Cost-effectiveness analysis (CEA) is a decision-making tool in which the costs and consequences of all the options are considered systematically [33]. CEA is always used in healthcare to assess specific interventions dominated by studies of prospective new interventions compared with current practice [34]. The estimation of protection costs is necessary for both the cost-effectiveness approach and the cost–benefit analysis approach. However, CBA is usually used to address those types of options that their performances can be measured by monetary values. In terms of CEA, the benefit is substituted with effectiveness analysis. In that case, CEA may be an alternative to overcome the problems associated with the monetarization of the costs related to undesired events. CEA is always used for decision-making between two different protection strategies or approving a new protection measure by estimating how much it costs to gain a unit of safety or security. Figure 6.6 illustrates a cost-effectiveness approach to determine whether a new strategy is adopted. Usually, an incremental cost-effectiveness ratio (ICER) [35] is defined as the ratio between the incremental cost (ΔC) and the corresponding incremental effectiveness (ΔE), The results of ICER can be divided into four categories: (i) If $\Delta C < 0$ and $\Delta E > 0$, the new strategy is dominant and should be recommended (less expensive and more effective); (ii) If $\Delta C > 0$ and $\Delta E < 0$, the current strategy is dominant and the new strategy (more

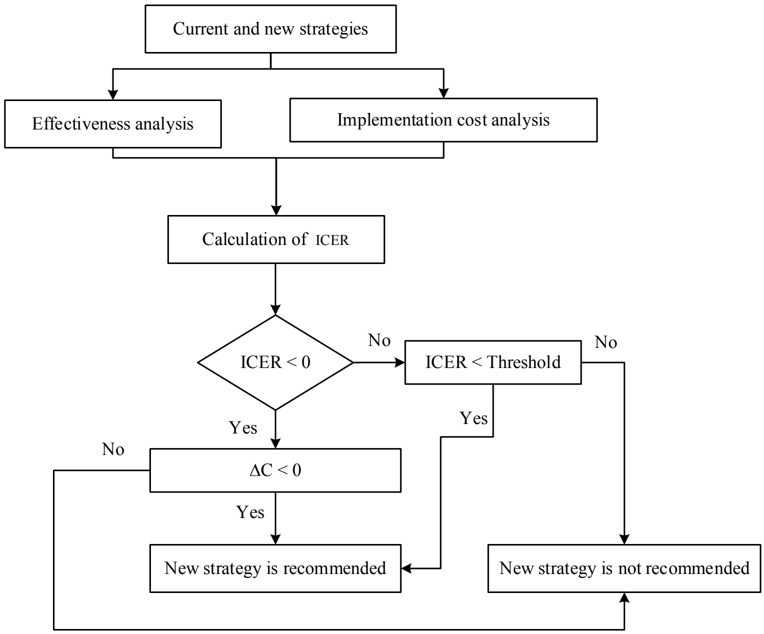

Fig. 6.6 A cost-effectiveness approach for judging whether a new strategy is adopted (Chen et al. [1])

expensive and less effective) should be rejected. (iii) If $\Delta C < 0$ and $\Delta E < 0$, it is a trade-off status in which the implementation of the new strategy can reduce implementation cost while decrease the effectiveness; (iv) If $\Delta C > 0$ and $\Delta E > 0$, it is also a trade-off status in which the implementation of the new strategy can improve effectiveness while needs more cost. In terms of the results of (iii) and (iv), a pre-determined threshold of ICER may be used to compare it with the actual ICER value. If the actual ICER is less than the threshold, the new strategy is recommended; otherwise, the new strategy is not cost-effective.

By applying the ICER, the units of protection cost and the protection outcome can be different from each other, making the CEA method more flexible than the CBA method. The protection outcome can be any indicator according to the decision-maker's preferences, such as fatalities, injuries, and the quality-adjusted life years (QALY).

6.2.5 Multi-objective Optimization

The decision-making on safety and security investment may involve multiple objectives, and the objective may be conflicting. For instance, the optimal safety and optimal economic benefit may not be simultaneously obtained since safety and economic benefits may be two conflicting objectives in the short run. As a result, multi-objective optimization may be an effective approach for balancing economic benefits and safety. Multi-objective optimization is a multiple-criteria decision-making approach to simultaneously optimize problems involving more than one objective function [36]. Multi-objective optimization has been used in inherent safety design to minimize the costs of a project and the corresponding risks [37] and minimize the operational costs in the entire life cycle [38]. In the design stage, the concept of inherently safer design can be used to reduce accident risk by using the principles such as substitution and simplification. However, the application of these principles may increase construction and operation costs. As a result, a multi-objective optimization model can be used in the design stage for optimizing the conflicting objectives: reduction of risk and construction and operation costs, as shown in Fig. 6.7.

The main task of multi-optimization is to identify and quantify the multi-objectives. As shown in Fig. 6.7, two objective functions can be obtained: (i) minimizing risk (or maximizing safety); (ii) minimizing safety cost. If we only consider one objective, a dominated solution can be obtained in which only one objective is optimal. By applying multi-objective approach and optimization algorithms (e.g., genetic algorithms and weighted sum methods), a set of Pareto solutions can be obtained. Pareto solutions refer to solutions in which there are no other solutions that can improve any objective without worsening one or more other objectives [11]. According to decision-makers' preferences, the final optimal strategy can be selected from a set of Pareto solutions. Because multi-objective optimization usually provides a set of Pareto strategies, the decision-makers need to selects the most preferred one.

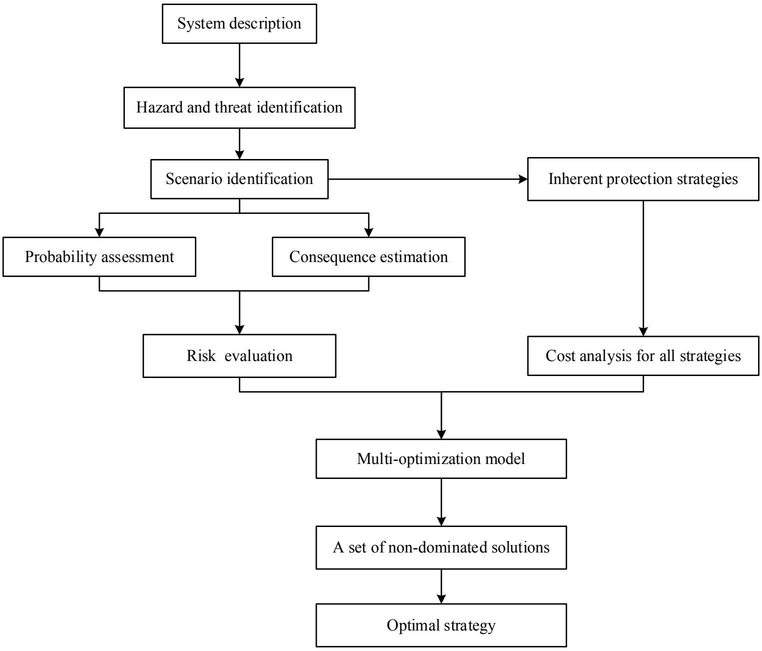

Fig. 6.7 A flowchart of a multi-optimization approach (Chen et al. [1])

Therefore, the decision-maker also plays an essential role in the optimization process, which is different from the above approaches that only have one solution.

6.2.6 Game Theoretical Approach

The preceding five methods are mainly used to deal with the decision-making problems involving only one single decision-maker. However, multiple decision-makers may be engaged in a protection investment. For instance, since the safety and security policy of a company always needs to follow the safety and security regulations, the decision-makers of the company are influenced by safety and security regulators [39]. The company may only be expected to maximize its economic benefits while the regulators aim to reduce the societal costs of undesired events. Besides, decision-making among different companies in a chemical cluster is also interdependent due to possible external domino effects [40, 41]. In own interdependent decisions, decision-makers may only want to maximize their benefits. In any case, it is very difficult to simultaneously maximize the benefits of all the decision-makers due to lack of information and myopic benefit conflicts. Nonetheless, protection decisions involving multiple decision-makers may be solved by using game-theoretical approaches.

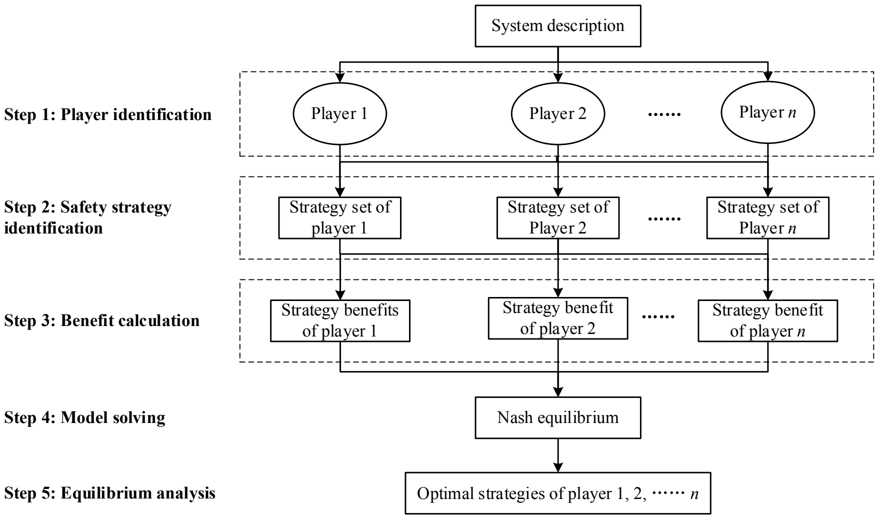

Fig. 6.8 An illustrative flowchart of a theoretical game approach (Chen et al. [1])

Game theory consists of mathematical models of strategic interaction among different decision-makers. In a game-theoretical model, decision-makers are always assumed to be intelligent and rational players who aim to maximize their benefits [42]. By solving the game, an equilibrium (trade-off) may be obtained to balance each player's benefits. Therefore, game theory may be an ideal tool for decision-making involving multiple stakeholders. Figure 6.8 shows the illustrative flowchart of a cooperative game used to achieve an optimal protection strategy.

To apply game theory in the safety and security domain, we first need to identify the stakeholders. For instance, in a chemical cluster, the players may be the chemical companies [43]. The next step is to identify the protection strategies of all players. Each player may have a set of protection strategies. Step 3 calculates the (net) benefits (objectives) of each player. In this case, possible external domino effects and safety strategies in nearby plants can be considered as well. The benefits of the players depend on all the players' motivations and strategies. In the chemical cluster case, the objective of each plant may be minimizing the total costs of damages or maximizing the net benefits. Based on the calculation of potential losses or benefits, a Nash equilibrium in which each player adopts its strictly dominant strategy may be obtained. If the equilibrium is not a pure strategy, Pareto optimal strategy of each player can be obtained.

6.3 A Cost–Benefit Analysis of Domino Effect Management

Section 6.2 introduces six economic approaches that may be used for decision-making on safety and security strategies. To deal with possible domino effects, a cost–benefit approach can be developed for decision-making on protection strategies.

6.3.1 *Protection Strategy Cost*

A protection strategy consists of one or more safety and security measures. To implement a protection strategy or update existing protection systems, a cost analysis is indispensable since the investment in protection strategies should meet a budget. In a protection cost analysis, all the costs related to choosing, developing, and implementing a protection strategy should be considered. As shown in Fig. 6.2, some protection costs consist of investments that only occur at the initial stage, such as initial costs and installation costs, and other costs that reoccur throughout the operation time of the measures [44]. The sub-categories of protection costs are described in Table 6.1.

As already mentioned, the initial cost does not need to be discounted to present values. In contrast, the costs that reoccur throughout the life of the protection measures (e.g., operation, maintenance, and inspection) should be discounted to present values [31]. As a result, the present value of costs ($PVC_{i,j}$) caused by the implementation of the j-th safety or security measure in a protection strategy i is the sum of the initiation costs, installation cost, and the discounted present value of reoccurring costs, as follows:

$$PVC_{i,j} = C_{i,j,\mathrm{ini}} + C_{i,j,\mathrm{ins}} + \frac{(1+r)^y - 1}{r_d(1+r_d)^y} C_{i,j,\mathrm{reo}} \tag{6.1}$$

Table 6.1 Categories of protection strategy costs (Chen et al. [1])

Cost category	Subcategories
Initiation	Investigation, selection and design material, training, changing guidelines, and informing
Installation	Production loss, start-up, equipment, installation team
Operation	Utility consumption and labor
Maintenance	Material, maintenance team, production loss, start-up
Inspection	Inspection team
Logistics and transport	Transport and loading/unloading of hazardous materials, storage of hazardous materials, drafting control lists, protection documents
Contractor	Contractor selection, training
Other	Office furniture, insurance

$$C_{i,j,\text{reo}} = C_{i,j,\text{ope}} + C_{i,j,\text{mai}} + C_{i,j,\text{ins}} + C_{i,j,\text{log}} + C_{i,j,\text{con}} + C_{i,j,\text{oth}} \tag{6.2}$$

where $C_{i,j,\text{ini}}$ denotes the initial costs of measure j in strategy i, $C_{i,j,\text{ins}}$ represents the installation costs of measure j in strategy i, $C_{i,j,\text{reo}}$ concerns the installation costs of measure j in strategy i, $C_{i,j,ope}$ represents the annual operation costs of measure j in strategy i, $C_{i,j,\text{mai}}$ denotes the annual maintenance costs of measure j in strategy i, $C_{i,j,\text{ins}}$ represents the annual inspection costs of measure j in strategy i, $C_{i,j,log}$ denotes the annual logistics and transport costs of measure j in strategy i, $C_{i,j,\text{con}}$ represents the annual contractor costs of measure j in strategy i, $C_{i,j,\text{oth}}$ represents the annual other costs of measure j in strategy i, r_d is the discount rate, y is the number of years that the protection measures can operate. Consequently, the cost of a protection strategy should be the sum of the cost of each protection measure, as follows:

$$PVC_i = \sum_{j=1}^{J} PVC_{i,j} \tag{6.3}$$

PVC_i represents the present value of the cost of protection strategy i, J is the total number of protection measures in protection strategy i.

6.3.2 The Costs of Domino Effects

The costs of domino effects refer to the potential financial losses caused by domino effects. The losses of domino effects should consider both the direct losses caused by the initiating accident and the losses induced by the subsequent domino effect. Possible intentional attacks and accidental scenarios that may induce domino effects should be considered. There may be multiple attack scenarios in terms of an adversary since an intelligent and strategic adversary may adapt to changing circumstances in terms of protection measures. Considering K attack scenarios and U accidental scenarios are identified in a chemical plant, the overall expected losses caused by the k-th ($k = 1, 2, 3, \ldots, K$) attack scenario and the u-th ($u = 1, 2, 3, \ldots, U$) accidental scenario can be simplified as the sum product of the installations' damage probabilities and their losses:

$$L_k = \sum_{n=1}^{N} P_{k,n} \cdot L_{k,n} \tag{6.4}$$

$$L_u = \sum_{n=1}^{N} P_{u,n} \cdot L_{u,n} \tag{6.5}$$

L_k represents the total loss caused by attack k. $P_{k,n}$ denotes the damage probability of installation n in attack scenario k, $L_{k,n}$ represents the loss of installation n in attack k; L_u represents the total loss caused by accidental scenario u. $P_{u,n}$ denotes the damage probability of installation n in accident scenario u, $L_{u,n}$ represents the loss of installation n in accident u.

The losses caused by domino effects ideally should consider fatalities, injuries, property loss, and any other influences such as psychological and political effects [45]. The casualties include not only the direct losses that are immediately visible and tangible but also the indirect losses that are intangible and invisible [15, 46]. The direct avoided losses refer to the losses caused by damage to installations, products, equipment, medical expenses, paying fines, and insurance premium rise. The indirect losses consist of capacity losses, production schemes, recruitment, and wage costs, for instance [28]. The estimation of indirect losses is more difficult than that of direct losses because they are much more hidden or invisible. If these hidden or invisible losses are ignored, the total loss caused by domino effects may be largely underestimated [46]. Nonetheless, several methods for the estimation of indirect losses are available in the literature. A straightforward method is to use the ratio of indirect to direct loss. In that case, the indirect losses can be expressed as the product of direct losses and the loss ratio. However, the ratio varies in academic literature, leading to difficulty for selecting a suitable ratio. For instance, a commonly used loss ratio of 4 was recommended based on an analysis of 7500 accidents, while a range of 1–20 was also proposed for different industrial sectors [25]. Besides, Reniers and Brijs [44] proposed eight categories of losses caused by major accidents. To address the losses related to intentional attacks, reputation costs, symbolism-, psychological-, and political financial effects may also be considered [15]. According to past studies, losses caused by domino effects can be divided into eleven categories, as shown in Table 6.2.

Table 6.2 Categories of protection costs (Reniers and Van Erp [15])

Cost category	Subcategories
Supply chain	Production, start-up, schedule
Damage	Damage to own material/property, other companies' material/property, surrounding living areas, public material/property
Legal	Fines, interim lawyers, specialized lawyers, internal research team, experts at hearings, legislation, permit, and license
Insurance	Insurance premium
Human	Compensation victims, injured employees, recruitment,
Environmental	Environmental damage and clean-up
Personnel	Productivity of personnel, training of new or temporary employees, wages
Medical	Medical treatment at the location, medical treatment in hospitals and revalidation, using medical equipment and devices, medical transport
Intervention	The service from the fire department, police department, or ambulance
Investigation	Accident investigation
Other	Reputational, symbolic, psychological, and political effects

Therefore, the loss of an installation n caused by intentional attack k ($L_{k,n}$) or accident scenario u ($L_{u,n}$) can be estimated [2], as follows:

$$L_{k,n} = L_{k,n,sup} + L_{k,n,dam} + L_{k,n,leg} + L_{k,n,ins} + L_{k,n,hum} + L_{k,n,env} + L_{k,n,per} + L_{k,n,med} + L_{k,n,int} + L_{k,n,inv} + L_{k,n,oth} \tag{6.6}$$

$$L_{u,\,n} = L_{u,n,sup} + L_{u,n,dam} + L_{u,n,leg} + L_{u,n,ins} + L_{u,n,hum} + L_{u,n,env} + L_{u,n,per} + L_{u,n,med} + L_{u,n,int} + L_{u,n,inv} + L_{u,n,oth} \tag{6.7}$$

where $L_{k,n,sup}$ represents the supply chain loss of installation n caused by attack k, $L_{k,n,dam}$ denotes the damage loss of installation n caused by attack k, $L_{k,n,leg}$ represents the legal loss of installation n caused by attack k, $L_{k,n,ins}$ denotes the insurance loss of installation n caused by attack k, $L_{k,n,hum}$ denotes the human loss of installation n caused by attack k, $L_{k,n,env}$ represents the environmental loss of installation n caused by attack k, $L_{k,n,per}$ represents the personnel loss of installation n caused by attack k, $L_{k,n,med}$ represents the medical loss of installation n caused by attack k, $L_{k,n,int}$ denotes the intervention loss of installation n caused by attack k, $L_{k,n,rep}$ denotes the reputation loss of installation n caused by attack k, $L_{k,n,inv}$ denotes the accident investigation and the cleanup loss of installation n caused by attack k, $L_{k,n,oth}$ represents other losses of installation n caused by attack k. $L_{u,n,sup}$ represents the supply chain loss of installation n caused by accident scenario u, $L_{u,n,dam}$ denotes the damage loss of installation n caused by accident scenario u, $L_{u,n,leg}$ represents the legal loss of installation n caused by accident scenario u, $L_{u,n,ins}$ denotes the insurance loss of installation n caused by accident scenario u, $L_{u,n,hum}$ denotes the human loss of installation n caused by accident scenario u, $L_{u,n,env}$ represents the environmental loss of installation n caused by accident scenario u, $L_{u,n,per}$ represents the personnel loss of installation n caused by accident scenario u, $L_{u,n,med}$ represents the medical loss of installation n caused by accident scenario u, $L_{u,n,int}$ denotes the intervention loss of installation n caused by accident scenario u, $L_{u,n,rep}$ denotes the reputation loss of installation n caused by accident scenario u, $L_{u,n,inv}$ denotes the accident investigation and the cleanup loss of installation n caused by accident scenario u, $L_{u,n,oth}$ represents other losses of installation n caused by accident scenario u.

6.3.3 Net Benefits Analysis

According to the hypothetical benefit assumption illustrated in Sect. 6.2.3, the benefits of an integrated protection strategy can be expressed as the difference between losses of domino accidents without and with the implementation of the protection strategy. To calculate the benefits of a protection strategy, a baseline ($k = 0$) can be defined as the strategy without any safety or security measures or the initial strategy before protection upgrade. Therefore, the benefits of a protection strategy i for a particular scenario can be defined, as follows:

$$B_{i,k} = L_{0,k} - L_{i,k} \tag{6.8}$$

$$B_{i,u} = L_{0,u} - L_{i,u} \tag{6.9}$$

$B_{i,k}$ represents the benefit of protection strategy i for a special attack scenario k, $L_{0,k}$ denotes the expected loss caused by attack scenario k under the protection of baseline strategy 0, $L_{i,k}$ represents the expected loss caused by attack scenario k under the protection of strategy i; $B_{i,u}$ denotes the benefit of protection strategy i for a particular accidental scenario u, $L_{0,u}$ represents the expected loss caused by accidental scenario u under the protection of baseline strategy 0, $L_{i,u}$ denotes the expected loss caused by accidental scenario u under the protection of strategy i.

In this chapter, possible intentional domino effects are considered. The attacker is assumed as a benefit maximizer aiming to maximize the damage while the defender aims to minimize the losses caused by both intentional and unintentional domino effects. According to the Stackelberg leadership model [47, 48], the defender can be considered the 'leader' who takes the prior decision on protection strategy while the adversary is regarded as the 'follower' who knows the complete protection information before launching an attack. For a protection strategy i, the adversary would adapt to the protection by selecting an attack scenario k maximizing the loss $L_{i,k}$. In other words, the benefit of a protection strategy i for intentional domino effects should be represented by the attack scenario with the minimum benefit. In that case, the total benefit of protection i for intentional and unintentional domino effects can be obtained, as follows:

$$B_i = \min_k B_{i,k} + \sum_{u=1}^{U} B_{i,u} \tag{6.10}$$

B_i represents the expected benefit of protection strategy i. Furtherly, the present value of benefits (PVB_i) of protection strategy i can be obtained, as follows:

$$PVB_i = \frac{(1 + r_d)^y - 1}{r_d(1 + r_d)^y} B_i \tag{6.11}$$

Consequently, the so-called proportion factor (PF) representing the ratio of the costs to the benefits can also be obtained [49], as follows:

$$PF_i = \frac{PVC_i}{PVB_i} \tag{6.12}$$

PF_i is compared with the disproportion factor (DF) to determine whether the protection strategy i is "grossly disproportionate" or not. A protection strategy i is usually recommended if PF_i is less than DF. The value of the DF is always no less than 3 and not more than 30 [49]. For more information on DF, the reader can be referred to Talarico and Reniers [49] and Reniers and Van Erp [15].

6.4 Optimization Algorithm

Based on the net present value of benefits (NPVB) obtained in cost–benefit analysis, we can judge whether a protection strategy is profitable. However, companies usually face budget limitations, and there may be thousands of strategies with an NPVB value greater than zero. Therefore, we need to find out the most profitable strategies from all the possible strategies under budget limitations.

The decision-making on the investment and allocation of protection measures in chemical industrial areas can be simplified, according to Reniers and Sorensen [50], as the well-known "Knapsack problem". As a result, a non-linear optimization model can be obtained as follows:

$$\begin{cases} \max\limits_{n} NPVB_i \\ C_i \le C_{\text{Budget}} \\ i = 1, 2, \ldots, I \end{cases} \tag{6.13}$$

The formula indicates that the protection strategy with the maximum *NPVB* value should be the optimal strategy, and the implementation cost of the protection strategy should not exceed the protection budget (C_{Budget}). To find out the optimization strategy, an optimization algorithm based on the "maximin" strategy called "PROTOPT" for PROTection OPTimization, is proposed to sequentially allocate protection measures, as shown in Fig. 6.9.

As shown in Fig. 6.9, the PROTOPT algorithm mainly consists of three steps: an implementation cost analysis, a benefit analysis, and an evaluation of *NPVB*. Based on all the available protection measures, we need to calculate the implementation cost of each one. The protection measure with an implementation cost lower than the budget will be the input of the second step. In the second step, the performance of each selected protection measure should be assessed based on vulnerability assessment models provided in Chaps. 2–5. Then a benefit analysis will be conducted to obtain the *NPVB* value of the protection measure. In the last step, the protection measures with the maximum *PVB* should be selected as one of the measures of the optimal strategy. The above calculation loop will continue until $PF > DF$ or the total implementation cost is greater than the budget [49]. Applying the optimization algorithm, we can obtain the optimal protection strategy under a protection budget and obtain a recommended protection cost based on *DF*.

6.5 Conclusions

Following the integrated management framework developed in Chap. 5, this chapter introduces an economic approach to support decision-making on investment and allocation of protection measures. In this chapter, some well-known economic approach methods used in the safety and security domain are presented in a nutshell, including

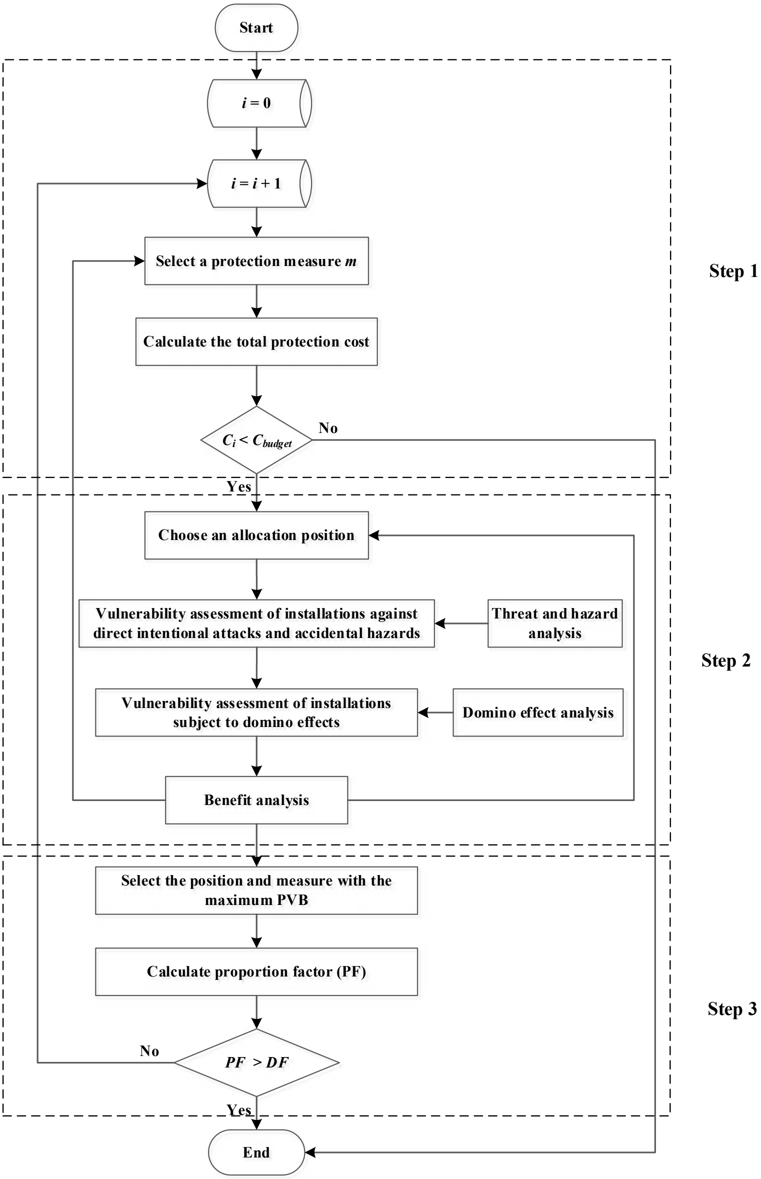

Fig. 6.9 The "PROTOPT" algorithm to achieve an optimal protection strategy (Talarico and Reniers [49] and Chen et al. [2])

risk-based optimization, minimal total safety cost approach, cost–benefit analysis, cost-effectiveness analysis, multi-objective optimization, and the game-theoretical approach. Based on a cost–benefit analysis and disproportion factor, a decision-making approach for preventing and mitigating intentional and unintentional domino effects is developed. Based on the approach, a sequential allocation algorithm is developed to obtain the optimal protection strategy under the limitation of the protection budget. If no protection budget is provided, an optimal protection budget can also be achieved by using the developed approach.

References

1. Chen C, Reniers G, Khakzad N, Yang M (2021) Operational safety economics: foundations, current approaches and paths for future research. Saf Sci 141
2. Chen C, Reniers G, Khakzad N (2020) Cost-benefit management of intentional domino effects in chemical industrial areas. Process Saf Environ Prot 134:392–405
3. Buncefield Major Incident Investigation Board (2008) The Buncefield incident, 11 December 2005: the final report of the Major Incident Investigation Board. Health and Safety Executive
4. Johnson D (2013) Vapour cloud explosion at the IOC terminal in Jaipur. Loss Prev Bull (229)
5. Reniers G, Soudan K (2010) A game-theoretical approach for reciprocal security-related prevention investment decisions. Reliab Eng Syst Saf 95(1):1–9
6. Reniers GLL, Audenaert A (2014) Preparing for major terrorist attacks against chemical clusters: intelligently planning protection measures w.r.t. domino effects. Process Saf Environ Prot 92(6):583–589
7. Janssens J, Talarico L, Reniers G, Sörensen K (2015) A decision model to allocate protective safety barriers and mitigate domino effects. Reliab Eng Syst Saf 143:44–52
8. Landucci G, Reniers G, Cozzani V, Salzano E (2015) Vulnerability of industrial facilities to attacks with improvised explosive devices aimed attriggering domino scenarios. Reliab Eng Syst Saf 143:53–62
9. Zhou J, Reniers G (2016) Petri-net based simulation analysis for emergency response to multiple simultaneous large-scale fires. J Loss Prev Process Ind 40:554–562
10. Hosseinnia B, Khakzad N, Reniers G (2018) An emergency response decision matrix against terrorist attacks with improvised device in chemical clusters. Int J Saf Secur Eng 8(2):187–199
11. Khakzad N, Reniers G (2019) Low-capacity utilization of process plants: a cost-robust approach to tackle man-made domino effects. Reliab Eng Syst Saf 191
12. Birk AM (2014) Cost-effective application of thermal protection on LPG road transport tanks for risk reduction due to hot BLEVE incidents. Risk Anal 34(6):1139–1148
13. Paltrinieri N, Bonvicini S, Spadoni G, Cozzani V (2012) Cost-benefit analysis of passive fire protections in road LPG transportation. Risk Anal 32(2):200–219; discussion 220–203
14. Poole RW (2008) Toward risk-based aviation security policy. OECD/ITF Joint Transport Research Centre Discussion Paper
15. Reniers GL, Van Erp HN (2016) Operational safety economics: a practical approach focused on the chemical and process industries. Wiley
16. Spengler J (1968) The economics of safety. Law Contemp Probs 33:619
17. Oi WY (1974) On the economics of industrial safety. Law Contemp Probl 38(4):669–699
18. Chen C, Reniers G (2020) Chemical industry in China: the current status, safety problems, and pathways for future sustainable development. Saf Sci 128
19. Kröger W, Fischer P (2000) Balancing safety and economics. Nucl Eng Des 195(1):101–108
20. Annas GJ (1983) Nuclear power: safety and economics. Am J Public Health 73(9):1099–1100
21. Chen C, Reniers G (2018) Risk assessment of processes and products in industrial biotechnology. Adv Biochem Eng Biotechnol

22. Taylor JR (2003) Risk analysis for process plant, pipelines and transport. Routledge
23. Cozzani V, Gubinelli G, Antonioni G, Spadoni G, Zanelli S (2005) The assessment of risk caused by domino effect in quantitative area risk analysis. J Hazard Mater 127(1–3):14–30
24. Jonkman SN, van Gelder PHAJM, Vrijling JK (2003) An overview of quantitative risk measures for loss of life and economic damage. J Hazard Mater 99(1):1–30
25. Dorman P (2000) The economics of safety, health, and well-being at work: an overview. ILO Geneva
26. Baladeh, A. E., Cheraghi, M., & Khakzad, N. (2019). A multi-objective model to optimal selection of safety measures in oil and gas facilities. Process Safety and Environmental Protection, 125, 71–82.
27. Sun L, Paez O, Lee D, Salem S, Daraiseh N (2006) Estimating the uninsured costs of work-related accidents, Part I: A systematic review. Theor Iss Ergon Sci 7(3):227–245
28. Gavious A, Mizrahi S, Shani Y, Minchuk Y (2009) The costs of industrial accidents for the organization: developing methods and tools for evaluation and cost–benefit analysis of investment in safety. J Loss Prev Process Ind 22(4):434–438
29. Arends BJ, Jonkman SN, Vrijling JK, van Gelder PHAJM (2005) Evaluation of tunnel safety: towards an economic safety optimum. Reliab Eng Syst Saf 90(2–3):217–228
30. Aven T (2015) Risk analysis. Wiley
31. Chen C, Reniers G (2020) Economic approaches for making prevention and safety investment decisions in the process industry
32. HSE principles for Cost Benefit Analysis (CBA) in support of ALARP decisions. https://www.hse.gov.uk/managing/theory/alarpcba.htm#:~:text=CBA%20aids%20the%20decision%20making,a%20comparison%20of%20like%20quantities.&text=For%20many%20ALARP%20decisions%2C%20the,costs%20and%20benefits%20may%20suffice. Accessed 12 March 2021
33. Levin HM (1995) Cost-effectiveness analysis. Int Encycl Econ Educ 2:381–386
34. Murray CJ, Evans DB, Acharya A, Baltussen RMJHe (2000) Development of WHO guidelines on generalized cost-effectiveness analysis. 9(3):235–251
35. Briggs A, Fenn P (1997) Trying to do better than average: a commentary on 'statistical inference for cost-effectiveness ratios.' Health Econ 6(5):491–495
36. Miettinen K (2012) Nonlinear multiobjective optimization, vol 12. Springer Science & Business Media
37. Eini S, Shahhosseini HR, Javidi M, Sharifzadeh M, Rashtchian D (2016) Inherently safe and economically optimal design using multi-objective optimization: the case of a refrigeration cycle. Process Saf Environ Prot 104:254–267
38. Ramadhan NJ, Wan YK, Ng RTL, Ng DKS, Hassim MH, Aviso KB, Tan RR (2014) Life cycle optimisation (LCO) of product systems with consideration of occupational fatalities. Process Saf Environ Prot 92(5):390–405
39. Gao Y, Fan Y, Wang J (2020) Assessing the safety regulatory process of compliance-based paradigm in China using a signalling game model. Saf Sci 126
40. Reniers GLL, Dullaert W, Ale BJM, Soudan K (2005) Developing an external domino accident prevention framework: Hazwim. J Loss Prev Process Ind 18(3):127–138
41. Hosseinnia B, Khakzad N, Reniers G (2018) Multi-plant emergency response for tackling major accidents in chemical industrial areas. Saf Sci 102:275–289
42. Myerson RB (2013) Game theory. Harvard University Press
43. Reniers G, Pavlova Y (2013) Using game theory to improve safety within chemical industrial parks. Springer
44. Reniers G, Brijs T (2014) Major accident management in the process industry: an expert tool called CESMA for intelligent allocation of prevention investments. Process Saf Environ Prot 92(6):779–788
45. Stewart MG, Mueller J (2011) Cost-benefit analysis of advanced imaging technology full body scanners for airline passenger security screening. J Homel Secur Emerg Manag 8(1)
46. Jallon R, Imbeau D, de Marcellis-Warin N (2011) Development of an indirect-cost calculation model suitable for workplace use. J Saf Res 42(3):149–164

47. Kroshl WM, Sarkani S, Mazzuchi TA (2015) Efficient allocation of resources for defense of spatially distributed networks using agent-based simulation. Risk Anal 35(9):1690–1705
48. Pita J, Jain M, Ordóñez F, Tambe M, Kraus S, Magori-Cohen R (2009) Effective solutions for real-world stackelberg games: when agents must deal with human uncertainties. In: Proceedings of the 8th international conference on autonomous agents and multiagent systems-Volume 1. International Foundation for Autonomous Agents and Multiagent Systems, pp 369–376
49. Talarico L, Reniers G (2016) Risk-informed decision making of safety investments by using the disproportion factor. Process Saf Environ Prot 100:117–130
50. Reniers GL, Sorensen K (2013) An approach for optimal allocation of safety resources: using the knapsack problem to take aggregated cost-efficient preventive measures. Risk Anal 33(11):2056–2067