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Operational safety economics: Foundations, current approaches and paths for future research

Chao Chen [a], Genserik Reniers [a,b,c,*], Nima Khakzad [d,*], Ming Yang [a,*]

[a] Safety and Security Science Group, Faculty of Technology, Policy and Management, TU Delft, Delft, The Netherlands
[b] Faculty of Applied Economics, Antwerp Research Group on Safety and Security (ARGoSS), University Antwerp, Antwerp, Belgium
[c] CEDON, KULeuven, Campus Brussels, Brussels, Belgium
[d] School of Occupational and Public Health, Ryerson University, Toronto, Canada

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ABSTRACT

Due to the COVID-19 pandemic in 2020, the trade-off between economics and epidemic prevention (safety) has become painfully clear worldwide. This situation thus highlights the significance of balancing the economy with safety and health. Safety economics, considering the interdependencies between safety and micro-economics, is ideal for supporting this kind of decision-making. Although economic approaches such as cost-benefit analysis and cost-effectiveness analysis have been used in safety management, little attention has been paid to the fundamental issues and the primary methodologies in safety economics. Therefore, this paper presents a systematic study on safety economics to analyze the foundational issues and explore the possible approaches. Firstly, safety economics is defined as a transdisciplinary and interdisciplinary field of academic research focusing on the interdependencies and coevolution of micro-economies and safety. Then we explore the role of safety economics in safety management and production investment. Furthermore, to make decisions more profitable, economic approaches are summarized and analyzed for decision-making about prevention investments and/or safety strategies. Finally, we discuss some open issues in safety economics and possible pathways to improve this research field, such as security economics, risk perception, and multi-criteria analysis.

1. Introduction

It has been witnessed in the COVID-19 pandemic that governments are often not able to minimize both deaths due to the coronavirus and economic loss (Anderson et al., 2020). Prevention measures such as quarantine, social distancing, and isolation have been demonstrated to effectively contain the extent of the epidemic although they are tough to follow and maintain by a majority of the population. In China, the effectiveness of implementing these measures has been undeniable. Nonetheless, the economic costs of the pandemic and its needed mitigation measures in China are also very high (keeping mortality as low as possible is the highest priority in China). China's GDP decreased by 6.8% in the first quarter of 2020, compared with the same period last year (Wang and Yao, 2020). The COVID-19 pandemic thus highlights the role of economic factors on decisions regarding the prevention and mitigation of undesired events such as pandemics, accidents, and natural disasters.

Safety (safety-I) can be considered a condition related to the absence of accidents, losses, etc. (Leveson, 2004). Therefore, safety science aim to prevent or minimize the losses from accidents such as casualties, and damage to installations and the environment. Safety could also be understood as the antonym of risk, and "safe" can be considered a condition or situation characterized by an acceptable risk (Aven, 2014). Besides, Hollnagel (2014) defines safety (Safety-II) as the ability to succeed by performance variability and adaptation under expected and unexpected conditions. Safety I always focus on "why things go wrong" while Safety-II concerns more on "why things go right". In that case, the purpose of safety science is to increase the probability of intended and acceptable outcomes as high as possible. Whether it is to avoid losses, reduce risks, or increase intended and acceptable outcomes, external (safety) methods and measures should be taken to obtain those objectives since safety does not naturally accompany human and production activities (Chen et al., 2021; Yang et al., 2018, 2020, Zeng et al., 2020, 2021). For example, there are many risk reduction strategies in the chemical industry, including inherent safety, passive barriers, active barriers, emergency procedural barriers, safety culture, safety

* Corresponding authors at: Jaffalaan 5, Delft 2628 BX, The Netherlands.
E-mail addresses: g.l.l.m.e.reniers@tudelft.nl (G. Reniers), nima.khakzad@ryerson.ca (N. Khakzad), m.yang-1@tudelft.nl (M. Yang).

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education, etc. (Khan and Amyotte, 2003; Reniers et al., 2011; Chen et al., 2020b). A set of methods, principles, and practices has been developed over the past century to identify and eliminate risks, avoid losses, and obtain acceptable outcomes.

Economics is a social science, including microeconomics and macroeconomics (Frisch, 1933). Macroeconomics focuses on aggregate economic quantities such as national output, unemployment, and economic growth. In contrast, microeconomics is concerned with the behavior of individual economic units, such as consumers, workers, and individual organizations. Economic analysis can be used throughout society, such as individuals, enterprises, governments, financial institutions, and non-profit organizations (Ge et al., 2020, 2021). Enterprises use microeconomics to pursue more economic benefits and induce costs. Governments always apply macroeconomics to increase economic growth, reduce unemployment rates, and use microeconomics for investment in health, education, etc. Even non-profit organizations need to use economic analyses to control costs and maximize their utilities. Economists generally assume that all decisions are made in a "rational" manner. As a result, the calculation of costs and benefits plays a crucial role in economic reasoning by estimating the likelihood and consequences of each possible outcome based on different decisions (Dorman, 2000).

Economics reminds us that safety resources are always limited, and the resources allocated to one investment are not available for others (Poole, 2008). The investment in safety is twofold: on one hand, it can be seen as an increase in production costs, and on the other hand, it can also save costs by avoiding accident losses. Economic analysis can facilitate the decision-making on prevention investment and optimize the avoidance of costs related to losses, leading to business strategies of long-term profitability and sustainability and intrinsically healthy organizations (Reniers and Van Erp, 2016). Swinbank (1993) analyzed the complex economic issues to balance the 'costs' and 'benefits' of increased food safety. Evans (2013) reviewed the statistics and economics of railway safety in developed countries and found that improving the financial health of the operators contributed can improve safety. In the chemical industry, many economic tools such as cost-benefit analysis and cost-effectiveness analysis have been used to support decision-making regarding safety investments (Reniers and Sorensen, 2013; Yuan et al., 2015; Eslami Baladeh et al., 2019; Chen et al., 2020a). Besides, economic models applied to security-related studies can provide insights into the motivation and strategy of terrorists from an economic perspective (Blomberg et al., 2004; Brück, 2007; Hausken, 2018; Misuri et al., 2018; Khakzad and Reniers, 2019). Moreover, many studies on health care also benefit the research on safety economics. For instance, Perry-Duxbury et al. (2019) summarized the research on the value of safety using questionnaires in health care. These methods for the value of safety may have been or can be used in the safety domain. The review work conducted by Niven (2002) on the application of health economics is also helpful for the application of safety economics. Moreover, the work on cost-effectiveness threshold in health care (Thokala et al., 2018; van Baal et al., 2019) may promote cost-effectiveness analysis in the safety domain.

Although the economic aspects of safety have been discussed in different domains, and economic tools have been used for decision-making on safety investments, many fundamental issues of safety economics have not been systematically investigated, such as the definition of safety economics and why safety economics is important. Thus, this study aims to study the fundamental issues of safety economics and put forward pathways for future safety economics scientific research. The outline of this paper is as follows. Section 2 defines the science field of safety economics, while Section 3 discusses the motivations of safety economics. Section 4 illustrates the main approaches that may be used in safety economics. A discussion of open-issues in future safety economics scientific research is provided in Section 5, and conclusions drawn from this study are presented in Section 6.

2. Safety economics

2.1. The origin of safety economics

Academic research focusing on safety economics can be traced back to the 1960 s when economics was considered one of the dimensions of safety (Spengler, 1968). Spengler (1968) proposed two tasks of safety economics: (i) to obtain an optimal balance between safety itself and the cost of providing the safety and (ii) to develop an optimal combination of rewards and penalties to balance the costs of safety measures under the framework of competition and bargaining. In that case, safety is regarded as a resource-absorbing product or service. Thus, the objective of safety economics is to produce safety in a suitable amount and as cheaply as possible (Spengler, 1968). Unlike traditional safety, safety economics considers more on the costs of safety measures. As a result, an optimal safety strategy (a combination of one or more than one safety measure) 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 (Oi, 1974).

In terms of operational safety, economic analysis can contribute to our understanding and management of safety (Dorman, 2000). The contributions of economics on safety may be divided into three categories: (i) identifying and measuring the economic costs of accidents, (ii) understanding the relationship between business and safety, and (iii) achieving a trade-off between safety and other goals of a company. Reniers and Van Erp (2016) considered operational safety economics as a tool to make decisions that are as good as possible (or "optimal") for organizations. Besides, the economics of operational safety can be used as a predictive instrument for individuals or organizations in the future, resolving consistency problems with risk analysis, utility theory, and risk acceptability, etc. (Reniers and Van Erp, 2016). Consequently, the concept of costs plays an essential role in the economics of operational safety (Dorman, 2000; Kankaanpaa et al., 2008). The costs mainly consist of the costs of safety measures and costs of accident scenarios (hypothetical and real).

Besides applying economics in safety, safety should be considered in economic activities since safety risk may be an obstacle to the sustainable development of economic organizations (Reniers and Van Erp, 2016). For instance, the concept "safety by design" (van de Poel and Robaey, 2017) addresses safety issues in the design phases of new technologies or equipment to enhance inherent safety and to ensure sustainability and long-term profitability. Besides, safety can be an essential factor for the feasibility of a new economic project such as nuclear power stations. In the 1980s the paradigm 'safety at all costs' was proposed for nuclear plants, but it may lead to questionable back fitting measures and the increase of production costs (Annas, 1983; Kröger and Fischer, 2000).

2.2. The concept of safety economics

In light of the past research on safety economics, in this study, safety economics is 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.

To further elaborate the definition of safety economics, a schematic diagram of the relationships among safety, economics, and safety economics is presented in Fig. 1. Fig. 1a represents a situation in which safety and economics are entirely independent, and the relationships between safety and economics are not considered in decision-making. For instance, Germany decided to shut down all nuclear power plants at the end of 2022 in light of the Fukushima disaster in 2011 (Bruninx et al., 2013). The decision mainly concerns the safety risks of nuclear power and neglects its economic benefits.

Fig. 1b shows the primary stage of safety economics. In this stage, the relationship between safety and economics are roughly considered such as safety distance based design (Gupta and Edwards, 2002). The diagram

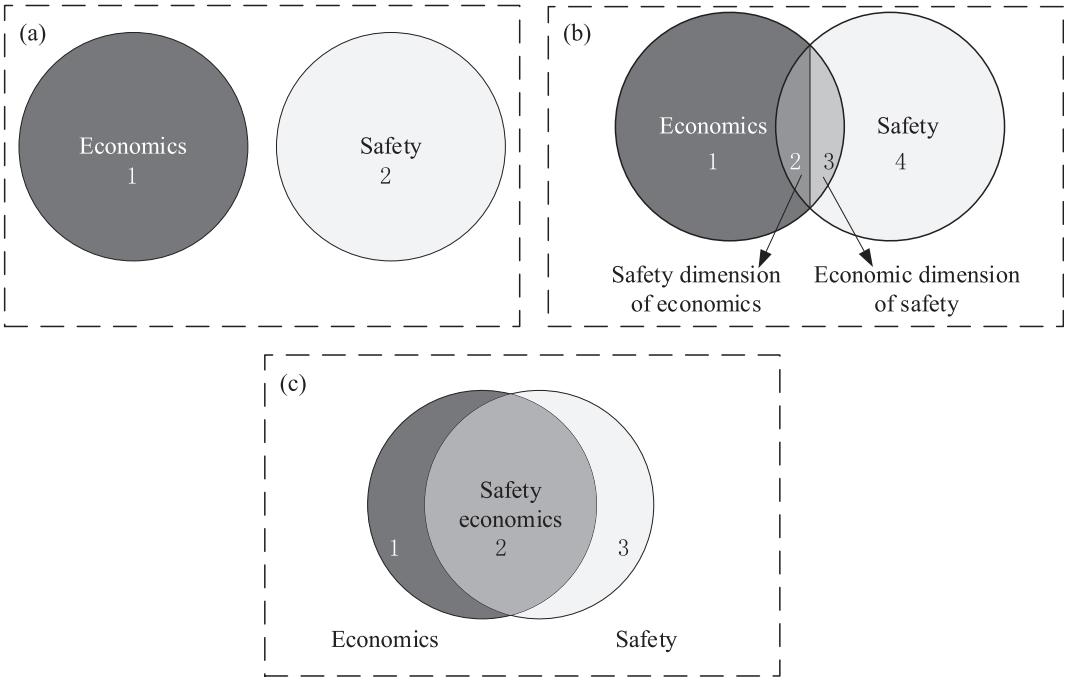

Fig.1. The relationships among safety, economics, and safety economics.

is divided into four parts (labeled as 1, 2, 3, and 4). Part 1 represents the economics without safety in which safety is not a factor to consider. Part 4 denotes the safety without economics in which economic aspects of safety are neglected. The intersection of the two circles (Parts 2 and 3) represents the interdependencies between safety and economics. Safety economics in this stage may be interpreted in two different dimensions: the safety dimension of economics (SDE) (e.g., considering safety distance in the layout design of chemical plants) and the economic dimension of safety (EDS) (e.g., considering safety budget in safety decision-making). Part 3 presents the SDE in which safety issues are considered in economic analysis to obtain long-term profitability and to improve sustainability. Alternatively, Part 2 presents the EDS in which economic factors are addressed in safety analysis to make safety-related decision-making more profitable.

Fig. 1c shows the ideal condition in which safety economics is established by integrating safety science and economics (Part 2), and it may also be regarded as an interdisciplinary field of decision-making. The research objects of safety economics can impact individuals and/or any economic entity concerned with safety. The objective of safety economics is to support decision-making on safety investments to make decisions more profitable within the frame of acceptable risk. It can be interpreted as balancing the costs of risks and economic benefits from an SDE viewpoint and balancing the costs for decreasing risks and safety benefits from an EDS perspective. Whether it is EDS or SDE, the critical issue is to model the interdependencies between economics and safety, that is, the link between safety and economics.

2.3. *The link between safety and economics*

Unsafety obviously can result in undesired events. The costs of an undesired event may be fatalities, economic losses, environmental damages, damage to reputation, etc. Consequently, safety (safety measures) may be regarded as a product or service to avoid these costs, while purchasing these safety measures also needs costs. Economic activity such as applying new technology can bring economic benefits, but safety risks may occur due to the new technology, resulting in potential costs. As a result, the costs can be a link between safety and economics, and modeling the costs of unsafety and safety measures is the primary task of safety economics. In safety science, the costs are always divided into two categories: “economic costs” that can be directly represented by money and “non-economic costs” that cannot directly be monetized, such as fatalities and environmental damages. In safety economics, both economic costs and non-economics costs may be monetized. Although the monetary value of non-economic costs cannot be obtained directly, it can be derived from those matters that can be directly monetized. For instance, human life value could be obtained by methods such as the human capital approach, the value of statistical life, and the willingness to pay method (Reniers and Van Erp, 2016). Based on monetary costs, economic analysis tools such as cost-effectiveness analysis can be used to support decision-making in safety management, and economic investments.

3. Why safety economics?

In the present study, safety economics is considered to be an interdisciplinary concept for combining safety and economics. Although it is only part of safety or economics, it indeed plays a valuable role in both safety management and economic decision-making. This section analyzes the motivations for safety economics and thus explores the role of safety economics in safety management and economic decision-making.

3.1. *Improving safety awareness*

People’s awareness and attitudes towards safety largely determine their behaviors and strategies for dealing with risks at work and in daily life. Many traditional methods are usually taken to raise employees’ safety awareness, such as education, training, safety laws, and regulations. The casualties in past accidents are often used in safety education for warning employees to follow safe practices and procedures. This kind of thought- forward and down-to-earth education may improve employees’ safety awareness better than the theoretical information provided by leadership. Moreover, managers may sometimes be more concerned with economic benefits since they may not be exposed to the risks. For instance, many large accidents occurred due to managers pursuing economic benefits while neglecting potential accident risks. On June 13, 2020, an LPG truck explosion in Wenling, China, led to 20

fatalities, and more than 170 injures. Although the company that owned the truck had been penalized 11 times by safety supervision authorities, it did not take adequate measures to decrease certain risks. This company may be held responsible for this accident. It may need to pay a tremendous amount of money to compensate for the victims, injuries, and nearby residents suffered from economic losses due to property damage. If the possible costs could have been calculated and conveyed to the company before the accident, the company management or leadership would have paid more attention to long-term economic benefits than pursuing economic benefits at the cost of potential accident scenarios. As a result, safety economics can remind people that specific accident scenarios may result in substantial economic costs, and paying more attention to safety can ensure long-term benefits.

3.2. Optimization of safety measures

Safety is not of no cost, and the investment in safety will inevitably reduce the investment in other activities. This phenomenon is known as "opportunity cost" (Green, 1894). Since there is always a budget limit for safety measures, it is impossible to take safety measures at all costs. The amount of an investment in a certain measure is not available for other measures (Reniers and Van Erp, 2016). Besides, the investment in safety measures usually follows the law of diminishing marginal returns, that is, the marginal benefits (e.g., reduced risk) gained from one unit of safety measure decreases with the incremental increase of the single measure (Chen et al., 2020a). As a result, safety economics may be used to optimize safety investments, maximize safety benefits, and avoid the waste of resources. Moreover, safety economics may provide an economic criterion for selecting safety measures, finding out the most "profitable" or the most cost-effective prevention strategies.

3.3. Tracking the conflicts between safety and economics

Safety may seem to be an obstacle to economic activity, resulting in side effects on production, etc. Conversely, blindly pursuing economic benefits may increase accident risk and may harm safety. For example, a lower flow rate may be recommended for the loading and unloading operation of flammable liquids to avoid charge accumulation (static electricity) in the pipeline or storage tank. However, it undoubtedly reduces the effectiveness of the operation, resulting in economic losses. As a result, there is a need to find a balance between the flow rate and the ignition risk caused by static electricity. A more impressive case that directly reflects the conflicts between safety (health) and economics is the infection prevention and control of Covid-19. A strict prevention or mitigation measure may lead to impacts on economics (e.g., the shutdown of a business, the rise of the unemployment rate) and mental health problems (e.g., fear and anxiety), while a lenient measure may result in a rapid epidemic spread, more fatalities, and perhaps social panic. The governments have to trade-off between economic developments and epidemic prevention based on risk assessment and economic analysis. These decision-making issues are beyond the scope of either safety or economics in which safety economics combining safety and economics can be a feasible solution.

3.4. Safety and the "license to operate" of technologies and industries

The development of new technologies or industries can bring about economic benefits, while it may also lead to new safety risks. These risks may be an obstacle to the sustainable development of the technology or industry if insufficient attention is paid to safety. For instance, China's chemical industry developed rapidly in the last two decades and became the largest in 2011 in the world (Chen and Reniers, 2020a). The development created more than 5 million jobs and 1.5 trillion dollars in 2017 (EMIS, 2019). However, thousands of chemical companies in China have been forced to close due to safety risks caused by too rapid development. Unlike the chemical industry in China, the sustainability of the nuclear energy industry in Europe is challenged due to the nuclear power phase-out policy (Bruninx et al., 2013). The policy was issued given the severe consequences caused by past accidents, such as the Three Mile Island accident in the United States in 1979, the Chernobyl nuclear accident in Ukraine in 1986, and the Fukushima catastrophe in Japan in 2011. Safety and economics thus obviously play dominant roles in the development of nuclear power and the chemical industry, and they are linked to the license to operate.

3.5. Comprehensive evaluation of accident consequences

An accident may result in different kinds of losses. Different units are used to measure different losses: the number of fatalities, the number of injuries, the economic losses caused by the damage to properties and the contaminated area, etc. Consequently, it is difficult to determine the severity level of accidents. For instance, accidents in China are subjectively divided into four levels (I, II, III, IV) based on multiple thresholds of fatalities, injures, and economic losses (Wang et al., 2018; Chen et al., 2020b). Due to different loss units, the prevention of accident losses may be regarded as a multi-objective issue, making safety management more complicated. Similarly, multi-objective optimization was widely used to deal with seemingly conflicting objectives such as safety and costs (Busacca et al., 2001; El-Halwagi et al., 2013; Khakzad and Reniers, 2015). In safety economics, the monetization of different kinds of losses can provide a comprehensive evaluation index for the severity of accidents and bridge the gap between safety and economics. In that case, many traditional economic analysis methods may be used in safety economics, as illustrated in the following section.

4. Approaches in safety economics

In Section 3, we highlighted the roles of safety economics in safety and economics to answer "why do we need to study safety economics?" This section will illustrate the possible approaches for safety economics in order to shed light on "how to use safety economics?"

4.1. Risk-based optimization

In safety economics, a common-used method is risk-based safety optimization in which the costs of safety measures and risk acceptance criteria are considered. This approach consists of three steps: risk assessment, risk management, and economic analysis, as shown in Fig. 2.

According to this approach, the first step is to describe the system. The system can be any individual, organization, company, etc. Risk acceptance criteria should be determined and used to judge whether the system risk is acceptable or not. If the risk is acceptable, then it is allowed to be operated. Otherwise, safety measures should be taken to reduce the risk. The acceptability of risk may vary within different systems or jurisdiction, and it can be determined by experience, standards, laws, etc. (Taylor, 2003). Hazard identification is the first step of risk assessment in which possible hazards should be identified. Hazard identification can be conducted by different methods, such as HAZOP, Checklists, and What-If analysis. Following the hazard identification, possible accident scenarios can be identified for risk assessment. According to the identified accident scenarios, the likelihood of each scenario needs to be estimated. Many methods can be used to support probability estimation, such as Fault tree, Bayesian network, and Monte Carlo simulation. Risk, as a combination of probability and consequence estimation, should be evaluated based on the relevant acceptance criteria.

Different risk criteria are available for decision-makers. For example, individual risk or societal risk criteria may be used if the decision-makers want to focus on possible fatalities caused by accident scenarios. Individual risk represents the likelihood of death if an individual is exposed to hazards. The societal risk, on the other hand, represents the

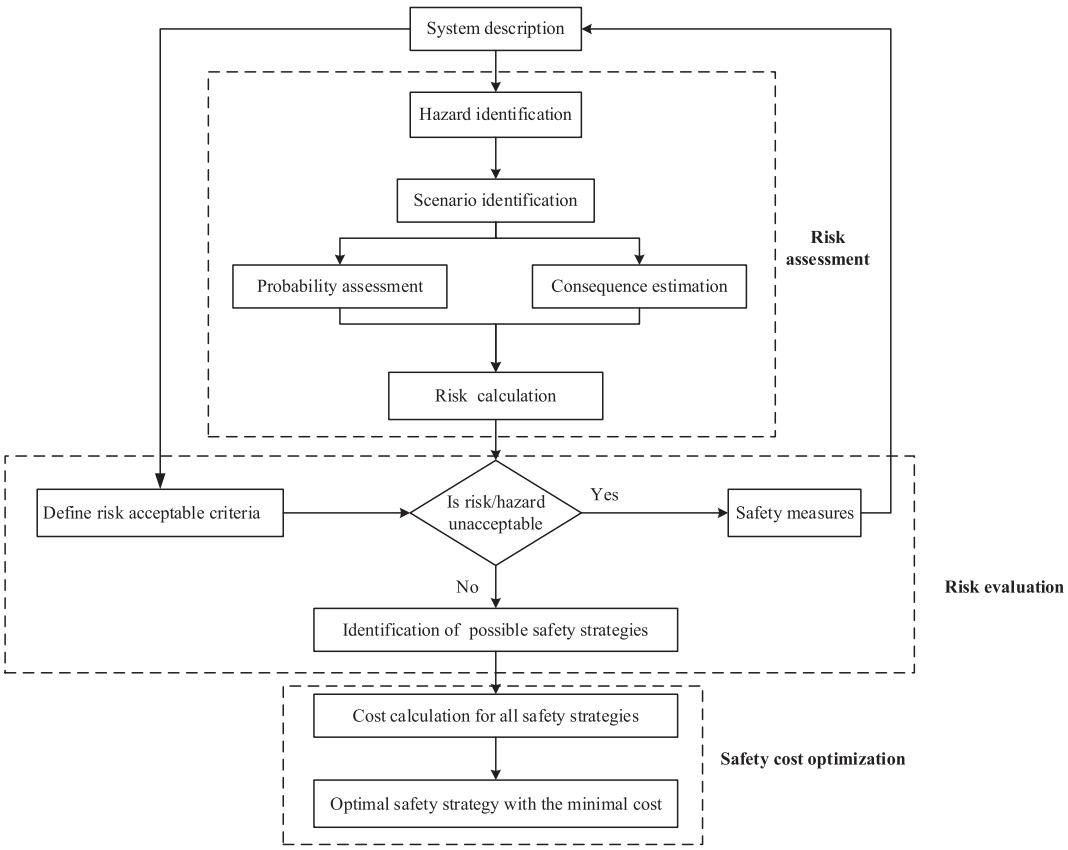

Fig. 2. Flowchart of risk-based safety optimization.

cumulative probability of N fatalities (using F-N curves) given a population is exposed to risks. Besides the individual and societal risk criteria, risk-based economic losses and environmental damage can also be applied (Jonkman et al., 2003). For every risk criterion, risk thresholds 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, measures should be taken to reduce the risk based on available and feasible safety measures. If required safety 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 safety investment strategies obtained in Step 2. The main task in this step is to calculate the costs of safety measures. Based on the previous studies (Dorman, 2000; Reniers and Van Erp, 2016), the costs can be divided into two categories: direct cost and indirect cost, as shown in Fig. 3.

The direct cost represents the economic investment used to implement the safety measures, including initial cost and recurring cost. The initial cost is a one-off expense that only occurs at the initial stage before the operation of safety measures. Initiation cost (e.g., material and design) and installation cost (e.g. labor cost and equipment cost) are the main sub-categories of initial costs. The recurring cost represents the ongoing expenses required for the regular operation of safety measures. Fig. 4 lists five main recurring costs: operation cost, maintenance cost, and inspection cost, etc. The initial safety cost and the recurring safety cost should be directly summed since they do not coincide. There are two ways to deal with this problem based on a discount rate: (i) converting the initial cost to an equivalent annual cost (EAC) and (ii)

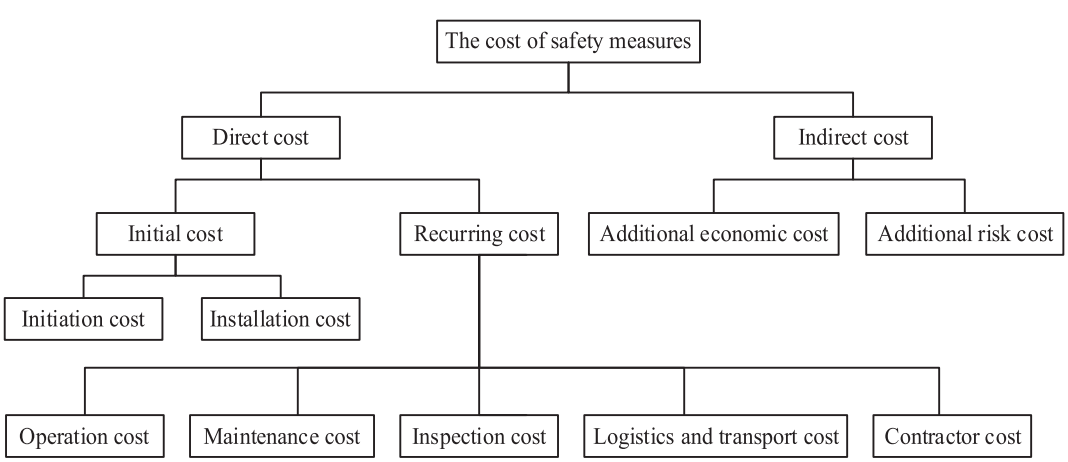

Fig. 3. The components of the costs of safety measures, based on (Dorman, 2000; Reniers and Van Erp, 2016).

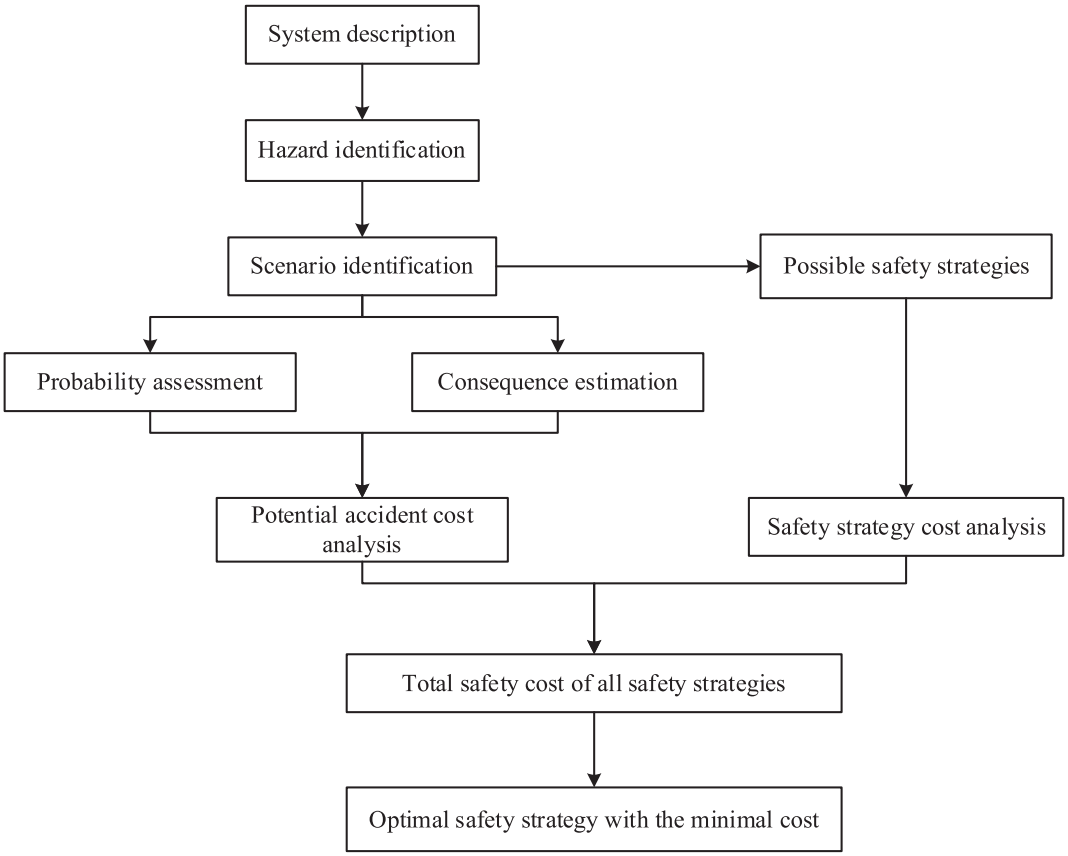

Fig. 4. Flowchart of the minimal total safety cost approach.

discounting the recurring cost to net present value (NPV). Besides the direct cost, the indirect cost involves additional economic loss and additional risk caused by safety measures. It may also play a leading role in safety economics. For instance, the direct costs of safety measures (e.g., social distance and face mask) used to prevent Covid-19 is much lower than the additional economic cost, i.e., economic recession and high unemployment rate. Simultaneously, these measures may also bring additional risks. For example, taking face masks may increase transportation accidents due to foggy glasses. It should be remarked that not all the costs listed in Fig. 4 are simultaneously present in a case, and some costs may be neglected if they are much lower than others. According to the costs of safety strategies obtained in Step 2, the optimal safety strategy can be obtained.

Taking the EAC method as an example, the annual cost of a safety strategy can be obtained, as follows (Schoemaker et al., 2016):

$$C_s = \frac{C_I r_D}{1-(1+r_D)^{-y}} + C_R$$

C_s is the equivalent annual cost of a safety strategy; C_I is the initial cost of a safety strategy; C_R is the recurring cost of a safety strategy; r_D is the discount rate; y is the number of years that safety measures are in operation.

4.2. Minimal total safety cost approach

In the risk-based approaches, risk acceptance criteria are used to select viable safety strategies that can reduce the actual risk. In contrast, the costs of these strategies are analyzed to obtain the optimal safety strategy with the prevention cost within a specific budget. In the minimal cost approach, both the safety strategy cost and the potential accident cost are considered. As a result, this approach aims to determine the optimal safety strategy with minimal total safety cost (Eslami Baladeh et al., 2019), as shown in Fig. 4. This approach also includes hazard identification, scenario identification, probability assessment, and consequence estimation. Based on the above steps, cost analysis is conducted to obtain the potential accident costs. Besides, cost analysis for possible safety strategies is also conducted to obtain safety strategy costs. The total safety cost is defined as the sum of the safety strategy cost and the potential accident cost. As a result, the optimal safety strategy can be obtained based on the principle of minimal total safety cost.

The cost analysis for safety measures in this approach is identical to that in the risk criteria approach. Thus the estimation and monetization of accident costs is a crucial step in this approach. Sun et al. (2006) divided accident costs into insured costs and uninsured costs. Gavious et al. (2009) divided accident costs into four categories: direct costs, indirect costs, payment (the increased payment to employees), and immeasurable costs. Reniers and Van Erp (2016) classified accident costs into ten categories. According to these studies, the ten main categories of accident costs are summarized in Fig. 5. In terms of the ten categories of accident costs, human loss is the most controversial issue since the monetization of human life is an ethical issue and thus not so easy to handle. Even though it is challenging to obtain the monetary costs of human life directly, it may be indirectly monetized via those that can be directly quantified. For instance, the willingness to pay (WTP) method uses money that people are willing to pay to reduce the risk of human loss to characterize the value of human life. The WTPs of a group of people can be used to estimate the average individual value called the Value of a Statistical Life (VSL) (Arends et al., 2005). The VSL is a local value that varies by region (normally in 1–10 million Euros) (Aven, 2015). Besides the two methods, the human capital method and the Quality-Adjusted Life Years (QALY) are also widely used in the safety and health domain (Chen and Reniers, 2020b).

Based on the monetary values of different losses, the expected cost

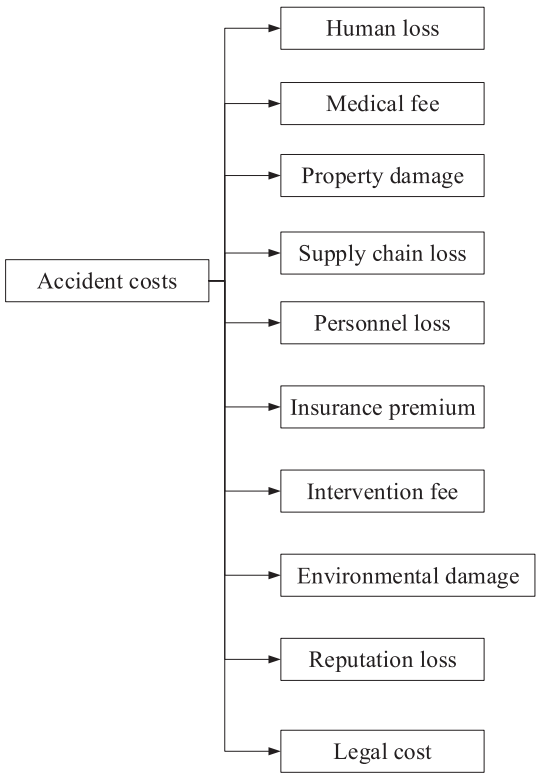

Fig. 5. The components of accident costs, adapted from (Reniers and Van Erp, 2016).

can be obtained considering different accident scenarios and their likelihoods, as follows:

$$C_A = \sum_{i=1}^{n} P_i \sum_{j=1}^{m} L_{i,j}$$

C_A is the potential accident cost; n is the number of accident scenarios considered in the analysis; m is the number of loss categories considered in the analysis; P_i is the probability of accident scenario i; $L_{i,j}$ is the loss of cost category j caused by accident scenario i. In this study, the accident cost refers to the loss (consequences) of accidents without considering the likelihood of undesired events. The potential accident cost is represented by a product of accident likelihood and accident consequences. So the potential accident cost can be regarded as a specific risk represented by monetary values. The total safety cost C_T is thus the sum of the safety strategy cost C_S and the potential accident cost C_A:

$$C_T = C_S + C_A$$

4.3. Cost-benefit analysis

Once safety measures are implemented, the cost of safety measures will become a sunk cost used to avoid and reduce accident costs. Avoided accidents thus can be considered as the hypothetical benefits thanks to the investment in safety measures. A baseline safety strategy needs to be defined to calculate the hypothetical benefit of safety investments. In this study, the strategy "without any safety investment" is considered to be the baseline (hence, the so-called "naked option"). As a result, the expected benefit of safety strategy k (B_k) can be expressed as the accident cost of baseline strategy ($C_{A,0}$) minus the accident cost of the safety strategy k ($C_{A,k}$), as follows:

$$B_k = C_{A,0} - C_{A,k}$$

In that case, the net benefit of safety strategy k (NB_k) can be easily represented as the difference between the expected benefit of safety strategy k (B_k) and the equivalent annual cost of safety strategy k, as follows:

$$NB_k = B_k - C_{S,k}$$

If the NB_k greater than 0, the safety strategy is profitable and may be adopted; otherwise, the safety strategy is non-profitable and may be abandoned. Furtherly, the safety strategy with the maximum NB will be regarded as the optimal safety strategy. The steps of the cost-benefit analysis approach are illustrated in Fig. 6.

4.4. Cost-effectiveness analysis

The computation of accident costs is necessary for both the total safety cost approach and the cost-benefit analysis approach. Nevertheless, it may be difficult to monetize all the accident losses as part of the work may be related to ethical and moral issues. Cost-effectiveness analysis (CEA) is an alternative to overcome the problems associated with the monetization of accident costs since the effectiveness is not required to be monetized. Cost-effectiveness analysis can be used for decision-making between two different safety strategies or approving a new safety measure by estimating how much it costs to gain a unit of safety. In cost-effectiveness analysis, a cost-effectiveness threshold (Thokala et al., 2018) needs to be determined when comparing two interventions. Usually, an incremental cost-effectiveness ratio (ICER) (Briggs and Fenn, 1997) is used to compare the incremental cost (ΔC) and the corresponding incremental safety outcome (△E), as follows:

$$ICER = \frac{\Delta C}{\Delta E}$$

$$\Delta C = C_{S_2} - C_{S_1}$$

$$\Delta E = E_{S_2} - E_{S_1}$$

C_{S_2} is the cost of safety strategy 2; C_{S_1} is the cost of safety strategy 1; E_{S_2} is the safety outcome caused by safety strategy 2; E_{S_1} is the safety outcome caused by safety strategy 1. The results of ICER can be divided into four categories: (i) If $\Delta C < 0$ and $\Delta E > 0$, safety strategy 2 is dominant and should be recommended (less expensive and more effective); (ii) If $\Delta C > 0$ and $\Delta E < 0$, safety strategy 1 is dominant and safety strategy 2 (more 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 safety strategy 2 can reduce safety strategy cost but will decrease the safety outcome; (iv) If $\Delta C > 0$ and $\Delta E > 0$, it is also a trade-off status in which the implementation of safety strategy 2 can improve safety while it needs extra cost. In terms of categories (iii) and (iv), a pre-determined threshold of ICER needs to be defined to decide whether safety strategy 2 should be implemented or not. If the actual ICER is less than the threshold, safety strategy 2 is recommended; otherwise safety strategy 2 is considered to be not cost-effective. CEA can also be used to compare multiple alternatives by defining a baseline strategy (S_0), as follows:

$$ICER_k = \frac{C_{S_k} - C_{S_0}}{E_{S_k} - E_{S_0}}$$

If $ICER_k$ greater than 0, the safety strategy with the minimal $ICER$ is the most cost-effective selection. Due to the application of the ICER, The units between the cost of safety measures and the safety outcome can be different from each other, making the CEA method more flexible than the CBA method. The safety outcome can be any safety indicator according to the preferences of decision-makers, such as fatalities, injuries, and the quality-adjusted life years (QALY).

4.5. Multi-objective optimization

As mentioned in Section 2, safety and economic benefits may be two conflicting objectives in which optimal safety and optimal economic benefit cannot be obtained simultaneously in short run. In that case,

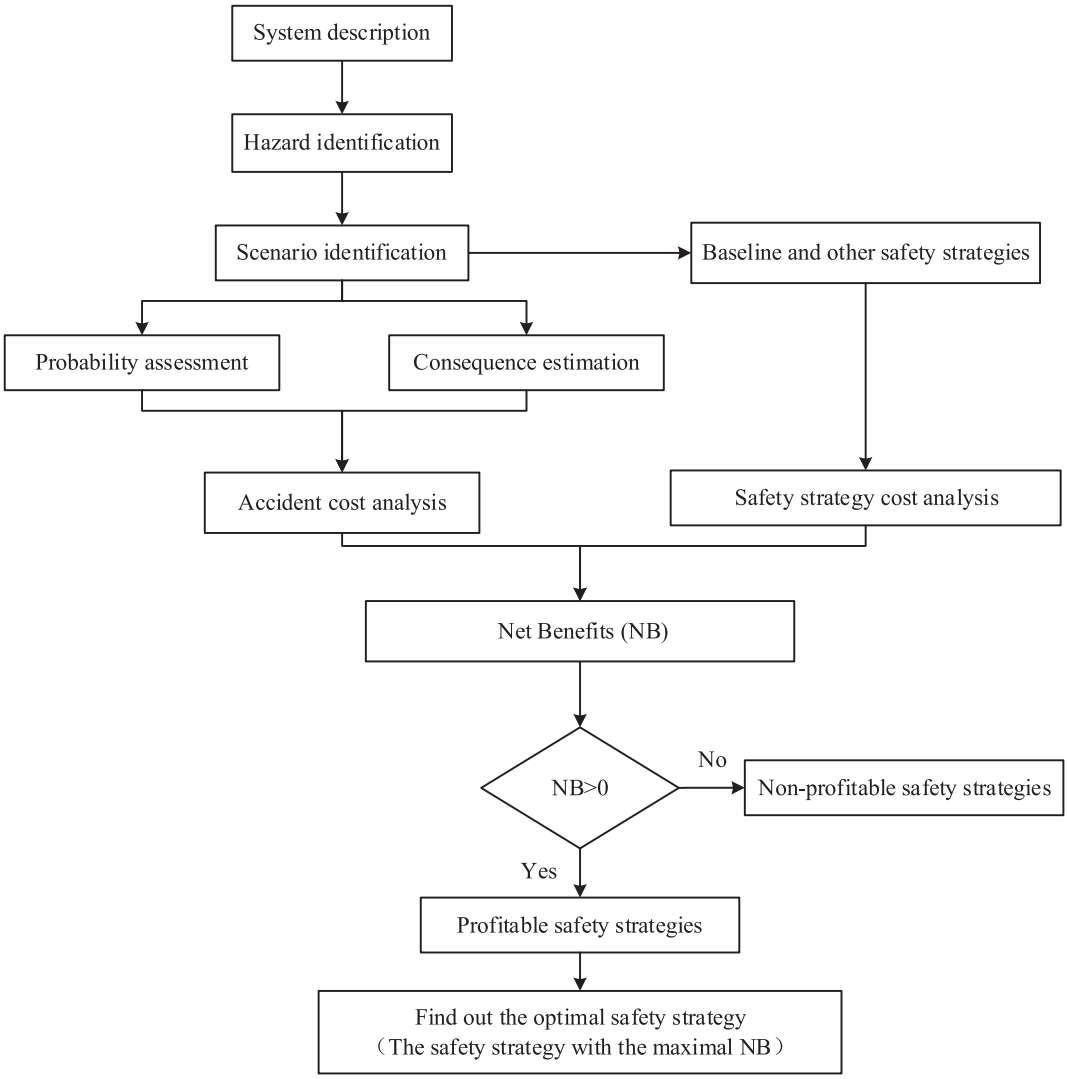

Fig. 6. Flowchart of cost-benefit analysis approach.

multi-objective approaches can be effective for balancing economic benefits and safety. Multi-objective optimization has been used in inherent safety design to minimize the costs of a project and the corresponding risks (Eini et al., 2016) as well as to minimize the operational costs in the entire life cycle (Ramadhan et al., 2014). In the design stage, inherent safety principles such as substitution and minimization can be used to reduce accident risk. But the implementation of these principles may increase different kinds of costs. As a result, a multi-objective optimization model in the design stage for optimizing the trade-off between accident risk and costs, can be developed, as shown in Fig. 7.

As shown in Fig. 7, based on a risk assessment and cost analysis, two objective functions can be obtained: (i) minimizing risk (or in other words, maximizing safety); (ii) minimizing safety cost. Two dominated solutions can be obtained by only considering one of the two objectives. By the application of optimization algorithms (e.g., genetic algorithms and weighted sum methods), a set of Pareto solutions[1] (Khakzad and Reniers, 2019) can be obtained. According to decision-makers' preferences, the final optimal strategy can be selected from the Pareto solutions. This method provides a set of Pareto strategies while the decision-maker selects the most preferred one. Therefore, the decision-maker also plays an essential role in the decision-making process, which is different from the above approaches.

4.6. Game theoretical approach

The preceding five methods are mainly used to deal with the decision-making for economic units in which only a single decision-maker is considered. However, multiple decision-makers may be involved in a safety investment. For instance, the safety policy of a company always needs to follow the safety regulations in which the decision-makers of the companies are affected by the regulators (Gao et al., 2020). In that case, the companies may only want to maximize their economic benefits while the regulators possibly aim to reduce the social costs of accidents. For instance, in terms of a chemical industrial area with multiple chemical companies, the decision-making among these companies is also interdependent due to the possibility of external domino effects (Reniers et al., 2005; Hosseinnia et al., 2018). In these interdependent decisions, decision-makers may only maximize their own safety benefits while it is impossible to maximize all the decision-makers' benefits due to lack of information and myopic benefit conflicts. Safety decisions involving multiple decision-makers may be solved by multi-objective optimization as well as game-theoretical approaches.

Game theory includes many (non–) cooperative models for decision-

[1] Pareto solutions refer to refers to a solution in which there are no other solutions that can improve any objective without worsening one or more other objectives.

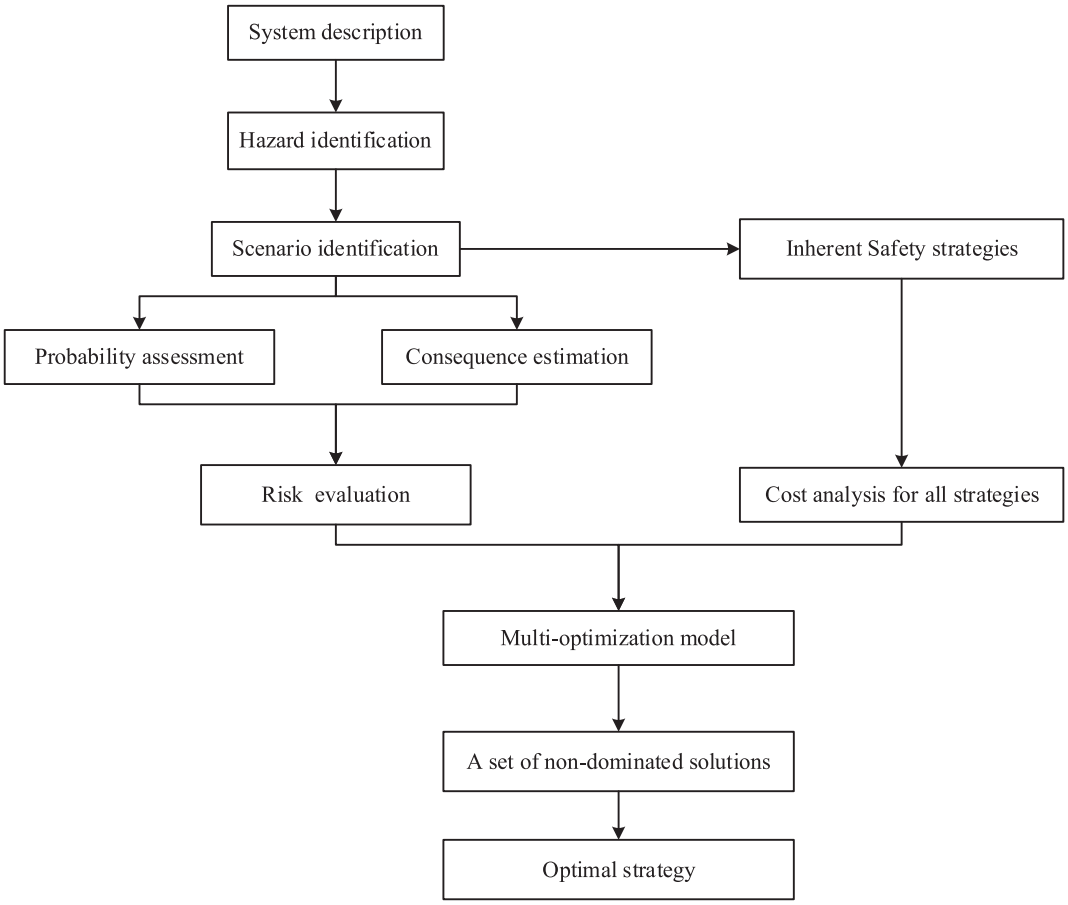

Fig. 7. Flowchart of multi-optimization approach for balancing accident risk and economic benefits.

making, for example, between intelligent and rational players (Myerson, 2013). In a standard game theatrical model, all the decision-makers are regarded as intelligent and rational players who aim to maximize their benefits. Finally, an equilibrium (trade-off) may be obtained to balance each player's benefits. Consequently, game theory may be an ideal tool in safety economics for decision-making involving multiple

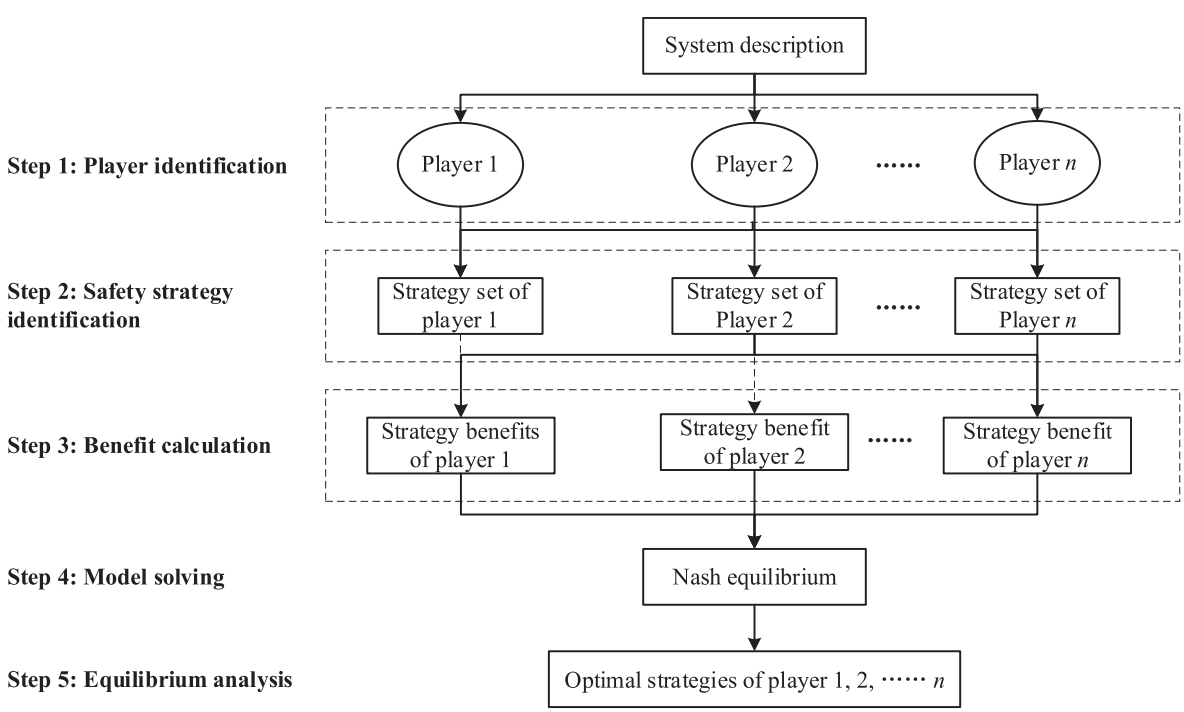

Fig. 8. Flowchart of game theatrical approach.

stakeholders. Fig. 8 shows the flowchart of a cooperative game used to achieve the optimal safety strategy.

To apply game theory in safety economics, we first need to identify the players in the game model. For instance, in a chemical cluster, the players may be constituent chemical plants (Reniers and Pavlova, 2013). The second step is to identify the strategies of all players (each player has a set of strategies). Step 3 calculates the (net) benefits (objectives) of each player, considering the possible external domino effects and safety strategies in nearby plants. The benefits of players depend on the players' motivations and strategies. In the chemical cluster case, the plants possibly aim to reduce the total costs of damages or maximize the net benefits. Based on the calculation of potential losses or benefits, a Nash equilibrium in which each player adopts their strictly dominant strategy may be obtained by solving the game theatrical model. If the equilibrium is not a pure strategy, the Nash equilibrium should be further analyzed to obtain the optimal prevention strategy, i.e., Step 5 in Fig. 8.

5. Paths for future research

In Section 4, we introduced six categories of approaches that are widely used in safety economics. Table 1 lists the advantages and disadvantages of these approaches.

These approaches can be used to support decision-making on safety and economics. However, there are still some open issues that need to be explored for safety economics in the future.

5.1. Economic data for the monetization of costs

The monetization of costs is a critical step in safety economic analysis. In practice, the lack of economic data for cost calculation is an obstacle to the application of safety economics. Although safety institutions such as the U.K. Department of HSE published appraisal values for fatalities and injuries, the topic stays controversial in the light of ethical dimensions. Moreover, the economic data for other categories (e.g., environmental costs) of accidents are limited. These economic data need to be collected based on real industrial practice and accident analysis. Besides, an open-access database for economic values of accident costs and the costs of safety measures may be developed to facilitate cost calculation. The rapid development of advanced tools such as data mining that may be used to collect and process these economic data is expected to alleviate this issue in the near future greatly. In that case, experts and operators in safety economics can obtain and update data more easily and thus focus on the relationship between safety and economics and the decision-making methods.

Table 1
. A comparison of approaches in safety economics.

Approach	Advantages	Disadvantages
Risk-based optimization	There is no need to monetize accident costs	A risk threshold should be determined
Minimal total safety cost	Decision-making only depends on one factor (total safety cost), which makes it easy to understand and use	Accident costs should be monetized
Cost-benefit analysis	It can directly show the gain induced by safety investment	The "benefit" in cost-benefit analysis is hypothetical
Cost-effectiveness analysis	There is no need to monetize accident costs and the effectiveness can be any safety indicator based on the preferences of decision-makers	It can only be used for comparative study
Multi-objective optimization	It can balance different optimization objectives	It is complex to solve the optimization model
Game theoretical approach	It considers conflicting interests of various stakeholders in the decision-making process	It may be difficult to know the strategies of other stakeholders

5.2. Indirect cost calculation

In accident cost calculation, the main concern in the direct cost calculation is the monetary costs of human life, such as VSL and QALY (Kniesner and Viscusi, 2019; Perry-Duxbury et al., 2019). Numerous methods are used to measure them, such as the widely used WTP approach based on decisions made by subjects in contingent valuation (CV) or choice experiments (CE) involving trade-offs between money and health risk (Mason et al., 2009; Hultkrantz and Svensson, 2012). However, many challenges still exist in this domain, such as ethical issues, methodological issues, and theoretical assumptions (Da and S, 2016). Indirect costs consist of indirect costs of accidents (e.g., legal costs and insurance costs) and indirect costs of safety measures (e.g., additional risk costs). The indirect costs are difficult to calculate since they are hidden, invisible, or difficult to quantify or monetize. However, indirect costs cannot be neglected since they may be much more than the direct costs. A simple method for calculating the indirect costs related to accidents is using the ratio of indirect costs to direct costs. According to accident statistics, Heinrich (1941) indicated that indirect costs could be four times higher than direct costs. Dorman (2000) concluded that the ratio depends on industrial sectors and ranges from 1 to 20. Although some other indirect cost calculation methods (Jallon et al., 2011) are available in the literature, the calculation accuracy still needs improvements. Besides, little attention has been paid to the indirect costs caused by safety measures, especially for the additional risk costs. To deal with the additional costs, the system hazard identification needs to be conducted again after implementing safety measures.

5.3. Security economics

Safety concerns unintentional events (e.g., corrosion caused release accidents) while security focuses on intentional events (e.g., terrorist attacks) (Khakzad et al., 2018; Reniers et al., 2020). Security has received increasing attention since the 9/11 terrorist attack in the US, in 2001. Both safety and security aim to reduce the losses caused by undesired events. The monetization of the costs of intentional attacks may be more complicated than those of accidental events since the former may be more relevant to reputation loss, symbolic effects, psychological impacts, and political influences. Due to the strategic and intelligent characteristics of attackers, the prediction of the attack strategies is also a challenge. Besides, the motivation of attackers may be unknown to defenders, making it difficult to calculate the benefits from attacker's point of view. As a result, risk assessment methods under data scarcity and techniques for rare events (Khakzad et al., 2015; Yang et al., 2015) may be used to overcome the challenges related to security economics. Besides, advanced tools such as big data and data mining may also be employed to obtain more insight into attack strategies and attackers' benefits.

5.4. Risk perception

In safety economics, personal risk attitude and perception may play an important role in decision-making on safety strategies considering the role of decision-makers (Fuller and Vassie, 2004; Reniers, 2015). In the safety domain, risk perception is defined as people's subjective judgments on the probability and consequences of accidents while it may also refer to the subjective judgments on the costs of accidents in safety economics Different decision-makers may adopt different safety strategies for the same risk due to the differences in perceptual costs. For instance, a risk-tolerance person may underestimate the costs of improbable large-scale accidents in chemical plants and select to neglect the risk, while a risk-averse person possibly adopts highly costly safety barriers to prevent such events. However, risk perception is usually neglected in safety economics approaches. In light of the significant role of subjective judgments, more attention should be paid to cost/risk perception in safety economics.

5.5. Safety economics approaches should be multi-stakeholders

Most of the approaches used in safety economics only consider one stakeholder, such as a chemical plant and a nuclear plant. Safety economic decision-making usually involves multiple stakeholders. For example, the local government may pursue economic benefits to build a nuclear plant while the safety supervisor may propose safety issues for the operation of the nuclear plant. Besides, the public nearby the plant may be opposed to the project due to nuclear leakage risk. In terms of these cases, neglecting any of the stakeholders can be considered unethical (May 1982). Besides, a company may select safety insurance to transfer its risk to other stakeholders rather than taking safety measures to reduce the risk. Moreover, a sound healthcare system may encourage the company manager to accept a higher risk since the costs of injuries can be externalized and thus be transferred to the public. If we only consider the direct stakeholder (the company) and neglect the accident costs provided by insurance companies or the public, these behaviors cannot be explained. More research is needed to represent multi-stakeholders in safety economics using advanced tools such as game theory, multi-agent models, and multi-actor approaches.

5.6. Safety economics decisions are multi-criteria

Safety economics may be considered a multi-criteria decision problem since both safety and economic factors are considered in decision-making. Multiple-criteria decision (MCD) is a sub-discipline of operations research that finds an optimal selection in a set of alternatives, considering multiple criteria (Velasquez and Hester, 2013; Khakzad et al., 2017). By applying multi-criteria decision methods (e.g., analytic hierarchical process, AHP, and analytic network process, ANP), decision-makers can select different criteria based on their preferences. For instance, because the value of life is a controversial topic in safety economics and potential casualties are an essential concern, we can deal with this situation by simultaneously considering three criteria: safety cost, safety benefit, and casualties. Based on multiple-criteria decision approaches, more safety criteria and economic criteria can be integrated into decision-making to satisfy different risk preferences and tackle controversial topics in safety economics.

5.7. Dynamic safety economics

The risks of an organization may evolve due to the variety of hazards and threats, the implementation of safety measures, and the update of equipment and techniques. As a result, the costs and benefits of safety may also change over time, and the trade-off between safety and economics may move accordingly. To deal with this problem, dynamic safety economics may be developed in the future. Dynamic safety economics refers to the dynamic decision-making process in which an organization continuously or periodically identifies hazards, assesses risks, estimates costs, calculates benefits, and thus dynamically adjusts safety strategies. Compared with static safety economics, dynamic safety economics is expected to timely update safety strategies according to the change of safety and economic parameters.

5.8. Insurance in safety economics

Insurance is a risk transfer method in which the potential costs of accidents are transferred to an insurance company. Companies may overestimate the investment in safety measures if insurance is ignored while underestimating the investment in safety measures when they purchase insurances (Abrahamsen and Asche, 2010). In that case, a company needs to balance the investment in insurances and safety measures. In the future, decision-making tools may be developed to determine resource allocation between safety measures and insurance.

6. Conclusions

In this study, safety economics is defined as a transdisciplinary and interdisciplinary field of research focusing on the interdependencies and coevolution of economics and safety for the decision-making between safety and economics. The main task of safety economics is to study the interdependencies between safety and economics, and safety cost is a link that connects safety and economics. According to the definition of safety economics, the role of safety economics in safety decision-making and production investments are summarized, including improving safety awareness and tackling the conflicts between safety and economics. The possible approaches in safety economics are summarized and analyzed, including risk-based optimization, cost-benefit analysis, and cost-effectiveness analysis. Finally, the roadmap for future safety economics are discussed: (i) Due to the lack of economic data, an open-access database may be developed to reduce the workload of collecting data; (ii) The calculation of indirect costs of safety and accidents is challenging, and more research is needed on this topic to improve the accuracy of safety economics; (iii) In terms of intentional undesired events, security economics is a potential research domain in the future; (iv) Risk perception may be considered in the calculation of costs and benefits to address the role of decision-makers in safety investments; (v) The research on decision-making involving multiple stakeholders needs to be further explored by modeling the interdependencies between different stakeholders; (vi) To make up for the limitations of decision criteria in safety economics, multiple safety criteria and economic criteria can be integrated by applying multi-criteria decision-making approaches; (vii) Dynamic safety economics may be formulated to obtain the dynamic trade-off between safety and economics and timely update safety strategies; (viii) Decision-making tools may be developed to balance the investment in safety measures and insurance.

Declaration of Competing Interest

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

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