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An Integrated Technical and Societal Risk Index for Ranking Major Accident Risks in Chemical Process Industries

Yuanyuan Xu[a], Shuaiqi Yuan[a], Genserik Reniers[a,b,c]*, Ming Yang[a]*

[a]Safety and Security Science Section, Faculty of Technology, Policy and Management, TU Delft, Delft, The Netherlands
[b]Faculty of Applied Economics, Antwerp Research Group on Safety and Security (ARGoSS), Universiteit Antwerpen, B-2000 Antwerp, Belgium.
[c]CEDON, KULeuven, B-1000 Brussels, Belgium
G.L.L.M.E.Reniers@tudelft.nl

Major accidents in the chemical process industry occur with low frequency but may lead to severe damages affecting a myriad of stakeholders. Managing major accident risks of chemical industrial systems is regulated in the Seveso Directive of the European Union. However, the conventional risk assessment mainly focuses on the objective aspects of risks and lacks in incorporating public concerns and context-related issues. Aiming to overcome this limitation and enhance the public's engagement and trust in risk assessment and management, the present study built an integrated risk index for ranking risks considering both technical aspects and societal concerns. A hypothetical case-study is used to demonstrate the application of the proposed risk index. At last, the outcomes of using the integrated risk index and the conventional risk assessment approach are compared and discussed.

1. Introduction

With the advent of industry 4.0 and social changes, the paradigm of industrial safety advancement shifts to meet societal concerns to include economic, moral, and ethical aspects in risk assessment (Reniers, 2017). Risk evaluation and ranking plays a vital role in risk assessment, and it helps set risk management priorities and decide which risk should receive more attention. Determining how risk is defined is a fundamental step in risk ranking exercise. Generally, risk is defined based on rational thinking by the products of the probability and magnitude of consequences (Xu et al., 2022). How to involve the societal expectations of laypeople in defining risk and risk assessment is a tricky problem to be addressed.

Since the beginning of the 21st century, continuous efforts have been made to lift risk assessment towards social processes beyond technical issues. Some studies advocate public participation in the risk assessment process (i.e., Florig et al., 2001). The gathered values and interests of the public were used as the basis for determining "which risk to be analyzed" and "how risk is analyzed". In addition, some studies have worked on expanding risk definitions to corporate social-oriented values. For example, Gardoni and Murphy (2014) extended the two-dimensional risk definition (probability and consequence) by introducing the source dimension to encompass moral concerns. Based on a combination of the levels of each dimension, risks were divided into 10 levels. Although this qualitative method is easy to use, its effectiveness is questionable when facing risk assessment requiring higher accuracy. Reniers and Van Erp (2016) have proposed an integrated risk ranking method called "quantitative and qualitative (Q&Q) risk index," which combines technical risk estimates and societal concerns together. The Q&Q risk index allows obtaining a combined index by aggregating the value of all risk attributes, including equity, fairness, voluntariness, etc. Nevertheless, the method doesn't consider the variance in public's preferences regarding different risk dimensions. Furthermore, the "qualitative indices" in the original approach need to be improved and augmented by the knowledge and information from the public.

Targeting the gaps in existing risk indexes and risk ranking methods, this paper develops a novel integrated risk index incorporating both technical aspects and societal concerns. The proposed risk index allows more public participation in the risk assessment process. In particular, social expectations in risk assessment from two aspects are considered in the risk index. First, the socio-economic impacts related to those affected or interested

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groups are considered in consequence assessment; second, subjective risk perceptions are considered in defining risk. The paper is structured as follows: Section 2 provides an overview of the methods and detailed developing process for risk ranking. Then, an illustrative case study is performed to demonstrate the application of the risk ranking method in Section 3. Finally, conclusions are presented in Section 4.

2. Methodology

2.1 Integrated technical and societal risk index

Risk can be understood as a function of several parameters. Generally, the technical or rational concept risk is defined by likelihood and consequence. To take account the public's input when comparing and ranking risks, factors that affect people's subjective risk perceptions are defined as "societal concerns" and fall into a new category of parameters to extend the risk concept. Ultimately, a composite risk ranking index by aggregating technical and societal parameters is formulated in Eq. (1). Generally, a higher value of the risk index indicates a greater degree of importance associated with the risk scenario.

$$R_i^* = L_i \times C_i \times X_i \tag{1}$$

Where R_i^* is risk index of risk event i; L_i being the likelihood of risk event i; C_i is the severity of consequences; X_i represents the societal concern about risk event i, the range of X_i is [0.5,2]. The parameters C_i and X_i are context-related and subject to the interested groups or stakeholders. For instance, C_i can be further broken down into effects on economy, human, environment, and society depending on the specific interests and concerns of stakeholders. Regarding to the parameter X_i, the psychometric paradigm of risk perception research has revealed a list of qualitative attributes related to lay-people judgments of risks (Fischhoff et al., 1978; Slovic et al., 2016). Although those attributes are not designed specifically for industrial domain, they can provide some insights for the selection of X_i. To aggregate various risk attributes into a single numerical value, the overall scores of the R_i^* is calculated by Eq. (2).

$$R_i^* = L_i \cdot \sum_{j=1}^{n} w(C_j) \times v(C_{ij}) \sum_{j=1}^{m} w(X_j) \times v(X_{ij}) \tag{2}$$

Where j is the jth attribute of C_i or X_i, w represents the weight of risk attribute, v is the value of risk attribute, n is the total number of attributes under the parameter C_i, m is the total number of attributes under the parameter X_i. Since C_i may have multiple dimensions, the value of C_{ij} was transferred to the numerical rating scales of that attribute.

2.2 Risk ranking procedure

Risk ranking mainly involves three steps, including identification, analysis, and prioritization. The overall scheme of the risk ranking method is illustrated in Fig.1. The following subsections provide a detailed description of each step of the proposed risk ranking method.

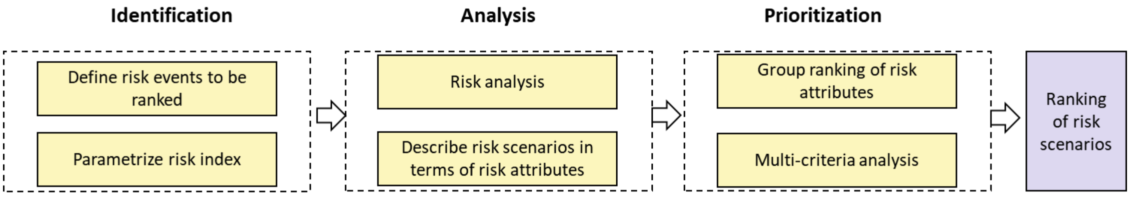

Figure 1: Overview of the risk ranking procedure.

2.2.1 Define and categorize risks

The first step of risk ranking is determining risk attributes and identifying risk scenarios/events to be ranked. According to different risk management schemes, risks in the industry can be categorized in different ways, such as sources (e.g., human-induced), effects (e.g., economic risk), and those affected (e.g., risk to the elderly). Determining specific risk attributes is a necessary step before risk analysis. It determines which risk attributes to be analyzed in the risk analysis. Theoretically, the specific risk attributes are context-related that need to be obtained through communication with the public or stakeholders. However, here the risk attributes used are mainly for illustration purposes rather than conducting real risk ranking. Therefore, we subjectively selected some risk attributes tailored to the industrial risk domain. Ultimately, a comprehensive set of 10 risk attributes has been curated to form a systematic index for the purpose of ranking risks (as shown in Fig.2).

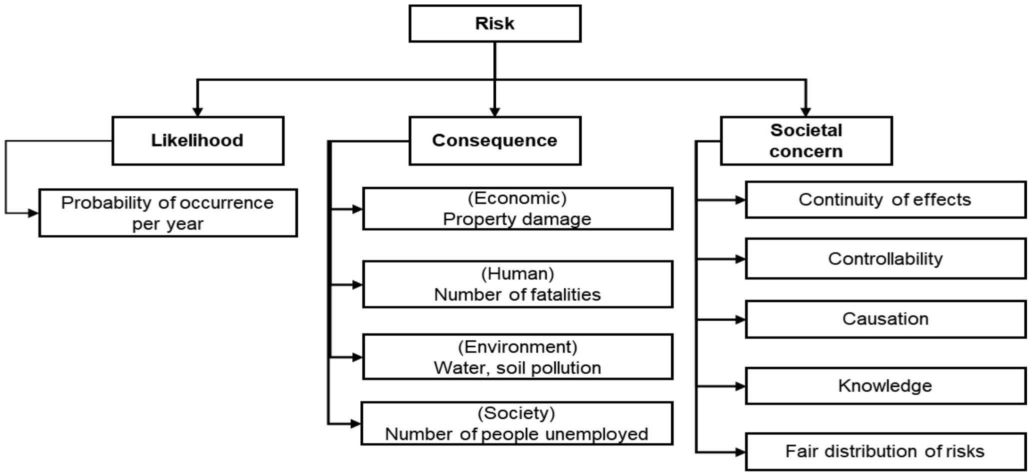

Figure 2: Hierarchy of risk index.

The 10 risk attributes and how they are characterized are described as follows:
1. Probability of occurrence per year. This attribute represents the expected likelihood of risk events.
2-5. Severity of effects on economy, human, environment, and society. The consequence dimension is divided into four categories: economy, human, environment, and society. Effects on economy is characterized by property damage. Effects on human mainly refers to number of fatalities. Effects on environment can be measured by quantity of water, soil polluted. Effects on society are counted by number of people unemployed.
6. Continuity of effects. Generally, in the conventional risk assessment practice, only the direct consequences of the accident were considered. However, some losses such as water and soil pollution due to leakage of harmful substances may last years or generations. This attribute can be used to characterize those indirect and long-term implications of accidents.
7. Controllability. Some risks are controllable and can be reduced or eliminated. For example, technical deficiencies can be addressed by improving system design or adding safety barriers. Enhancing the safety culture, education and training can prevent accidents resulted by human errors.
8. Causation. This attribute means the source of accidents. For example, the causation of industrial accidents includes accidental due to management or technical factors, intentional attack, or indirect NaTech events. Based on different source level, the causation can be ranked from low to high as “not culpable”, “reckless”, “negligence”, and “intentional”.
9. Knowledge. This attribute refers to the related strength of scientific knowledge regarding risk judgment. The attribute can be indirectly measured by considering the following 5 conditions: the assumptions made are reasonable; large amount of data/information are available; high degree agreement level among experts; the studied phenomena is well understood by current science; the knowledge has been examined (Aven, 2017). The more criteria are fulfilled, the higher the quality of scientific knowledge.
10. Fair distribution of risks. This attribute refers to the distribution of costs and benefits and reflects moral principle of “fairness”. A fair distribution of risk is morally preferable to an unfair distribution (Roeser, 2006).

2.2.2 Risk analysis

After risk scenarios are identified and risk attributes are selected, risk analysis is performed to estimate the likelihood and severity of consequences. Then, both L_i and C_i are transferred from numbers or qualitative descriptions to “five-point” scales (as listed in Table 1 and Table 2).

Table 1: Rating scale for the subdimension of consequence; based on The French Bureau for Analysis of Industrial Risks and Pollutions (BARPI) (2019).

Rating	Economic (Property damage€/ million)	Human (number of fatalities)	Environment	Society
5	≥200	≥50	Very high	≥500
4	50-200	20-49	High	100-499
3	10-50	6-19	Medium	20-99
2	2-10	2-5	Low	6-19
1	0.1-2	0-1	Very low	0-5

Table 2: Rating scale for likelihood dimension; based on Reniers & Van Erp (2016).

Rating	1	2	3	4	5
Likelihood	Impossible and unlikely (Occurs less than 10000 years)	Remote (Occurs between 100 and 10000 years)	Occasional (Occurs between 10 and 100 years)	Probable (Occurs between 1 and 10 years)	Frequent (Occurs more than once per year)

In addition to probability and consequence, social concerns also influence the magnitude of risk. X_i is a qualitative parameter and has a value range. Specifically, empirical survey data were used here to determine the values of X_i (as shown in Table 3).

Table 3: Values and ranges of societal concerns. Based on Plattner et al. (2006).

X_i-value								
0.5	0.625	0.75	0.875	1	1.25	1.5	1.75	2

It should be noted that some societal concerns are positively correlated with risk level, while others are negatively correlated. Referred to Florig et al. (2001), it is hypothesized that the higher the controllability, quality of scientific knowledge, and equity of distribution of risks, the lower the risk index. By contrast, the longer the effects and the higher the degree of intentionality of causation will increase the level of risk. X_i=1 represents neutral attitudes towards risk events. When people are neutral or indifferent about risk events, the score of risk index is equal to rational risk level. X_i<1 decreases the risk level. X_i>1 increases the risk level. For example, one may overestimate the risk level due to the unfair distribution of risks. In this case, the rational risk estimate may increase X_i=1.75. Once all risk scenarios are analyzed and calculated, the generated data concerning different risk attributes are documented.

2.2.3 Risk prioritization

Risk prioritization mainly involves assigning weights of risk attributes and then creating a composite ranking by aggregate the numerical ranks for each dimension. The ranking procedure can be carried out through some techniques such as workshop or questionnaire survey to obtain different preferences and concerns about risk attributes among different groups. Before conducting risk ranking tasks, the participants would receive risk with detailed descriptions of different risk scenarios. After reading the risk summary sheets, participants need to rank risk attributes in different dimensions separately, with 1 being the most important risk attribute. Here, each group of participant's ranking is considered equally important. The attribute rankings are computed using the geometric mean. Then, modest technical tools are utilized to translate the geometric mean of ranks into weights. In this paper, the weight of attribute C_j is formulated as (Florig et al., 2001):

$$w(C_j) = \frac{1/R_{C_j}}{\sum_{j=1}^{n} 1/R_{C_j}} \tag{3}$$

Where $w(C_j)$ is the weight of the attribute C_j, R_{C_j} is the rank of attribute C_j, n being the total number of attributes of consequence dimension. Likewise, the weight of attribute X_j can be obtained through the similar mathematical process. After the judgments of weights and ratings/values of all attributes are collected, the scores of each risk event can be calculated through Eq. (1) and (2). Finally, the overall risk rank is obtained based on the ordinal rank of risk scores. A risk that was ranked 1 implied the risk received the greatest concern.

3. Case study

To illustrate the application of the proposed methodology of risk ranking, we consider the risks of an industrial park consisting of three chemical plants. This section is not intended to provide definitive data and scenarios associated with those plants that require more in-depth risk analysis. Rather, it is used as an illustration of the process of the risk ranking method based on hypothetically generated data.

3.1 Case description

Three chemical plants produce and store flammable, explosive, toxic and harmful substances, which may lead to toxic gas leaks, fires and explosions, and domino effects. These consequences may result in casualties, property losses, environmental pollution, and social impacts. This paper selects five different risk scenarios based on the consequences and causation of the accidents (as shown in Table 5).

Table 5: Risk scenarios considered in the case study. RS=risk scenario

Consequences	Causation		
	Accidental	Intentional	NaTech
Release of toxic gas	RS1	Not considered	Not considered
Fire or explosion	RS2	Not considered	Not considered
Domino effects	RS3	RS4	RS5

3.2 Results

At the first step, participants and experts are required to identify the risk attributes that need to be considered. For illustrative purpose, 4 group of participants (Group A, Group B, Group C, and Group D) represents different stakeholders are assumed, and the risk attributes are referred to Section 2.2.1. Subsequently, risk analysis and associated societal concerns analysis results are conducted to obtain different values of risk attributes for various risk scenarios. In practice, this step should be performed by a group of experts from different backgrounds. The hypothetical data for different risk attributes concerning 5 risk scenarios are summarised in Table 6.

Table 6: Results of risk analysis.

Risk attributes	RS1	RS2	RS3	RS4	RS5
Probability of occurrence per year	2	2	1	2	1
Property damage	2	3	5	3	4
Number of fatalities	1	1	3	2	1
Water, soil polluted	4	1	1	1	1
Number of people unemployed	1	1	4	1	3
Continuity of effects	1.75	1.25	1.75	1	1.5
Controllability	0.625	0.875	1	1	1.5
Causation	0.75	1.25	1.25	2	0.5
Knowledge	0.625	0.75	1	1.25	1.25
Fair distribution of risks	1	1.5	1.75	1.75	1.5

After obtaining the risk analysis results of the above scenarios, the 4 group of participants are required to rank the importance of risk attributes under “consequence” and “societal concerns” parameters. Then, the geometric mean of 4 different rankings are used to generate weights of risk attributes using Eq. (4). The ranking results are shown in Table 7 and Table 8. It can be seen from the results that number of fatalities and controllability receives greatest weights in separate dimensions.

Table 7: Group ranking of consequence dimension.

Consequence	Group A	Group B	Group C	Group D	Geo Mean	Weight
Property damage	3	2	1	2	2	0.24
Number of fatalities	1	1	2	1	1	0.48
Water, soil polluted	4	3	4	4	4	0.12
Number of people unemployed	2	4	3	3	3	0.16
Sum						1

Table 8: Group ranking of societal concern dimension.

Societal concerns	Group A	Group B	Group C	Group D	Geo Mean	Weight
Continuity of effects	2	1	2	3	2	0.22
Controllability	1	3	1	1	1	0.44
Causation	5	2	5	5	5	0.08
Knowledge	3	4	3	4	3	0.15
Fair distribution of risks	4	5	4	2	4	0.11
Sum						1

At last, the generated data and deducted weights of risk attributes of different risk scenarios are aggregated to obtain the final risk ranking. To compare the impact of different risk dimensions on risk ranking, the results of ranking with or without consideration of societal concerns are depicted in Fig.3. From the results, it can be seen that different methodologies lead to different risk rankings. For instance, in conventional risk ranking method, RS2 receives lower risk score than RS1. However, due to lower level of controllability and unfair distribution of risks, RS2 ranks higher than RS1 using the integrated technical and societal risk index. For such cases, risk management should pay more attention to controllability and distribution risk dimensions.

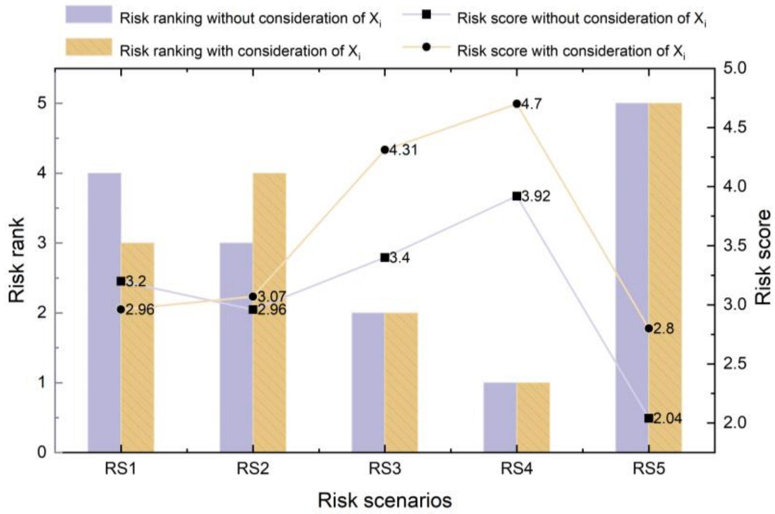

Figure 3: Comparison of risk rank and risk scores with or without consideration of societal concerns (X_i).

4. Conclusions

To incorporate societal values into risk assessment, this paper proposed a novel integrated technical and societal risk index and a new risk ranking method based on the knowledge of behavioural social science, risk analysis, and decision theory. Compared to conventional risk ranking methods relying on probability and direct physical consequences, the proposed risk index adds a third dimension called “societal concerns” to risk index and introduced social impacts in “consequence” dimension. The results examined in the illustrative case study showed that the newly added risk attributes may have influence on the overall risk scores and rankings. Future research will be carried out to further refine the proposed approach and to discuss more sophisticated real-life problems.

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