Delft University of Technology

Integrating Rational and Emotional Risk Management: A Stepwise Approach and Practical Implications

Xu, Y.; Reniers, G.L.L.M.E.; Yang, M.

DOI
10.1016/j.jnlssr.2025.02.004

Publication date
2025

Document Version
Proof

Published in
Journal of Safety Science and Resilience

Citation (APA)
Xu, Y., Reniers, G. L. L. M. E., & Yang, M. (in press). Integrating Rational and Emotional Risk Management: A Stepwise Approach and Practical Implications. *Journal of Safety Science and Resilience*. https://doi.org/10.1016/j.jnlssr.2025.02.004

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

Journal Pre-proof

Integrating Rational and Emotional Risk Management: A Stepwise Approach and Practical Implications

Yuanyuan Xu , Genserik Reniers , Ming Yang

PII: S2666-4496(25)00029-5
DOI: https://doi.org/10.1016/j.jnlssr.2025.02.004
Reference: JNLSSR 203

To appear in: *Journal of Safety Science and Resilience*

Received date: 18 November 2024
Revised date: 13 February 2025
Accepted date: 13 February 2025

Please cite this article as: Yuanyuan Xu , Genserik Reniers , Ming Yang , Integrating Rational and Emotional Risk Management: A Stepwise Approach and Practical Implications, *Journal of Safety Science and Resilience* (2025), doi: https://doi.org/10.1016/j.jnlssr.2025.02.004

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2025 China Science Publishing & Media Ltd. Publishing Services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd.
This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/4.0/)

Integrating Rational and Emotional Risk Management: A Stepwise Approach and Practical Implications

Yuanyuan Xu[1*], Genserik Reniers[1,2,3], Ming Yang[1]

[1] Safety and Security Science Section, Faculty of Technology, Policy and Management, TU Delft, Delft, The Netherlands

[2.] Faculty of Applied Economics, Antwerp Research Group on Safety and Security (ARGoSS), Universiteit Antwerpen, B-2000 Antwerp, Belgium.

[3.] CEDON, KULeuven, B-1000 Brussels, Belgium

[*]Corresponding author: Y.Xu-8@tudelft.nl

Journal Pre-proof

Abstract: Decisions in complex systems need support from formal risk management. Traditional risk management, based on a "rational" idea of risk (the actual damage linked with probabilities), often diverges from public perceptions, leading to conflict between expert-led evaluations and societal acceptance. Two research directions have emerged to bridge this gap: enhancing stakeholder participation in risk management and incorporating emotional factors into risk assessment. Building on these efforts, we propose a systematic methodology integrating stakeholders' emotional considerations into formal risk management. Our approach combines a refined risk conceptualization with a structured stakeholder engagement process. An illustrative example involving an ammonia plant site-selection risk problem is presented to demonstrate the applicability of the proposed approach. The proposed approach offers a potential way to resolve conflicts and enhance public trust in risk management.

Keywords: Risk management; Risk concept; Stakeholders; Rational; Emotional

1 Introduction

People need to consider risks in the face of decisions in many situations, such as daily life, an investment, an operation system, etc. Naturally, people deal with risks implicitly and consider several alternatives without specific risk assessment training. However, with the increase in complex systems, human capability is limited to cope with numerous factors. In response, formal risk assessment emerges as a scientific field and offers a systematic and scientific way of decision-making in a complex and uncertain world [1]. Over the past 40-50 years, risk management has been widely applied to address hazardous exposures across state agencies, industry, the academic community, and other fields concerning public health and environmental safety.

The risk management process typically consists of similar key stages: establishing context, risk analysis, risk evaluation, and risk treatment [2]. Typically, risk analysis is conducted by experts involving the estimation of probabilities and consequences of risk events. The risk analysis results will enter the risk evaluation stage, providing information to judge the acceptability of risk. However, many psychological studies of risk suggest a distinction between how experts and laypeople perceive and judge risk [3, 4]. The skeptical attitude of laypeople toward science is often attributed to their lack of knowledge. In line with this view, much of the early research focused on educating the public to accept expert perspectives. Nonetheless, it has become increasingly clear that simply attempting to persuade laypeople to adopt expert viewpoints is not a practical approach. In recent decades, conflicts between scientific risk assessments and public perception have intensified, particularly in response to emerging technologies such as nuclear power and wind farms. A notable example is the Yucca Mountain nuclear waste repository [5]. Despite multiple Quantitative Risk Assessments (QRAs) conducted by the U.S. Department of Energy, which concluded that the risks were negligible, public opposition remained strong. Concerns over the safe disposal of nuclear waste led to continuous protests and political resistance, ultimately resulting in the project's permanent abandonment.

In the past decades, many new initiatives and theories have emerged to reconcile conflicts between rational risk analysis and layperson risk judgment. We distinguished two prominent themes in contemporary studies: the involvement of stakeholders in risk management and broadening risk descriptions. Firstly, several social science and management literature assume that the discrepancy between experts and laypeople is due to a lack of communication. Consequently, approaches within this category advocate for enhanced collaboration with stakeholders in risk management to leverage transparency and procedural justice and ultimately improve their acceptance of risk decisions [6]. This method is commonly referred to in the scientific literature as participatory risk management, also described as collaborative, integrative, interactive, or comprehensive risk management [[7],[8],[9],[10]], etc. Unlike traditional risk management, which primarily highlights information delivery, participatory risk management focuses on dialog and

Journal Pre-proof

co-determination between laypeople and experts. This approach, which combines scientific risk analysis and public deliberations, is also known as the analytic-deliberation model [11, 12]. Through communication with stakeholders, their societal considerations and risk perceptions can be obtained and propagated in the risk assessment process. Currently, stakeholder participation in risk management is implemented through various approaches. For example, stakeholders can contribute by identifying risks and uncertainties based on their personal and sector-specific experiences, analyzing major consequences according to their concerns, and jointly determining the most critical risks for risk control planning [13].

Although many experts employ various methods to enhance the accuracy of risk analysis and minimize uncertainty, some sociologists pointed out that laypeople's distrust in science stems more from insufficient information and less from accuracy [4, 14]. For example, social science studies have shown that the acceptability of risk is not only influenced by technical concept of risk but also by societal considerations, such as justice, distribution of adverse consequences, equality, rights, and more [15]. Psychometric theorists argue that laypeople's risk attitudes towards hazards could be explained mainly by three factors: dread, familiarity, and exposure [3, 16]. This phenomenon is explained by a hybrid rational and emotional decision-making model, suggesting that analytical reasoning and affective responses shape how individuals perceive and respond to risk [17]. Traditional risk analysis, however, is primarily based on rational choice theory, which assumes that an individual makes decisions based on the utility of the desired outcome and the chance of that outcome occurring. Consequently, experts with scientific training tend to use rational methods of measurement (utility of the consequence and the probability of the consequences) as a primary basis for risk evaluation, risk treatment, and risk communication. In contrast, laypeople who make decisions rely more on experienced feelings and are influenced by "emotions" such as fear, anger, and surprise [[18],[19],[20]]. As a result, formal risk analysis, based on rational thinking, is sometimes insufficient to fully capture the general public's more encompassing and multi-facet values. Recognizing these limitations, scholars influenced by social science perspectives have proposed an alternative approach. The second branch of study advocates adding emotional considerations, such as voluntariness, equity, and fairness, into rational risk concepts, thereby broadening its scope and making risk analysis less blameworthy, see [[21],[22],[23]]. Aligned with the hybrid rational and emotional decision-making model, we refer to the layman's view of risk as the "emotional" approach in the following context. Here, "emotional" is used to differentiate it from the rational method and is not synonymous with "irrational".

However, implementing the two methods separately has several drawbacks and limitations. On the one hand, while stakeholder engagement allows diverse opinions to be voiced, formal risk analysis remains grounded in technical assessments, limiting the scope of inquiry to predefined scientific parameters. The judgment of "what needs investigation" is confined to technical language. On the other hand, introducing emotional factors in risk ranking or evaluation is a direct way to incorporate laypeople's attitudes in risk analysis. However, these methods lack generalizability and are limited to pre-set dimensions of risk. The emotional criteria introduced are typically based on experts' subjective judgment, which may not accurately capture the public's genuine concerns. To address this gap, Xu et al. [24] proposed an integrated technical and societal risk ranking approach. Their method first identifies key stakeholders before conducting risk analysis, allowing them to define the primary risk indicators. Based on these stakeholder-driven criteria, risk assessment is then carried out, with final rankings determined through a Multi-Criteria Analysis (MCA) approach. Despite this advancement, a standardized risk management framework that systematically integrates rational and emotional perspectives is still lacking. To meet the above challenges, we aim to develop a method for systematically integrating stakeholders' emotional risk perspectives into the formal risk management process. More specially, the aim is to develop:

- A generalized risk conceptualization to capture emotional considerations
- A practical and systematic risk management procedure for stakeholder participation

The remainder of this paper is structured as follows: we first propose a modified risk definition and a risk description which opens opportunities for broader risk characterization in section 2. Then, we present the foundations and the integrated rational and emotional approach for risk management in section 3. To demonstrate how to implement the approach, an illustrative example of a site-selection risk problem is presented and discussed in section 4. Before concluding, the significance of this study and its relevance to existing works are discussed in Section 5.

Journal Pre-proof

2 A modified conceptualization of risk

2.1 Risk definition

Current risk definitions fall short of stressing the role of human values. To illustrate, we introduced some representative definitions of risk that allow us to discuss.

(a) Risk is equal to a set of triplets (s_i, l_i, x_i), where s_i is a scenario identification or description; l_i is the likelihood of that scenario; and x_i is the consequence or evaluation measure of that scenario [25].

(b) Risk is a situation or event where something of human value (including humans themselves) has been put at stake and where the outcome is uncertain [26].

(c) Risk is uncertainty about and severity of the consequences of an activity with respect to something that humans value [1].

(d) Risk is effect of uncertainty on objectives [27].

It should be noted that definition (a) is commonly used in most safety management practices and related fields. The definitions have some variations in interpretations. But generally, most definitions can be attributed to three main components: an event A and consequences C, and uncertainty U about the event and consequences.

For simplicity, risk can be formalized to formula (1) without specifying the events:

$$R = (C, U) \tag{1}$$

This mathematical definition of risk will serve as the foundation for the following discussion. Now, let us revisit the four descriptive definitions. The key distinction between definitions (b) and (c) compared to definition (a) lies in the inclusion of ethical and emotional stakes related to human concerns. Such stakes can be interpreted as some state of reality of human concern or interest. Similarly, the term "objective" in definition (d) can be interpreted as "what individuals, organizations, and societies (as collectives of individuals) desire, need, pursue, or strive to achieve." Thus, it is also related to human stakes [28]. Following the definitions of (b), (c), and (d), when we judge whether we face risks, we introduce our values about consequences or outcomes. If human values are not attached to the potential consequence, even if the outcome is large, risk is absent.

Journal Pre-proof

Journal Pre-proof

However, when risk is discussed, e.g., in an operational system, we normally don't emphasize this hint of thought. This does not mean that risk analysts ignore "human stakes" when conducting a risk assessment today. Instead, the definition of "what human values" is determined by experts' subjective judgment. Ultimately, the assessment of risk reflects the experts' values. In many cases, expert judgment is sufficient for decision-making, particularly when those conducting the risk assessment also bear the risks. However, in situations where decisions are highly complex, ambiguous, and uncertain—especially when they affect diverse stakeholders, including individuals, organizations, and institutions—it may be necessary to incorporate the perspectives of laypeople, policymakers, and the broader public

This would bring new considerations to the risk assessment process: whose stakes should be considered? To address this consideration, we suggest that "human at stake" in risk events should be explicitly specified. We denote the people at stake in risk events as "η". Accordingly, a modified risk definition is suggested as:

$$R = (C, U)_\eta \tag{2}$$

For example, assume the specific risk event to be observed is a specific loss of containment accident A. We are uncertain U about what consequences C will happen and when they will happen. To define risk, we need to specify people at stake η, e.g., the plant managers. Plant managers might focus on the financial state of a chemical process plant. In this case, the potential consequences might be formalized as reduced capacity of production, supply chain production, etc.

Furthermore, when communicating about risk, naturally, "when" and "where" the risk will happen is implicitly considered. For example, Logan et al. [29] proposed an adjusted risk definition that highlights the role of time τ in risk and risk analysis. In this study, however, our primary focus is on the role of emotions and values of humans in shaping risk and risk analysis.

2.2 Risk description

Risk definition and risk description are two different concepts. A risk definition helps determine whether a potential risk exists, while a risk description estimates the magnitude of the risk [30]. Several representative risk descriptions include:

(a) The combination of probability and consequences.

(b) Risk is a triplet (C', Q, K), C' concerns specified consequence, Q indicates a measure of uncertainty, and K is the background knowledge supporting C' and Q.

Basically, these descriptions are all developed from a technical analyst's perspective. However, these descriptions may not always fully capture the attributes of risks, particularly when societal and perceptual factors play a significant role.

To illustrate, consider two risk scenarios: (1) T is exposed to second-hand smoke, and (2) T is exposed to smoke because he/she smokes tobacco products himself/herself. From an emotional perspective, scenario (1) is more blameworthy than (2) due to the exposure being involuntary. This distinction cannot be expressed through purely rational risk descriptions. Obviously, voluntariness cannot be reduced to a specific kind of consequence. However, the concept is related to the "sources" of risk events. In this context, the "source" of a risk refers to the agents involved in the creation or maintenance of a risk [22], including potential contributing factors to an accident.

Ideally, a risk description should reflect all the influencing factors, rational and emotional, on how an individual views two risk scenarios differently. If we regard risk as an event chain, risk sources α may lead to an event A, and there is uncertainty U about what event may take place and when it will happen. The event A would result in uncertain consequences C. When we discuss risk, the important aspects may focus on α, U and C.

It is essential that all those considerations are expressed in risk descriptions. Based on the "risk" defined in formula (2), a more informative risk description R' can be defined as:

$$R' = (\alpha, C', U')_{\eta} \quad (3)$$

Where α are the specific risk sources, C' are the specific consequence, and U' is a measure of uncertainty.

Moreover, in practice, discussions of risks cannot be separated from the reference system in which they are analyzed. One commonly used tool in risk management is the bow-tie diagram. As shown in Figure 1, an event may arise from several sources and lead to potential consequences of human stakes. Safety management delivery systems and safety barriers are shown as controls to prevent events and mitigate consequences. In some cases, event A may take place, but its consequences are not severe due to the presence of effective mitigation barriers.

Journal Pre-proof

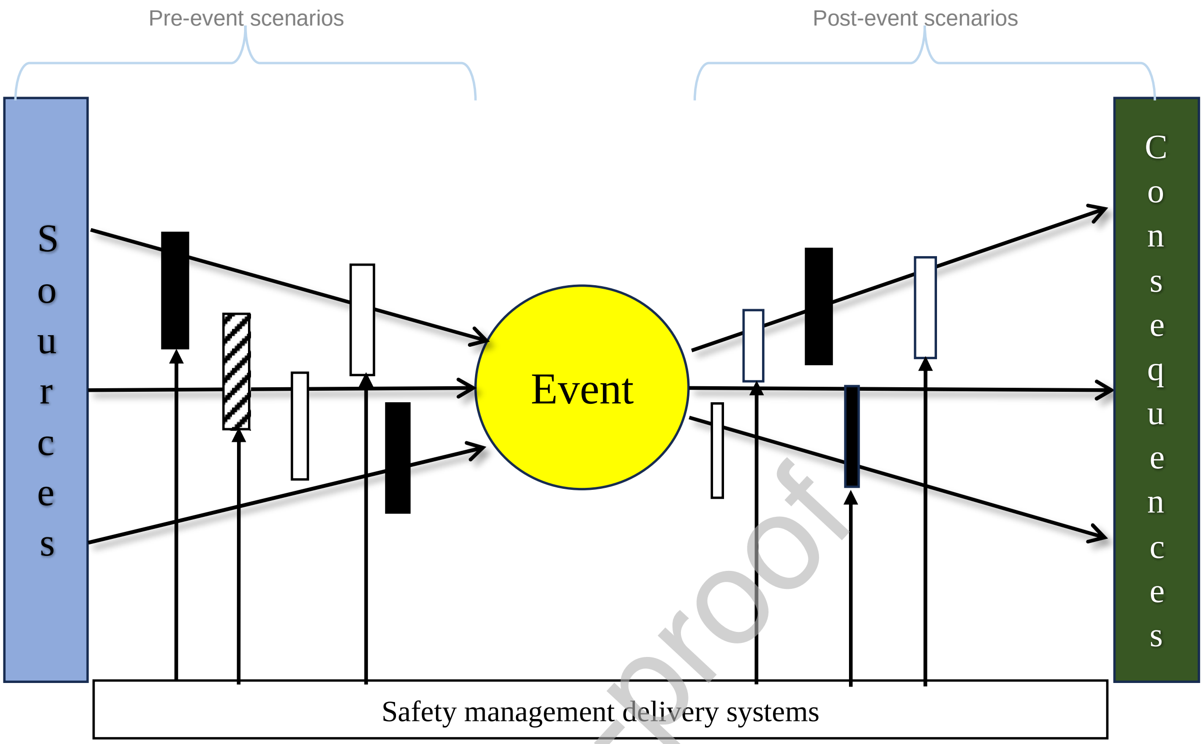

Fig 1. Bow-tie diagram representing risk scenarios. The black, white, and striped boxes represent different types of safety barriers.

Obviously, the consequences on the right-hand of the bow-tie diagram depend on the manageability M of the risk. Therefore, to denote a risk R' in a system with certain management controls M', we write:

$$R' = (\alpha, C', U', M')_\eta \quad (4)$$

M' is a measure of the extent to which the risk can be controlled or mitigated through management measures. To further illustrate the risk and risk descriptions, consider a risk assessment of a chemical process plant. The risk description is as follows:

- α: The causation of the event is considered, e.g., the risk event is caused by a terrorist attack.
- C': A supply chain production loss is considered, e.g., the company will lose 20 million euros.
- M': Mitigation barriers are considered, e.g., the emergency shutdown system works successfully.
- U': The uncertainty on α, C', M'.

Journal Pre-proof

3 Method

3.1 Foundations of the approach

Before presenting and discussing the suggested approach for risk management, it is important to clarify the underlying assumptions. Some of the assumptions face controversies in the risk field.

- *Definition of stakeholders*: The definition of "stakeholders" is not used constantly in the literature and may cause confusion sometimes. The definition of stakeholder is founded on Freeman's early stakeholder theory. In some management literature, distinctions are made between stakeholders and the public. To avoid ambiguity, this study adopted the IRGC [31] definition: "a stakeholder is an individual or an organized group that is or will be affected by the outcome of the risk event or the activity". Thus, stakeholders include not only those directly affected (organized) groups but also directly affected (unorganized) public.
- *The role of stakeholders*: There are two main types of actors in conventional risk management--decision-makers who have responsibility for the decisions and risk analysts with expertise in risk problems. In this approach, stakeholders are the third type of actors, and they are viewed as people with experiential and value-based knowledge and can provide valuable insights to supplement rational analysis. Their preferences, interests, and values can provide the basis for experts to analyze the aspects. At the same time, they are invited to make decisions regarding risk ranking and prioritizing risk treatment strategies.
- *Subjectivity*: Some may be skeptical of the involvement of stakeholder's emotional perspectives of risk would introduce subjectivity to risk analysis. However, risk analysis is not a pure objective activity, encompassing value judgments [32]. On the one hand, risk analysis relies on experts' experience, memory, and common sense and is susceptible to bias [33, 34]. On the other hand, the judgment manifests itself in using generic categories of objectives to represent evaluation criteria, such as determining what consequence to analyze, which group is affected, and more. From a philosophical perspective, it is better to let those who may influenced by adverse impacts decide what to analyze.
- *Legitimacy*: Some may be specious about laypeople who do not receive specific training to make "legitimate" decisions. A reasonable individual can be defined as who "exercises the degree of attention, knowledge, intelligence, and judgment that society requires of its members for the protection of their own and of others' interests" [22]. Although laypeople

Journal Pre-proof

may have more contextual considerations than experts, they should be able to make reasonable decisions for themselves and the communities they represent.

- *Uncertainties and conflicts*: Due to differences in how various types of stakeholders value specific inputs, the increased uncertainties and ambiguities brought by the involvement of stakeholders in risk management are inevitable. Nevertheless, disagreements or cognitive conflicts among experts about physical facts are familiar even in traditional risk analysis. The participation of stakeholders is a way of helping resolve conflicts at the early stage, and it can be systematically addressed as part of the risk management process. The point is we should investigate how to employ negotiation and mediation methods and tools to deal with the newly brought societal conflicts. Furthermore, various conflict resolution methods can be found in scientific literature, such as round tables, mediation, alternative representative surveys, public hearings, focus groups, and more [35, 36].

Risk is a future state of the world. Risk assessment is the description and measurement of risks, seen through the eyes of risk analysts and stakeholders based on knowledge, experience, and values. Risk assessment is, at least, partially subjective and can cause normative conflicts among different parties. It may be impossible to reach a consensus among all parties on what needs to be investigated and what should be analyzed. However, it is still possible to reach a consensus on how to solve the risk problem through communication. The approach is not designed to seek the best answer, but to find a mutually acceptable solution.

3.2 An approach for integrating rational and emotional risk management

The starting point of this approach is that a decision-maker faces some decision points associated with the production, operation, and disposal of systems. For example, implementing a new technology, choosing a risk management policy, etc. The focus is on Type II risks with large uncertainties and potential extreme consequences (e.g., explosions, fires, toxic releases) [37]. Typically, this type of risk has the characteristics of broad geographical dispersion and temporal extension and can affect a wide range of people and institutions. Risk assessments are considered valuable support for decisions in such situations.

The high-level objective of decision-making is not only to minimize the adverse effects on the environment, health, and safety but also to take into account human rights, and normative principles to ensure the decisions are socially acceptable. The stepwise decision-making process

Journal Pre-proof

for risk management is presented in Figure 2. The approach contains six main steps. The detailed process of the approach is described in the following subsections.

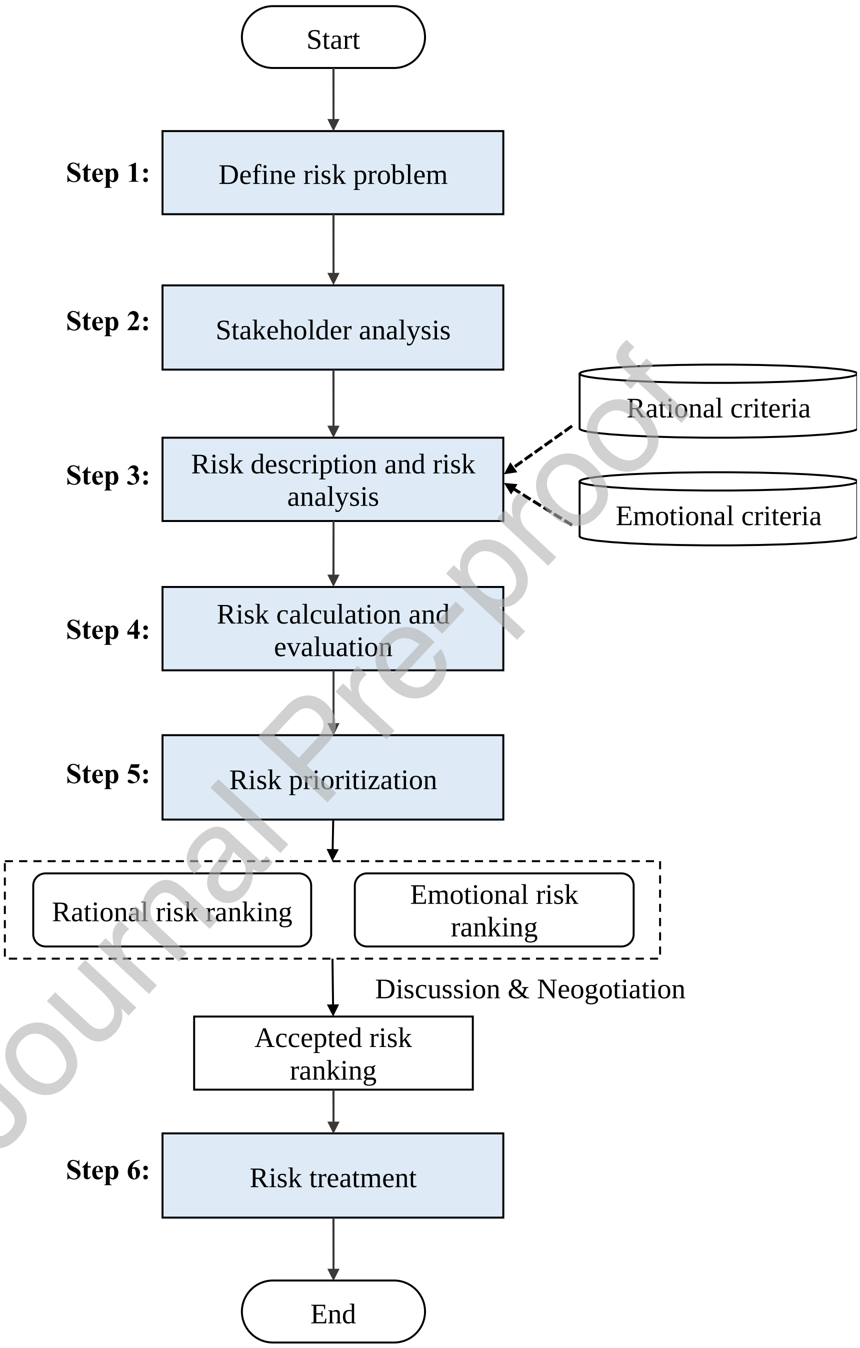

Fig 2. Overview of the integrated rational and emotional risk management approach.

Journal Pre-proof

Journal Pre-proof

3.2.1 Step 1: Define risk problem

In the preparation stage, it is essential to clarify what problems are to be solved, the context of the problem, and the boundaries you want to cover. There are three main steps in this stage:

Step 1.1 Define the risk problem and objectives

Step 1.2 Establish internal and external context

Step 1.3 Set the system boundaries

In the beginning, it is essential to have a clear scope of what to be analyzed. The selection of problems can be made through internal company meetings or by consulting external experts. When the decision problem is identified, the context that frames the problem should be established. The external context incorporates the economic, environmental, political, social, and technological environment that forms the context for the problem being analyzed. The internal context incorporates the elements of the industrial system, for example, establishment, layout, process systems, safety management systems, emergency systems, pipelines, storage tanks, etc. [38].

To analyze the risk problem, it is necessary to specify the boundaries of risk assessment. For instance, the period of time over which the activities are observed, the length of time after an event occurs for which we evaluate the consequences of that event, geographical scope within which consequences are analyzed, etc. The discussion process and results, including diverse points of views should be formally documented and publicly reported.

3.2.2 Step 2: Stakeholder analysis

Stakeholder analysis is a newly brought step in this approach compared to the status quo. The aim of stakeholder analysis is to assign different tasks to different stakeholder groups. Generally, stakeholder analysis incorporates the following procedures:

Step 2.1 Identify stakeholders

Step 2.2 Establish contacts with stakeholders

Step 2.3 Determine stakeholders' participatory strategy

Identifying who has stakes in risk problems is the first task of stakeholder analysis. This could be done by brainstorming or look information from documents research articles through a series of meetings or focus groups [39]. For example, in the safety management system, the type of stakeholders may include [40]:

Journal Pre-proof

- The plant (e.g., owners, managers, labor force)
- Public (e.g., affected people)
- Public authorities (e.g., local government)
- Emergency responders (e.g., firefighters, medical emergency responders)
- Others (e.g., business organizations, research institutes)

Once the general stakeholder groups are identified, it is time to establish initial contact with stakeholder groups. This could be done by public meetings. In the meetings, it is essential to decide on representing individuals of each stakeholder group that are expected to participate in the management process and ensure their willingness and availability to participation.

After stakeholders agree and accept the stakeholder participation plan, it is time to determine the targeted participatory techniques to support a practical stakeholder participation process. There are various participation techniques can be used to achieve this goal based on the aim of participation. For instance, newsletters, reports, presentations, public hearings, and internet webpage are suitable for informing or educating stakeholders about risk events. Interviews, questionnaires, surveys, citizen advisory panels, and Delphi techniques can help obtain stakeholder information. Multicriteria analysis, workshops, round tables, and focus groups are suitable for directly engaging stakeholders in decision-making [35]. Available time, budget, geographic locations, stakeholders' availability, and degree of complexity of participation are factors that need to be taken into account in determining participatory strategies [41]. The determination of stakeholder participatory approaches should balance those aspects and communicate with stakeholders until all groups agree on the final engagement plan.

3.2.3 Step 3: Risk description and risk analysis

This step has two main tasks: (1) define how risk is described and represented in risk analysis, and (2) use scientific tools and methods to analyze those attributes to attain an overall picture of risk. The rational concept of risk based on frequency and consequences is still a necessary basis, but it may not be able to capture the complexity and diversity of risk. Risk description is proposed to open the opportunity to integrate rational and emotional factors in risk assessment.

3.2.3.1 Rational criteria

The actual damage linked with the occurrence probabilities of an event is the focal point of the rational concept of risk. Risk analysis based on the rational concept of risk is to capture the objective nature of risks (physical impacts). Therefore, the conventional description of the extent of damage and probability is appropriate to represent the rational concept of risk. Scientific risk analysis performed by experts is considered the most appropriate way to achieve safety goals. More detailed analysis and higher degree of qualification are helpful for meaningful results. Well-known approaches such as Quantitative Risk Analysis (QRA) are commonly used for risk analysis.

3.2.3.2 Emotional criteria

The emotional concept of risk highlighted the subjective risk perception that deviated from the rational risk concept. Societal, psycho-perceptual, and contextual concerns from stakeholders should be treated as valid inputs in the risk description process. It should be noted that the risk description in formula (4) only provides a simple framework that allows risk to be described mathematically. Identifying more specific indicators associated with each dimension is necessary, allowing risks to be calculated and compared.

In practice, risk analysts should work closely with stakeholders to define how their perceptions can be quantified and integrated into risk assessments. Typically, the identification process involves directly soliciting stakeholder opinions through formalized deliberation approaches, such as a series of facilitated workshops or interviews. To avoid a fixed mindset, a list of pre-defined risk indicators can be provided to guide discussions while allowing stakeholders to modify, add, or remove indicators. Several scientific studies have explored the indicators, and those lists are not identical; see [[3], [16], [22], [42], [43], [44], [45]]. Some factors irrelevant to the industrial sector risk assessment for significant accidents are excluded. Some variables with similar meanings were merged into one indicator. Finally, we summarized and compiled a list of indicators for this study. Those indicators are grouped into four categories based on the risk description formula (4) previously introduced, aligning with its four key components: sources, consequences, uncertainty, and manageability (as shown in Figure 3).

Journal Pre-proof

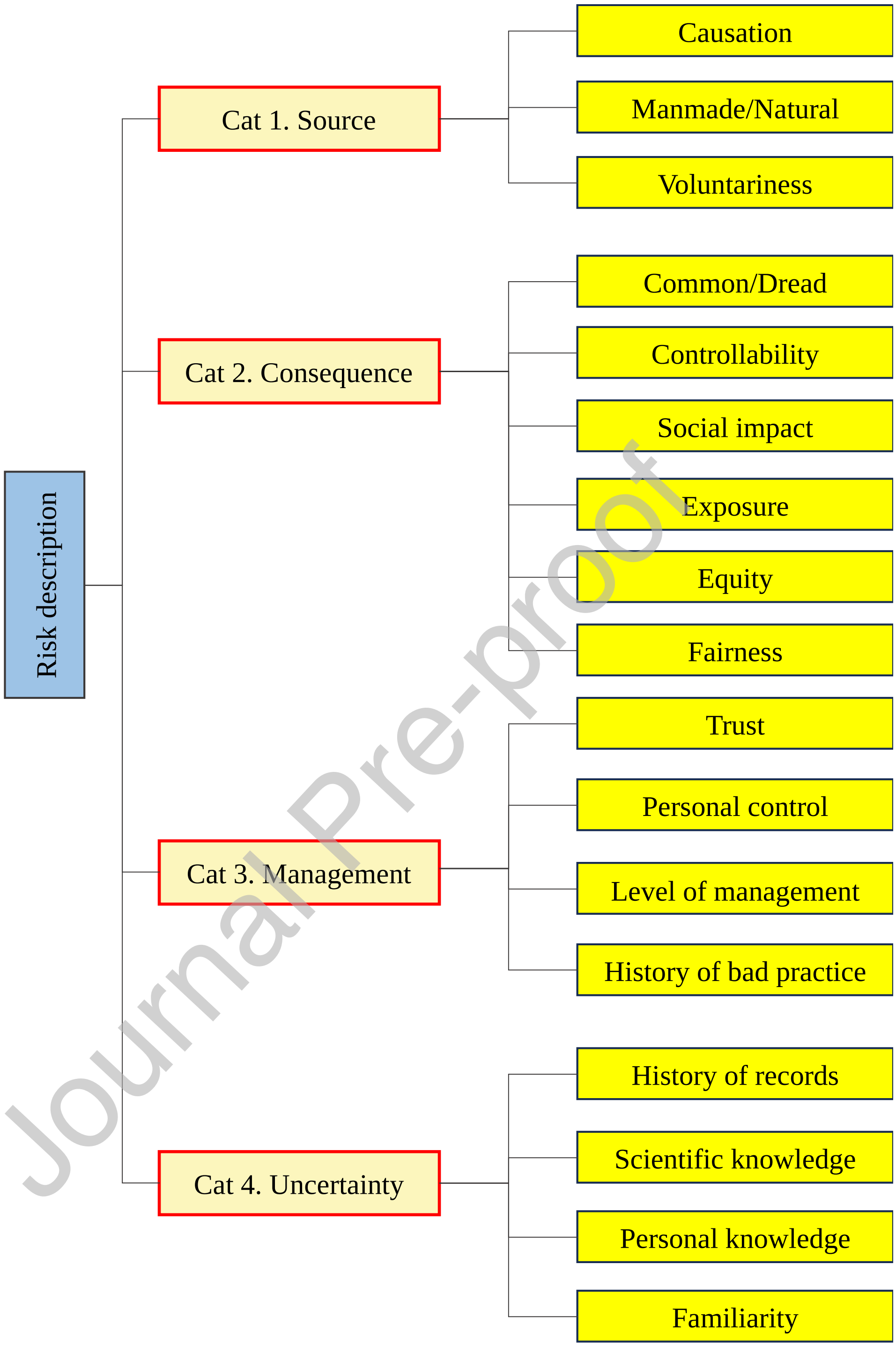

Fig 3. A non-exhaustive overview of criteria of risk, based on [[3], [16], [22], [42], [43], [44], [45]].

Indicator cat.1 Source

- Causation: It distinguishes the ways in which cause harm or risk (intentionally, recklessly, or negligently). It is a concern relating to moral responsibility. From a moral perspective, intentional action is more unacceptable than negligent [22].
- Manmade/Natural: It concentrates on whether risks are induced by human factors or natural hazards. Risks induced by humans seem to be a greater worry than natural risks [3, 45].
- Voluntariness: It concerns with an individual's ability to decide his/her exposure to a given risk. Voluntary risks are less troublesome than involuntary risks [42].

Indicator cat.2 Consequence

- Common/Dread: It is a subjective concern associated with consequences. It refers to the emotional response to risks and can be called "fear of harm" [3, 45]. The fear of harm may be aroused from unusual experiences, ethical concerns, affect sensitive people, etc. [44].
- Controllability: It is related to whether risks are easily reduced or not easily reduced [3].
- Social impacts: Physical effects will interact with psychological, cultural, social, and institutional processes that amplify or attenuate public experience of risk and result in secondary (social) impacts [46]. It includes economic, environmental, ecology, psychological impacts, etc.
- Exposure: It refers to the number of people exposed to the adverse effects. It might be possible to merge it into "dread" [16].
- Equity: Allocation of risks and benefits. It concerns whether risks and benefits are distributed equally [45].
- Fairness: It is related to the distribution of adverse consequences (equitable and inequitable) [22].

Indicator cat.3 Management

- Trust: It is defined as the public trust towards government, experts, and company. People are more concerned about risks when they don't trust the people or system that manages them [44].
- Personal control: It is related to the personal skills of the risk bearers to avoid adverse effects [44, 45].

Journal Pre-proof

Journal Pre-proof

- Level of management: It refers to the ability and resources of the company to prevent or mitigate accidents [44].
- History of bad practice: It refers to the previous history of accidents related to the company [44].

Indicator cat.4 Uncertainty

- History of records: This is related to the frequency of occurrences of hazards in history. For instance, have accidents occurred in similar facilities in the past decades? [44, 45].
- Scientific knowledge: This indicator concerns to what extent the risks are understood by the scientific community, e.g., lack of knowledge about precisely which factors may influence the consequences or likelihood of a given risk [44].
- Personal knowledge of experts: It refers to the experts' knowledge about the mechanism of risk [45].
- Familiarity: It is related to the public's knowledge of the mechanisms of risks. It can also be referred to as personal experience and associated with accessibility to information [3, 45].

It is worth noting that the identified list of indicators is intended to provide guidance for practitioners. In practical applications, other unidentified factors may exist. The identified indicators will be used as supplement criteria to the rational concept of risk and together as the main criteria in the following risk assessment steps.

Some information about the criteria is evident, such as whether the risk event is manmade or natural-induced. However, some require detailed risk analysis and expert judgment. When "consequences" appear in the rational approach, it usually refers to the outcome or the events that have happened. Typically, it is calculated as the direct impacts brought by physical changes (i.e., pressure changes, temperature changes). Since emotional values are also regarded as aspects of the nature of risk in this category, some input to societal and psycho-perceptual variables in risk analysis may come from affected stakeholders. Those variables may not easily be quantifiable, but there exist some specific approaches to measure this type of data indirectly using indicators such as willingness to pay (WTP), willingness to accept (WTA), quality-adjusted life years calculation (QALY), and the alike. However, some may prefer to utilize social science techniques such as focus group discussions, surveys, questionnaires, and interviews to keep the richness of the criteria.

3.2.4 Step 4: Risk calculation and risk evaluation

The aim of this step is to define whether a risk is acceptable and to identify what scenarios/risks require further risk treatment.

The rule of risk evaluation behind the rational approach is that "the calculated risk is sufficiently low." The premise is that there is a standard risk acceptance criterion that can be used to compare a calculated risk level with this absolute criterion. A risk is unacceptable if the risk value exceeds the criterion. Generally, social risk acceptance criteria are deemed appropriate for this type of problem, as risk acceptance criteria are usually focused on the numbers of fatalities and frequencies. For instance, the absolute risk criterion, which is used more often, is "the frequency of death due to a specific hazard shall not exceed 10^{-6} per person-year" [47]. Instrumentally, the risk matrix and FN curves (frequency versus numbers of fatalities) can be used as visualization tools to better understand risks [2].

However, the absolute risk criteria lose their meaning when stakeholders' input is considered. Additional criteria, in addition to probabilities and consequences, will influence the acceptance of risk. Risk perceptions play an important role in this context. For example, the calculated level of a risk may be situated below certain risk acceptance criteria, but it may be judged unacceptable due to its unequal distribution of adverse effects. Different from the rational approach, which focuses on the expected utilities, in this approach, additional focus should be paid on the moral rightness of the risk action or the consequences. From the physical aspects, "the uncertainties and possible consequences (e.g., loss of lives) are required to be reduced to a level that is as low as possible." The residual criteria can be evaluated through weighing the burdens and benefits [48]. For example, exposure of a person to a risk is deemed acceptable if and only if one or more normative rules are satisfied:

- The exposure is outweighed by a more significant benefit
- This exposure is voluntary or works to his/her advantage
- The exposure is part of an equitable social system of risk-taking
- The exposure can be avoided by adopting precautionary measures

In theory, there can be universal normative rules among certain groups or specific members. Hence, instead of applying objective risk criteria so everyone receives the same treatment, risk

Journal Pre-proof

Journal Pre-proof

analysts can consult the affected groups through negotiation and mediation methods to define risk acceptance criteria.

3.2.5 Step 5: Risk prioritization

Risk prioritization is conducted to systematically compare different risks to decide which risks are more severe. The objective of this step is to reconcile perspectives among experts and stakeholders to obtain a generally accepted risk ranking. It starts with risk ranking based on a rational concept of risk (rational risk ranking). Then, a risk ranking with additional emotional considerations is conducted. We refer to it as emotional risk ranking to distinguish it from rational risk ranking. Finally, the two risk ranking results will enter a negotiating process until a final generally accepted risk ranking is achieved among stakeholders. There are many different types of consensus methods that may be used to synthesize stakeholders' opinions. Delphi, nominal group technique (NGT), and consensus development panel approaches are the most commonly used formal consensus methods in group decision-making [49]. The rational and emotional risk ranking methods are compared and discussed in the following context.

3.2.5.1 Rational risk ranking

Expected value is a commonly used method in standard risk ranking. It is established on a rational concept of risk probability and consequences. For instance, the expected value of a risk can be interpreted as the center of gravity of the probability distribution of the weighted average of all possible outcomes. Mathematically, it can be written as:

$$R_i = \sum_{i=1}^{n} p_i C_i \tag{5}$$

Where n is the number of accident scenarios i, p_i is the probability of occurrence (per year) of scenario i, C_i are the consequences (fatalities) of scenario i.

The rational risk ranking procedure according to the rational approach is straightforward. After determining the scenarios, the probabilities and consequences of the scenarios need to be determined. Furthermore, the data are integrated based on a risk calculation formula consisting of probability and consequences which can be prioritized.

3.2.5.2 Emotional risk ranking

If stakeholders require additional emotional aspects to be considered in risk ranking, approaches that could combine rational and emotional attributes are needed. There is no unique method to tackle this problem. Those methods vary according to whether the outcome is semi-quantitative or qualitative. We summarized some key methods and their main steps to tackle this problem.

Qualitative risk scale is a method proposed by Gardoni and Murphy [22] and in this work, they first proposed adding a "source" dimension to the risk definition. Qualitative risk scale is a simple and quick approach focusing on crude grading for each risk. It is conducted by combining all the levels of each attribute to create a composite scale. Risk ranking according to the qualitative risk scale can be performed based on the following procedure. Firstly, each criterion of risk should be classified by some type of categorization system, e.g., low, moderate, high. The classification of levels can be derived based on experts' or stakeholders' opinions. Secondly, the possible combinations of the dimensions are grouped and ranked and form a specific risk scale. Ultimately, risks can be compared and prioritized using the developed risk scales.

The integrated quantitative and qualitative (Q&Q) risk index is a method developed by Reniers and Van Erp [23] to combine emotional and rational considerations. The emotional factors could be seen as influencing factors that amplify or attenuate rational risk.

$$R_i = \frac{p_i C_i^a}{\beta_i\left(E_i F_i^b\right)} \tag{6}$$

Where β_i is policy factor that varies with the degree of participation in the risk due to event/scenario i being voluntary, E_i is a parameter representing an equity principle, and F_i is a parameter representing a fairness principle, a is aversion factor towards consequences, and b is a factor representing the level of recklessness of a risk decision. In the integrated Q&Q risk index approach, the qualitative data are calculated by a scoring system (0.1-very low, 0.5-low, 1-medium, 1.5-high, 2-very high). In theory, this approach should be based on an empirical analysis and represents the realistic link between quantitative and qualitative data. Nevertheless, in the current situation where theoretical and empirical data are insufficient, the relationships between parameters are largely based on subjective assumptions. For example, it assumes that a higher level of voluntariness, equity, and fairness results in a lower level of risk. This is true because such risks will be prioritized lower than risks with lower voluntariness for decision-making. Secondly, β, E,

Journal Pre-proof

Journal Pre-proof

F are dimensionless parameters, and the determination of their ranges of values would have significant effects on the risk value. The suggested value range of these parameters is from 0.1 to 2. It implies that involuntary risk (β=0.1) is 20 times higher than voluntary risk (β=2). However, some psychology surveys reflect different outcomes; this number in [42, 43] is 1000 and 100 respectively.

This method is established as a function of the expected value and weighted sum of the scores of subjective considerations. The rational aspects are similar to the standard approach. The emotional elements are calculated as a composite score obtained by multiplying scores and weights. Mathematically, it can be written as:

$$R_i = P_i C_i \sum w_i \times X_i \tag{7}$$

Where w_i is the weight of each criterion of risk, X_i is the score of each criterion of risk. Typically, weighted scoring can be conducted according to the following steps. Firstly, the variables need to be classified into several categories by communication between risk analysts and stakeholders. Then, each category needs to be assigned a score (i.e., 1, 2, 3) for further calculation. To assign weight to an attribute, a range of Multi-Criteria Decision Analysis (MCDA) weighting methods can be used (i.e., AHP, swing weights) [50, 51]. Specifically, the research group of Carnegie Mellon University developed a standard procedure of deliberative risk ranking, and the weights are derived based on stakeholders' preference [52]. This approach is much easier compared to conventional MCDA methods. At last, the overall scores and weights are calculated to derive the overall value of risks.

3.2.6 Step 7: Risk treatment

Risk treatment comprises (1) decision-making and (2) implementation of risk treatment strategies. The focus of decision-making is to compare and select the most optimal risk treatment strategies by weighing the impacts brought by the alternatives on risks. Decision-making is an iterative process; this step often requires reassessing the impact of risk treatment measures when new risk treatment strategies are to be compared. There are many decision tools that can be used to assess risk treatment options. Generally, the cost of implementing the risk treatment strategy is the only criterion in addition to risk in the standard approach. When it comes to emotional-based approaches, sometimes other ethical and societal factors also need to be compared. There are many other criteria that may be considered. Examples include cost, timing, equity, fairness,

Journal Pre-proof

administrative efficiency, compatibility, individual freedom, etc., to deal with this variety of normative criteria, negotiation tools such as workshops, focus groups, MCDA and whatever you can apply.

Implementation involves reviewing the decision process as well as implementation of the decision. In practical implications, the outcome of decisions usually cannot keep everyone satisfied. Review is a step to review the decision procedure, the result of decision, and the decision itself. For instance, when reviewing, issues that should be focused on may include [53]: are the decision processes documented and traceable? Are all the relevant stakeholders identified? Are there some concerns from stakeholders that have not been considered? In theory, the decision should ensure that no critical protest exists. The opinions of the minorities or the presence/absence of controversy over the issue should be documented. If there is no critical protest towards the decision, implementation of the final option can be carried out.

4 An illustrative example

The proposed stepwise approach is applicable to a number of Type II risk problems (major accidents that occur with low frequencies and high consequences) [23]. This section aims to use an illustrative example to demonstrate the applicability of the approach to fundamental modeling instead of its application to a specific case. Thus, we do not go into detail about every step of the approach. The primary focus is on how risk is described and prioritized with consideration of emotional factors. Nevertheless, to make the example more concrete, a hypothetical site selection problem for an ammonia plant was chosen to provide further details. The rationale for selecting this risk problem is that site selection involves multiple factors and requires a combination of scientific risk assessment, ethical considerations, and stakeholder participation, by which the proposed risk management approach can be clearly illustrated and compared.

4.1 Problem definition

The example considers the problem of deciding where to locate an ammonia plant. After a preliminary site screening of land policy, regulations, traffic conditions, public facilities, and other issues, three alternative locations are being considered for the following risk assessment and decisions:

- Location A: an industrial park

Journal Pre-proof

Journal Pre-proof

- Location B: a suburban area
- Location C: a flood-prone area

To analyze and compare the risks of major hazards of each location, three representative accident scenarios are selected for further risk assessment based on regulatory requirements, historical data, and environmental characteristics: (1) location A: a domino effect leading to damage of ammonia containment and a gas cloud of ammonia caused by the neighboring plant in the industrial park; (2) location B: a major accident within the plant leading to an ammonia cloud to a residential area; (3) location C: a large-scale leakage of ammonia caused by a flood. In the following context, they are referred to as RS1, RS2, and RS3.

4.2 Stakeholder analysis

One of the primary goals of the approach is to reconcile different values between scientific risk assessment and stakeholder risk perception. A broader risk characterization that can reflect the concerns of stakeholders is required. In this example, five groups of stakeholders, including ammonia plant, local government, Non-Government Organizations (NGOs), residents, and the neighboring plant, are involved in risk management process.

On one hand, the plant itself, including owners and managers, consists of an important type of stakeholders. The local government has a financial stake by funding part of the construction costs of the plant. Another important group is Non-Government Organizations (NGOs). When it comes to major accidents, their stakes are primarily focused on environmental protection, public health, and social justice. Local residents are crucial stakeholders in the operation of ammonia plants, as they are vulnerable to major accidents. Their stakes involve various aspects of safety, environment, and social well-being. Finally, the neighboring plant in the cluster park will also be threatened by major accidents that could have a negative impact on production and the economy.

4.3 Risk description and risk analysis

The approach focuses on reconciling different values and interests to reach a consensus among stakeholders. Broader risk characterization that can reflect the concerns of affected groups and the public is required. Following the procedure in Section 3, we assume that a list of concerns, in addition to rational criteria, has been gathered through dialogs among stakeholders:

Journal Pre-proof

- History of records: it concerns the history of accidents regarding similar facilities
- Social impacts: it denotes the greatest environmental impact in a single event
- Controllability: it examines if risk is easily/not easily reduced
- Knowledge: it refers to current scientific knowledge of the cause-effect mechanism of risk scenarios
- Dread: it refers to emotional response towards risks

To determine the level of the emotional criteria, a crude qualitative risk analysis (low, moderate, high) can then be carried out by risk analysts. The categorization of different variables can be conducted through a series of questions posed to stakeholders. For instance, how many deaths do you think should be rated as low, moderate, and high? To illustrate, we assumed a categorization system was established to classify risk attributes into three levels based on stakeholders' risk appetite (as shown in Table 1).

Table 1. Hypothetical criteria developed for this example.

Criteria	Rating		
	Low	Moderate	High
History of records	History provides no records	History evidence is recorded but from a considerable time ago	History evidence is recorded within the past few years
Controllability	Easily reduced	Partially controllable	Difficult or impossible to control
Social impact	Minimum and negligible environmental damage	Moderate and immediate environmental damage	Large-scale and long-lasting environmental damage
Knowledge	A large amount of information and historical data are available	Some factors and variables are unknown, but the model used is reliable	Information and historical data are very limited or absent
Dread	Only employees or workers within the plant/park are impacted	Many people, including the local community, will be affected	Widespread impact beyond the local community, potentially affecting a large population.

Journal Pre-proof

After the criteria of risk analysis are determined, risk analyst conducted risk analysis to collect data regarding the criteria. The rational criteria of risk that probability and consequences can be estimated based on the classic QRA approach. Those emotional aspects are assessed by a scoring system: low=0.1, moderate=1, high=2. Since our purpose is to demonstrate how the decision process works, the risk analysis has been simplified, assuming the value of those risk criteria are known. The illustrative results of risk analysis are listed in Table 2.

Table 2. Illustrative risk analysis results.

Criteria	Risk Scenario (RS)		
	RS1	RS2	RS3
Frequency (year)	$1*10^{-7}$	$1*10^{-4}$	$1*10^{-5}$
Consequence (€)	$1.5*10^{8}$	$2*10^{6}$	$1.2*10^{8}$
History of records	0.1	2	0.1
Controllability	2	1	2
Social impact	1	1	2
Knowledge	2	1	1
Dread	1	1	2

For the sake of clarity, the underlying assumptions of rating of emotional criteria are illustrated below:

4.2.3.1 History of records

A score of 2 has been given to RS2 because the accident database shows the record of major ammonia accidents in the past few years. By contrast, a score of 0.1 has been given to RS1 and RS3 because there is no evidence of similar accidents in history.

4.2.3.2 Controllability

A score of 2 has been assigned to RS1 because the multiple chemical plants in the industry park increase the complexity of managing the interactions among different facilities. A score of 1 has been given to RS2 because the complexity of a single event is relatively moderate, and the event can be partially avoided. A score of 2 has been given to RS3 because the flood may damage the safety control system, and floods may accelerate the spread of chemicals and expand the geographical area of pollution.

Journal Pre-proof

4.2.3.3 Social impact

A score of 1 has been given to RS1 and RS2 because the release of ammonia will affect a large area of soil and cause harm to the ecosystem but not necessarily a catastrophic one. A score of 2 has been given to RS3 because the spread of ammonia contamination might affect a broader geographic area.

4.2.3.4 Knowledge

A score of 2 has been assigned to RS1 because domino effects are a kind of complex and highly uncertain process. It is hard to give an accurate prediction of the occurrence probability and consequences. A score of 1 has been given to RS2 and RS3 because although similar accidents don't occur often, the knowledge of the cause-effect mechanism of a single event is higher than domino effects.

4.2.3.5 Dread

A score of 1 has been assigned to RS1 because the large-scale release of ammonia may cause casualties in nearby chemical plants. A score of 1 has been given to RS2 because it can directly affect the vulnerable populations living nearby. People may feel dread when facing such events. A score of 2 has been given to RS3 because the impacts brought by the leakage of chemical substances into a flood is highly unpredictable. The influence may be long-lasting and cannot be observed.

4.4 Risk prioritization

4.4.1 Rational approach

The focus of the rational approach is on safety and technical aspects. The natural way is to perform QRA on the criteria of consequences and associated probabilities, see formula (5). The ranking is expressed in ordinal order, with 1 being the highest-ranked risk and 3 being the lowest-ranked risk.

Table 3. Results of standard risk ranking approach.

Risk scenario	Risk value	Risk ranking
RS1	15 €/ year	3
RS2	200 €/ year	2
RS3	1200 €/ year	1

Journal Pre-proof

From the results, the rankings of different risk scenarios can be observed. Following the rational risk ranking, RS3 is the highest-ranked risk. From risk management point of view, location A, an industrial park, would be the most appropriate site to construct the ammonia plant. Based on the criteria defined, location B is the second-best selection, and location C is the worst choice.

4.4.2 Emotional approach

When applying an emotional approach, it is essential to consider stakeholders' emotional criteria across different risk scenarios. To illustrate, the risk index method (see formula (6)) is applied to measure and integrate emotional factors into risk ranking. In this example, we assume that the history of records, severity, social impact, and dread are positively correlated to risk value, while controllability and knowledge are negatively related to risk value. Finally, the overall risk scores are obtained following the procedure mentioned in section 3. Based on the scores, a ranking of risks are obtained (Table 4).

Table 4. Results of emotional risk ranking approach.

Risk scenario	Risk value	Risk ranking
RS1	0.4	3
RS2	2	1
RS3	0.8	2

Based on the results, the rankings of different risk scenarios can be observed. In both ranking approaches, RS1 achieved the lowest score, but the rankings of RS2 and RS3 changed. Despite RS3 receives higher score than RS2 when only probability and consequences are considered. However, with additional consideration of the emotional factors assumed above, RS2 receives the highest score among the three scenarios. Accordingly, if emotional risk ranking is applied, location A might be the best construction site. In contrast, suburban areas became the least favorable option.

4.4.3 Discussion and negotiation

After obtaining the results of two different risk ranking strategies, risk analysts and stakeholders should discuss the results and reach a consensus. Different opinions regarding categorizations may exist. As mentioned in Section 3.2.5, some mediation techniques can help to achieve consensus. Due to this being an illustrative example, we assume that the stakeholder groups reached an

Journal Pre-proof

agreement on how risks are prioritized through the consensus methods. The three risk ranking results are listed in Table 5.

Table 5. Comparison of standard, emotional-based, and final generally accepted risk ranking of major risk accidents of the three locations.

Risk scenario	Standard risk ranking	Emotional risk ranking	Accepted risk ranking
RS1	3	3	3
RS2	2	1	1
RS3	1	2	2

After discussion, a final generally accepted risk ranking is developed. RS2 has the highest risk and is considered the least suitable location for ammonia plant construction. RS1 receives the lowest risk level. Accordingly, location A is considered the most suitable place to construct the ammonia plant.

5 Discussion

Technology risks brought by human activities constitute the most major adverse impacts on the safety and well-being of individuals, social groups, and non-human entities. The conflicts between scientific risk analysis and laypeople's risk perception are increasingly intensified. Prior studies suggested that public distrust in science can be attributed to a lack of communication and insufficient information. The expert-lay discrepancies can be explained as the differences between rational and emotional manner of thinking. In this study, we propose a stepwise integrated rational and emotional risk management approach that enables stakeholders to obtain scientific information related to risk decisions that may affect them.

Firstly, a modified risk definition is proposed with the involvement of the element "human at stake." The modified risk definition acknowledges the physical components of risk but also objectively or depends on human judgments. The social science approach to risk believes risk is constructed within cultures and societies [15]. The concept of risk is always linked with groups' values and interests and shaped by human interventions and social organizations [54]. What is deemed worthy of investigation may vary depending on the stakeholder group being considered. Based on the Bow-tie model, risk is represented by four dimensions: sources, consequences, management, and uncertainties. Compared with earlier scientific works on extending risk

Journal Pre-proof

Journal Pre-proof

descriptions, see [[22], [23], [52]], this work provides a more dynamic and adjustable approach without loss of generality. Contrary to pre-define the attributes, our definition provides a general framework that allows stakeholders to develop more specific risk descriptions. This indicates that risk description should not be viewed as homogenous in a society. Rather, we emphasize individuals' sovereignty in risks that affect them. From a long-term view, risk is not static; values are dynamic and can change with the development of society. Changes in constraints of political, economic, and social boundaries would introduce new characteristics in risk descriptions.

Secondly, to target major hazards involving potentially high risk and multiple conflict interests, a systematic risk management procedure with the engagement of stakeholders is developed. This approach distinguishes itself from conventional risk management in three aspects: (1) a *stakeholder analysis* step that allows affected groups and the public to engage in risk management process; (2) a *risk description* step in which the stakeholders can interpret their concerns to determine what to be analyzed in risk assessment; (3) a *risk prioritization* step which is designed for resolving the conflicts between scientific risk analysis and laypeople's risk judgments. In the long run, the approach helps reconcile conflicts between stakeholders and experts to ensure the solution can be socially acceptable. This could be seen in the illustrative example. Obviously, risk ranking based on pure rational thoughts yields a different outcome compared with risk ranking considering additional emotional aspects. The plant managers and experts may not be interested in emotional considerations such as dread and knowledge in risk ranking. However, NGOs and residents may prefer to have a more comprehensive description of risk to make a more informative judgment. By involving stakeholders in risk decision-making process, their concerns and values can be clearly expressed and observed. This decision is co-determined by stakeholders and risk analysts, which is believed to be accepted by the plant, local government, NGOs, residents, and neighboring plants.

This approach is not intended to replace the traditional risk management framework but to extend it. In the past, risk management norms considered laypeople's risk perception to be "heuristics and biases" that deviated from rational risk analysis [51]. However, many risk perception studies suggest that layman emotional risk assessment actually provides richer perspectives for managing risks. Yet, many of these studies have limited their research findings within the social science field without direct application in the domains of risk management [33,

Journal Pre-proof

55]. Some of today's risk management guidelines, for example, Managing Risks to the Public: Appraisal Guidance [44] and IRGC risk governance framework [31], do acknowledge the importance of emotional considerations in decision-making. However, they advocate that risk perceptions and societal considerations are assessed in "concern assessment" to supplement "scientific risk analysis" to avoid introduce biases to the system. While it is true that a layman's perception can be biased or an error, risk analysts are not immune to mistakes, especially when provided with inappropriate data. As mentioned earlier, in situations where data is scarce, experts often use model outputs as heuristic tools to generate missing information. This reflects the reality that laypeople usually have unequal access to scientific risk information when facing some of today's risks compared to experts. By systematically involving stakeholders in risk management, they have the opportunity to voice their views and gain a deeper understanding of the scientific perspective. Early engagement helps to address and resolve potential conflicts between expert assessments and lay perceptions from the start rather than after decisions have already been made.

While this study proposes a possible way to reconcile conflicts between science and societal acceptance by integrating rational and emotional perspectives, there are several limitations that require future development and improvement. The current model represents an initial attempt to incorporate public values, such as fairness, equity, and emotional response, into formal risk management. The model is relatively crude, with simplified assumptions about how stakeholders express their values and interests and how various stakeholders reach a consensus on an emotional risk ranking. Furthermore, the details of this methodology remain conceptual and high-level, such as how to identify key stakeholders, and the interplays of negotiation and discussion process. More detailed methodology may enhance the applicability of the approach. The case study utilized in this paper is hypothetical and intended to demonstrate the potential of the proposed approach. The practicality of the approach should be tested with real-life scenarios in future studies.

In summary, this approach offers a potential solution for reconciling expert-lay conflicts and enhancing public trust in risk management by integrating rational and emotional concepts of risk. While the approach may not always lead to desired results, the negotiation process is meaningful for narrowing down the gap between experts and the public.

Journal Pre-proof

6 Conclusions

This article aims to propose a normative risk management model aimed at resolving conflicts between scientific risk analysis and public risk judgments. The article explains the reasons behind the discrepancies between expert and lay perspectives and highlights the importance of incorporating stakeholders' emotional considerations within risk management.

By updating the risk definition $(C, U)_\eta$ with involvement of people at stakes η, this paper emphasizes the indispensability of human values in shaping the concept of risk. The modification of risk definition provides a reasonable basis for stakeholders to participate in risk management. Following this, the paper introduces a stepwise, integrated approach that combines rational and emotional perspectives in risk management, specifically designed for risks with high consequences and significant uncertainties. An illustrative example is presented to demonstrate the approach's applicability, showing that following this systematic procedure enables the effective integration of stakeholder input into rational risk analysis, ultimately supporting the policy-making process. Including stakeholders and incorporating their perspectives into risk assessment is expected to help bridge the gap between scientific risk analysis and public concerns.

In the future, the challenge will be utilizing more precise tools and approaches to manage risks with the approach.

Acknowledgement

This work is supported by the China Scholarship Council (Grant No:202106340031).

References

1. Aven, T., *On how to define, understand and describe risk.* Reliability Engineering & System Safety, 2010. **95**(6): p. 623-631.
2. Ale, B., T. Aven, and R. Jongejan. *Review and discussion of basic concepts and principles in integrated risk management*. in *European Safety and Reliability Conference (ESREL 2009)*. 2009. Prague, CZECH REPUBLIC.
3. Fischhoff, B., et al., *How safe is safe enough? A psychometric study of attitudes towards technological risks and benefits.* Policy sciences, 1978. **9**: p. 127-152.
4. Hansen, J., et al., *Beyond the knowledge deficit: recent research into lay and expert attitudes to food risks.* Appetite, 2003. **41**(2): p. 111-121.
5. Slovic, P., J.H. Flynn, and M. Layman, *Perceived risk, trust, and the politics of nuclear waste.* Science, 1991. **254**(5038): p. 1603-1607.

Journal Pre-proof

6. Begg, C., *Power, responsibility and justice: A review of local stakeholder participation in European flood risk management.* Local Environment, 2018. **23**(4): p. 383-397.
7. Almoradie, A., V. Cortes, and A. Jonoski, *Web‐based stakeholder collaboration in flood risk management.* Journal of Flood Risk Management, 2015. **8**(1): p. 19-38.
8. Maskrey, S.A., et al., *Participatory modelling for stakeholder involvement in the development of flood risk management intervention options.* Environmental modelling & software, 2016. **82**: p. 275-294.
9. Nouzari, E., T. Hartmann, and T. Spit, *Interactive governance for satisfaction measurements: Stakeholder involvement in design processes for flood risk management.* Journal of Flood Risk Management, 2020. **13**(4): p. e12650.
10. Weale, V., et al., *Workplace musculoskeletal disorders: A systematic review and key stakeholder interviews on the use of comprehensive risk management approaches.* International Journal of Industrial Ergonomics, 2022. **91**: p. 103338.
11. NRC, *Understanding risk: Informing decisions in a democratic society*. 1996, National Academy Press Washington, DC.
12. Renn, O., *A model for an analytic− deliberative process in risk management.* Environmental Science & Technology, 1999. **33**(18): p. 3049-3055.
13. Gerkensmeier, B. and B.M. Ratter, *Governing coastal risks as a social process—Facilitating integrative risk management by enhanced multi-stakeholder collaboration.* Environmental Science & Policy, 2018. **80**: p. 144-151.
14. Sjöberg, L., *Limits of knowledge and the limited importance of trust.* Risk analysis, 2001. **21**(1): p. 189-198.
15. Xu, Y., G. Reniers, and M. Yang, *A multidisciplinary review into the evolution of risk concepts and their assessment methods.* 2024.
16. Slovic, P., B. Fischhoff, and S. Lichtenstein, *Facts and fears: Understanding perceived risk*, in *The perception of risk*. 2016, Routledge. p. 175-191.
17. Li, Y., N.M. Ashkanasy, and D. Ahlstrom, *The rationality of emotions: A hybrid process model of decision-making under uncertainty.* Asia Pacific Journal of Management, 2014. **31**: p. 293-308.
18. Roeser, S., *The role of emotions in judging the moral acceptability of risks.* Safety science, 2006. **44**(8): p. 689-700.
19. Williams, S.J., *4 Is rational choice theory 'unreasonable'?: The neglected emotions*, in *Rational Choice Theory*. 2013, Routledge. p. 57-72.
20. Kassam, K.S., *Emotion and decision making.* Annu. Rev. Psychol, 2015. **66**: p. 33-1.
21. Vlek, C.A., *A multi-level, multi-stage and multi-attribute perspective on risk assessment, decision-making and risk control.* Risk decision and Policy, 1996. **1**(1): p. 9-31.
22. Gardoni, P. and C. Murphy, *A scale of risk.* Risk analysis, 2014. **34**(7): p. 1208-1227.
23. Reniers, G.L. and H.N. Van Erp, *Operational safety economics: a practical approach focused on the chemical and process industries*. 2016: John Wiley & Sons.
24. Xu, Y., et al., *An Integrated Technical and Societal Risk Index for Ranking Major Accident Risks in Chemical Process Industries.* 2024.
25. Kaplan, S. and B.J. Garrick, *On the quantitative definition of risk.* Risk analysis, 1981. **1**(1): p. 11-27.
26. Rosa, E.A., *Metatheoretical foundations for post-normal risk.* Journal of risk research, 1998. **1**(1): p. 15-44.

Journal Pre-proof

Journal Pre-proof

27. Iso, I., *Risk management–Principles and guidelines.* International Organization for Standardization, Geneva, Switzerland, 2009.
28. Blokland, P. and G. Reniers, *An ontological and semantic foundation for safety and security science.* Sustainability, 2019. **11**(21): p. 6024.
29. Logan, T.M., et al., *The role of time in risk and risk analysis: Implications for resilience, sustainability, and management.* Risk Analysis, 2021. **41**(11): p. 1959-1970.
30. Aven, T., *On the gap between theory and practice in defining and understanding risk.* Safety science, 2023. **168**: p. 106325.
31. Florin, M.-V. and M.T. Bürkler, *Introduction to the IRGC risk governance framework.* 2017.
32. Fischhoff, B., *The realities of risk-cost-benefit analysis.* Science, 2015. **350**(6260): p. aaa6516.
33. Pidgeon, N., *Risk assessment, risk values and the social science programme: why we do need risk perception research.* Reliability Engineering & System Safety, 1998. **59**(1): p. 5-15.
34. Lichtenstein, S., et al., *Judged frequency of lethal events.* Journal of experimental psychology: Human learning and memory, 1978. **4**(6): p. 551.
35. Renn, O., *Stakeholder and public involvement in risk governance.* International Journal of Disaster Risk Science, 2015. **6**: p. 8-20.
36. Florin, M.-V. and S.D. Parker, *Involving stakeholders in the risk governance process.* 2020.
37. Meyer, T., & Reniers, G. L. L. M. E., *Engineering risk management. (2 ed.)* 2016: Walter de Gruyter.
38. Norway, S., *Risk and emergency preparedness analysis, NORSOK Standard Z-013.* 2010.
39. Reed, M.S., et al., *Who's in and why? A typology of stakeholder analysis methods for natural resource management.* Journal of environmental management, 2009. **90**(5): p. 1933-1949.
40. Reniers, G.L., et al., *Designing continuous safety improvement within chemical industrial areas.* Safety Science, 2009. **47**(5): p. 578-590.
41. Jones, N. and H. Preskill, *A practical guide for engaging stakeholders in developing evaluation questions.* 2009.
42. Starr, C., *Social benefit versus technological risk: what is our society willing to pay for safety?* Science, 1969. **165**(3899): p. 1232-1238.
43. Litai, D., *A risk comparison methodology for the assessment of acceptable risk*. 1980, Massachusetts Institute of Technology.
44. Treasury, H., *Managing Risks to the Public: Appraisal Guidance, June 2005*. 2005.
45. Achille, J., K. Ponnet, and G. Reniers, *Calculation of an adjusted Disproportion Factor (DF∗) which takes the societal acceptability of risks into account.* Safety Science, 2017. **94**: p. 171-180.
46. Kasperson, R.E., et al., *The social amplification of risk: A conceptual framework.* Risk analysis, 1988. **8**(2): p. 177-187.
47. Vanem, E., *Ethics and fundamental principles of risk acceptance criteria.* Safety science, 2012. **50**(4): p. 958-967.
48. Hansson, S.O., *Ethical criteria of risk acceptance.* Erkenntnis, 2003. **59**(3): p. 291-309.
49. Humphrey-Murto, S., et al., *The use of the Delphi and other consensus group methods in medical education research: a review.* Academic Medicine, 2017. **92**(10): p. 1491-1498.

50. Morgan, K.M., et al., *A deliberative method for ranking risks (II): Evaluation of validity and agreement among risk managers.* Risk Analysis, 2001. **21**(5): p. 923-923.
51. Plattner, T., T. Plapp, and B. Hebel, *Integrating public risk perception into formal natural hazard risk assessment.* Natural Hazards and Earth System Sciences, 2006. **6**(3): p. 471-483.
52. Florig, H.K., et al., *A deliberative method for ranking risks (I): Overview and test bed development.* Risk analysis, 2001. **21**(5): p. 913-913.
53. König, A., et al., *The SAFE FOODS framework for improved risk analysis of foods.* Food Control, 2010. **21**(12): p. 1566-1587.
54. Renn, O., *Concepts of risk: An interdisciplinary review part 1: Disciplinary risk concepts.* GAIA-Ecological Perspectives for Science and Society, 2008. **17**(1): p. 50-66.
55. Slovic, P., B. Fischhoff, and S. Lichtenstein, *Why study risk perception?* Risk analysis, 1982. **2**(2): p. 83-93.

Journal Pre-proof

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

☐ XX is an editorial board member for Journal of Safety Science and Resilience and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.