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Review

A Multidisciplinary Review into the Evolution of Risk Concepts and Their Assessment Methods

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Abstract: Risk is a complex and multi-faceted concept defined and addressed differently across disciplines. Recent years have seen a growing recognition of the need for a more comprehensive and integrated risk perspective combining insights from various disciplines. However, those works have rarely been analyzed in literature reviews. This article explores the possible way of advancing how we assess and manage risks by reviewing the theories, approaches, models, and other fundamental aspects of different disciplines relevant to risk concepts. Additionally, we compare the origins, connections, and differences between state-of-the-art risk science and risk concept research in various disciplines. Some suggestions and future directions are provided for improving risk assessment. This paper helps to deepen the understanding of the risk concept and advance the development of the risk management arena.

Keywords: risk concept; multidisciplinary risk perspective; risk; risk fundamentals; risk assessment

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1. Introduction

The risk concept is the foundation of the approaches and methods of risk management, as terminology can affect and become a part of the theoretical framework in which we study risk and how we cope with it [1]. The practices of modern formal risk management have only emerged in recent decades, nevertheless, people have been dealing with risk problems for a long time. Since the 1990s, there has been increasing interest in redefining and refining the concept of risk, and substantial knowledge has been added to this fundamental area [2]. The distinction between risk and related concepts also received much attention (i.e., risk and hazard; risk and risk perception [3,4]. Aven's work provides a historical perspective, showing how the definition of risk has shifted in recent decades from probability-based thinking to an emphasis on uncertainty [5]. Boholm explored how Swedish government agencies define risk and identified inconsistencies between usage and definitions [6].

Modern society is increasingly occupied with preventing, managing, and mitigating all types of risk across a range of societal sectors, such as insurance, common law, natural disasters, epidemic disease, pollution, food contamination, building and fire codes, transportation accidents, and traffic injuries [7,8]. The literature on formal risk studies has expanded across multiple disciplines, each contributing unique insights on the taxonomy of risk perspectives. For instance, Jasanoff identified "two cultures" divide in risk analysis: disciplines such as mathematics, biostatistics, toxicology, and engineering, contribute to quantitative risk analysis on one side, while law, psychology, sociology, and economics contribute to nonquantitative side [9]. Althaus's multidisciplinary survey of risk literature uncovered conflicting attributes of risk across fields, with risk being viewed as objective or subjective, knowable or unknowable, individual or collective, and both rational and emotional [10]. Similarly, Renn's review highlights a distinct divide between the technical and natural sciences, which focus on the physical impacts of risk, and the economic, psychological, and social sciences, which emphasize the relationship between risk and society [11,12].

In recent years, formal risk management is increasingly recognized in organizations as a systematic approach to avoid losses and disasters. Many integrated risk management frameworks are developed to identify, assess and treat risks, from organizational context to national safety and security. These frameworks—such as the COSO Enterprise risk management framework [13]; the risk framework of the Dutch Government [14]; and the ISO 31000 standard on risk management [15], Cabinet Office [16]—cover a broad spectrum, including infectious diseases, ecological safety, cyber threats, major accidents, social and political stability, terrorism, international and military threats, economic, etc. Despite ongoing scientific debate on the multidimensional nature of risk, nearly all integrated frameworks are based on the rational idea that risk is a combination of probability/uncertainty and consequences, with little attention to contextual factors [17].

Nonetheless, many real-world risk problems are complex and multi-faceted, requiring a new risk management paradigm that bridges the disciplinary divide and allows for a more holistic approach to address the complexity of modern risks. While prior research has reviewed disciplinary perspectives on risk, there remains a need for studies that systematically analyze how definitions of risk are linked to disciplinary backgrounds, and how these different perspectives might collaborate effectively. This paper re-examines the concept of risk from a multidisciplinary perspective, with a focus on risk definitions and assessment methods. It is hoped that this review will:

- Mitigate the tendency to view and assess risk without considering its context;
- Clarify the reasons why risk is understood and assessed differently across disciplines;
- Shed light on the intellectual origins of current approaches to risk;
- Provide a foundation for future interdisciplinary collaboration.

The literature review is organized as follows. Section 2 elaborates on the literature review methodology of this study. Section 3 explores the historical development of risk research in different disciplines, with a focus on the initial engagement of different fields in the study of risk and main contributions. Section 4 identifies and categorizes diverse definitions and interpretations of risk. Section 5 explores "how" risk is assessed according to these varied definitions and interpretations. Before concluding, Section 6 discusses the impact of multidisciplinary perspectives on current risk theories and anticipates potential future directions in risk management.

2. The Review Methodology

The objective of this study is not to provide a thorough review to cover all risk concepts and its assessment methods. It is unrealistic to cover all relevant studies for such a broad topic. The primary aim is to establish the perspectives and methods of major disciplines in addressing risks. Snowballing is a literature review method that identify additional papers from reference list or citations [18]. We utilized a structured approach that integrates a backward snowballing literature review (from the reference lists) approach, complementary database search, and personal knowledge in this study. The detailed flowchart of snowballing literature review process is shown in Figure 1.

The included articles are limited to the period of publication from 1900 to September 2023. Articles not written in English are excluded. To avoid bias that some publishers may be in favor of certain fields of study as well as to avoid overlooking some obscure papers, Google Scholar is set as the main database. The literature review study is divided into two phases. It starts with the snowballing sampling method. Firstly, the initial highly relevant and highly cited papers are identified using keyword search ("risk definition" OR "risk concept" OR "risk assessment") from the Google Scholar database. Then, the identified initial known papers are included in the snowballing sampling process. The backward snowballing process is an iterative process involves several steps. First, based on the screening results, the highly cited papers were selected for further review by looking at the title and abstract. Then, the references of the initial selected sample were reviewed and examined by reading the title and abstract. At last, the new set of relevant literature was included in another round of the snowballing process. The new set of literature underwent the same snowballing process until new papers did not contribute insight. To improve the after that, complementary database research is applied to identify articles that may have been omitted in the first phase. Finally, the identified articles are categorized by discipline for further characterization analysis.

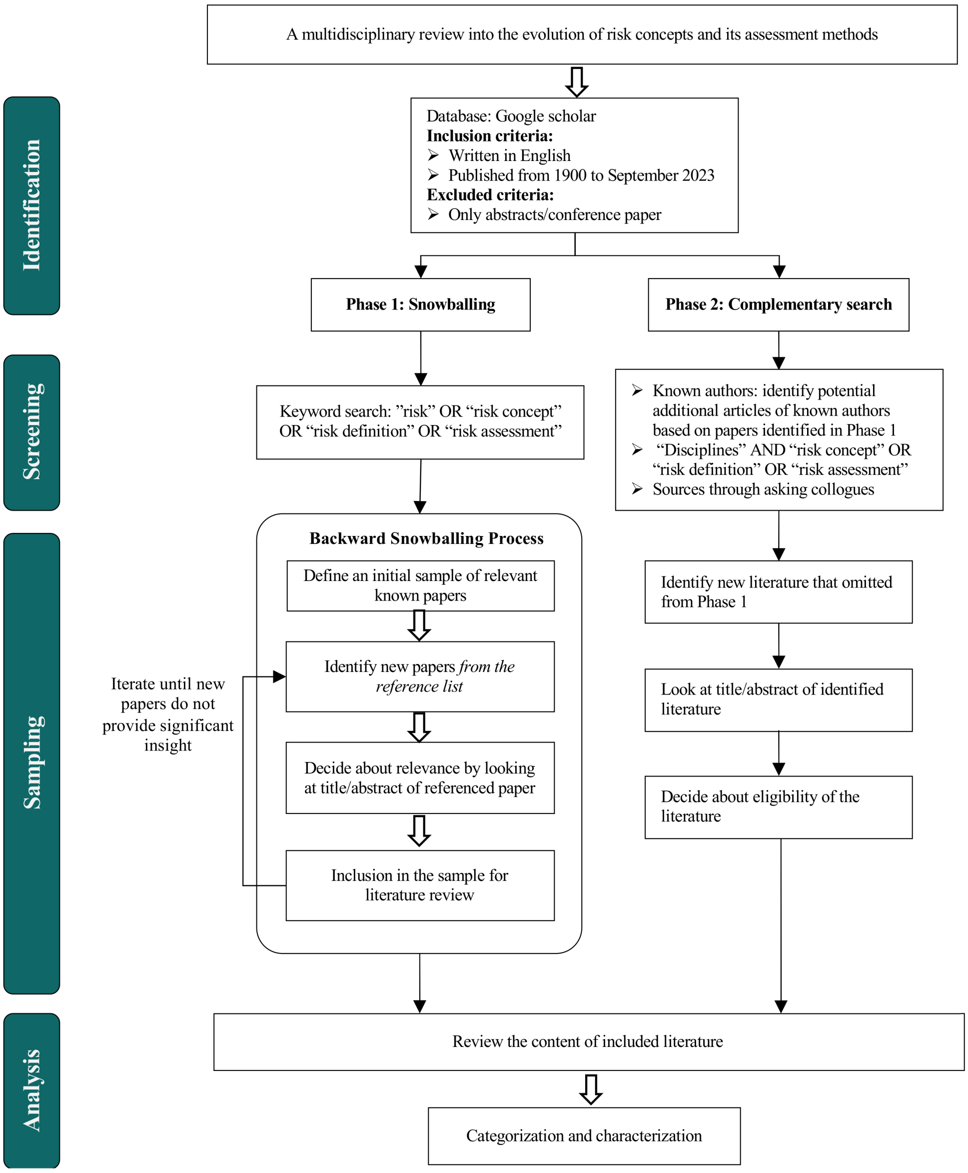


Figure 1. Flowchart of the snowballing literature review process.

3. Historical Development of Risk Studies

Before diving into how risk concept is defined and assessed, it is essential to understand the origins and evolution of risk studies. A historical timeline that begins in 1600 is presented in Figure 2. The classification of disciplines mainly refers to Ref. [10]. Nine disciplines—mathematics, philosophy, economics, anthropology, psychology, sociology, law, engineering, and medicine—are discussed. The upper markers along the timeline indicate the sequence of initial engagement of different fields in the study of risk. The notes below the timeline mark significant risk theories, approaches, or phenomena in certain periods.

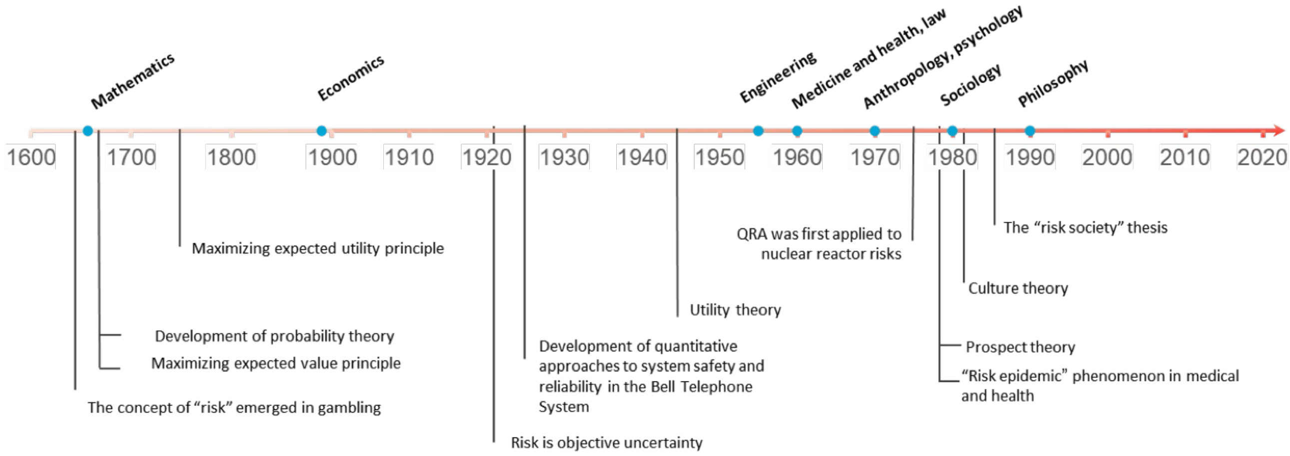


Figure 2. Timeline of multidisciplinary engagement in the study of risk and key milestones in development of risk theories and applications.

It should be noted that the aim of this section is to grasp a broad overview of how different disciplines approach risk, serving as a foundation for readers to understand the antecedents of various risk definitions and assessment methods. The in-depth discussions on perspectives of risk can be found in more specific studies on the topic.

3.1. Mathematics

Many documents [10,19,20] suggest that the concept of risk may have emerged from significant developments in social, intellectual, and economic life in the Middle Ages. In 1657, mathematician Blaise Pascal introduced probability theory. After that, the mathematical calculation of chance was soon applied to gambling and economic ventures, investments, and insurance [21]. This heuristic was further enhanced by Pascal's work in 1662, which proposed the maximizing expected value principle (agents facing risk would maximize the expected value) for calculating the fair price of a gamble [22]. Daniel Bernoulli would later build upon this insight in 1738, when he introduced the concept of utility and formulated the maximizing utility principle that explained why people would pay only a small price for a game of infinite mathematical expectation [23]. The probability theorems of 17th-century mathematicians provided the groundwork for the prevailing conceptions and practices of risk today [24].

3.2. Economics

The earliest discussion of risk in scientific economics evolved around the 1890s when research began to be undertaken on formulating a theory of distribution related to profit [25]. This sparked an interest in risk and risk-bearing, which manifested itself in the insurance literature. At the same time, applied mathematics sought to apply statistical methods to economics, resulting in the use of relative frequency as a measurement approach for risk. By 1920, the dispersion of a relative frequency distribution had been identified as risk [26]. In 1921, to make a distinction between measurable uncertainty and unmeasurable one, economist Frank Knight defined risk as "objective uncertainty" that is measurable when enough evidence is collected [27]. In the mid-1940s, building on Bernoulli's expected utility principle, John von Neumann and Oskar Morgenstern developed the Expected Utility (EU) theory [28]. Utility can be understood as benefit, advantage, pleasure, good, or happiness [29]. The Expected Utility (EU) theory is one of the most influential normative decision theories to specify how individuals make decisions under risk [30]. It is built upon utility theory—people value risks subjectively according to the utility value of gains and losses, which is related to ones' wealth status [31]. For instance, people who are risk averse will overestimate the loss while less sensitive to gain. Since the Second World War, the EU theory has played a significant role in management (especially decision science), economics, and psychology [23].

3.3. Engineering

With the development of industrial society, a growing number of large and complex systems combined with operational risks gave rise to scientific risk research of engineering to systems safety [32]. Around 1924, the development of quantitative approaches to system safety and reliability in the Bell Telephone System constituted an important building block for the emergence of Probabilistic Risk Assessment (PRA) in various fields of complex engineering systems [33]. After World War II (1939–1945), the profound development of technologies, especially in the chemical and nuclear industries, brought about potential catastrophic and long-lasting consequences, resulting in systematic attempts to study societal risks [34]. This led to the establishment of modern risk management studies in 1955 [35]. Since the 1970s, as late modern societies began to pay more attention to the uncertainties accompanying the increasing ignorance and rapid development of modern technology and industry, risk research and risk management have become increasingly scientific issues [36]. The engineering sector has been influenced by the statistical method in finance of calculating probabilities to develop the idea of risk [37]. Engineering problems gave rise to a quantitative approach to system safety, the foundation of the emergence of quantitative risk assessment (QRA). QRA establishes connections between threats and consequences [38]. As a core method in engineering risk research, QRA was first applied to nuclear reactor risks in 1975 and has since been used in various non-nuclear situations [39]. Scientific methods for identifying causal links between adverse health effects and different types of hazardous activities and mathematical theories of probability jointly built the roots of modem risk analysis [7].

3.4. Medicine

The disease panorama in Western countries has changed considerably over the last century, moving from acute to more chronic disease, which caused a shift to more preventive medical activity [40]. Meanwhile, calculating risk entrenched in the scientific world provides the theoretical bases for health-related decision-making in clinical settings. Widespread techniques and methods for the analysis of "risk" in the professional literature on health and health care have developed since the 1960s. Health risk appraisal/assessment/management began to emerge in the medical field in that period [41]. Since the 1980s, "risk" has appeared more often in medical journals, especially in epidemiological literature. This phenomenon was defined by Skolbekken as a "risk epidemic" [42]. In evidence-based medicine, efforts are made to gather the data of risk factors and how they lead to the outcome. The emergence of health risk assessment has also brought about many controversies, such as how to avoid over-medicalization; human bodies are non-linear systems which cannot be measured by linear models that are risk-assessment-based.

3.5. Law

With the increasing moral anxiety of modern lawyers and the societal disappointment in their ethical regulation, legal systems underwent a dramatic change in the 1960s, and risk management norms gradually took over contemporary law and society [43]. Contemporary legislation developments turn to the preventive, future-oriented logic of risk. Modern law adopted the conception derived from economics that an action can be said to generate loss if it increases the probability of a loss [44]. The probabilistic process helps the legal system to adopt a broader and more expansive view of the sources of loss. It is devoted to risk control, with less focus on strict causation than on contribution to the occurrence of harm. The same trends could be seen in criminal law. Risk-driven law diminishes the appreciation of the moral choices facing lawyers in practice and the other-regarding obligations of lawyers in society [43]. Since the early 1980s, criminal law has attempted to act as a preventive force to control the risk of future crime. Risk-driven criminal law focuses on managing the risk of crime rather than the crime itself [45]. Sentencing offenders as dangerous, rather than sentencing them for a specific offense, appears to have increased in recent years [46].

3.6. Anthropology

Since the 1970s, more participation of anthropologists has shifted toward risks and hazards, as they are aware that populations' lives are affected by the environment [47]. Technological progress has brought about many more man-made risks to modern society than traditional societies, so the scientific community has become more aware that social concerns must be considered while promoting new technology. This initiative allows cultural and social anthropologists to delve into previously unexplored territory [48]. Culture is anthropology's leading innovation and core explanatory tool; it is proven to be the key to understanding why and how people worldwide deal with risks [21]. The concept of "culture" came to refer to the distinctions between thoughts and manners of behavior of people around the globe. In its deep and holistic framework, it incorporates kinship, subsistence, economics, politics, dress, food, exploitation of place, scheduling of time, arrangement of space, classification of humans, social roles and relationships, child raising, laws, rules, and more [49]. There are various definitions of "culture". Generally, culture can be understood as "that complex whole which includes knowledge, beliefs, arts, morals, laws, custom, and any other capabilities and habits acquired by a (human) as a member of society".

In 1982, social anthropologists Douglas and Wildavsky proposed "culture theory" that assumes "risk" is created within a culture [50]. Cultural theory is an approach of interpreting how and why individuals form judgements about danger and threat. The point of cultural theory is that such judgments are formed dependent on social context, and related to rights to know, justice for those likely to be affected by damage or loss of peace of mind, and about blame, responsibility and liability. Thus, what is considered as risk, and how serious a risk is thought to be being perceived differently among organizations or groups became the main focus of cultural approaches to risk [51].

Furthermore, cultural theory made valuable contributions to the deliberative process in risk management [52]. The normative implications of cultural theory in the context of risk assessment, particularly emphasizes "fairness" as the key to resolving conflicts between these different perspectives [53]. The fairness is related to how to treat different groups appropriately and may involve consensus building, and appropriate use of compensation or liability rules. A pure technical concept of risk that focuses on "how safe is safe enough" may never produce a satisfactory answer. The normative procedural recommendations of cultural theory are that "how fair is safe enough" is more important than "how safe is safe enough". Moreover, "trust" towards the institutions that create and regulate risk is of great interest [53]. Cultural theory promotes and supports direct incorporation of citizen's viewpoint in decision-making process.

3.7. Psychology

The interest in risk studies in psychology fields began with economic psychologists. Around the 1970s, a group of economic psychologists with a long experiment tradition rejected the rational choice theory of microeconomics [37]. Under the rational choice theory of economics, people are risk-neutral to optimize the expected cost or profit [54]. However, the experimental evidence demonstrated that people making judgments under uncertainty do not fully adhere to rational thought based on assessing the likelihood and severity of outcomes; yet people follow a way of intuitive thinking that makes decisions quickly and unwittingly [55–57]. This was published in the seminal work by Kahneman and Tversky, in which they demonstrated that "cognitive illusion/bias" stem from heuristics [55]. In the same work, they identified three main heuristic types, including representativeness, availability bias, adjustment and anchoring [37]. To integrate these behavioral observations into rational decision theory, Kahneman and Tversky developed an alternative risk choice model: prospect theory [58].

The other main branch of psychology studies on risk emphasizes social and cultural influence on misperception of risk. This branch of work streamed from studies on risk acceptability [59] and applied empirical psychometric approaches to quantifying risk [60]. The distinguishing feature of the psychometric approach is using various psychometric scaling methods to produce quantitative measures of perceived risk [61].

3.8. Sociology

Since the 1980s, the notion of risk has become extremely popular in many areas of social science, from policy and theory to international relations and political science. Its effect is particularly marked in sociology, where a distinctive "sociology of risk" has emerged [62]. In the mid-1980s, social scientist Beck proposed the famous "risk society" theory to replace "industrial society", arguing that risk is becoming increasingly central to our global society [63]. These risks are not only connected with industrial activities but also to how actors deal with what they perceive as risks. Risk management is no longer limited to certain technological risks but has become integral to all aspects of social life. Sociology highlights the importance of context (social, material, economic, cultural) for understanding social life. the social construction of misperception of risk, the social amplification of risk, and the social construction of risk [64]. Thus, risk management focuses not only on how organizations deal with the technical calculation of risks but also with the actors they perceive as possible threats and potential risks to the stability of the organization. Meanwhile, the urgent need for managing today's risk has promoted the creation of a new discipline that is risk assessment [60].

In 1998, Kasperson et al. proposed the Social Amplification of Risk Theory (SART) [65]. The SART framework explains how the information process, institutional structures, social-group behavior, and individual responses determine the consequences and how the "ripple effect" of risk events introduces the temporal and geographical extension of impacts. The SART recognizes the role of engineering and science understanding of risk, however, it argues the deficiencies of technical risk analysis cannot provide information about social indirect impacts.

3.9. Philosophy

Philosophy is distinguished by the fact that it has linkages with every other academic discipline. In the 1990s, philosophers increasingly identified a wealth of risk-related issues in need of philosophical elucidation [66]. Philosophers have illuminated new insights into the terminological clarification of risk, the ontological base and epistemic status of risk, risk and moral principles, its decision–theoretical aspects, the implications of risk in political philosophy, and various other topics [67–71]. Furthermore, the philosophers' argumentation analysis has also led risk experts in other fields to start examining the "value-laden" aspects of risk. For example, when it is ethically acceptable to expose another person to risk [68,71]? How can the definition of risk be extended to consider moral principles [72]? How can risk analysis account for the possibility that risk analysis itself is "wrong" [73]?

4. Definitions and Interpretations of Risk

After understanding the historical progression, the next step is to identify what risk means in different contexts. There is a wealth of literature discussing risk concepts. It focuses on analyzing the linkage between the definition and the disciplinary background to uncover the reasons why risk is approached differently across disciplines. To have a more coherent understanding of these definitions, four overarching categories are compared: economics and decision science, engineering and science, social science, and philosophy. We subjectively compiled a list of definitions or interpretations of risk from diverse disciplinary literature, summarized in Table 1.

Table 1. Compilation of risk definitions and interpretations from the literature.

Reference	Year	Descriptions, Definitions, and Understanding of Risk	Source
[74]	1895	If there is any uncertainty as to whether or not the performance of a given act will produce a harmful result, the performance of that act is the assumption of a risk.	Social Science & Medicine
[27]	1921	Risk is objective uncertainty.	"Risk, uncertainty and profit"
[75]	1944	Risk is expected loss.	The Quarterly Journal of Economics
[76]	1953	Risk is the variance of the probability distribution over the utilities of all possible consequences.	Econometrica
[77]	1975	Risk is expected value, encompassing both the outcomes of a decision and some representation of the probability of the outcomes.	"Decision Making and Training"
[78]	1977	Risk is the variance or dispersion of outcomes.	Journal of Accounting Research
[79]	1981	A function of the probability of loss and the distribution of losses.	Theory and Decision
[80]	1981	Risk is a set of triplets.	Risk Analysis
[50]	1982	Risks are the dangers that societies define as troublesome.	Risk Analysis
[81]	1992	A systematic way of dealing with hazards and insecurities induced and introduced by modernization itself.	Theory, Culture & Society
[82]	1998	Risk is the relationship of responsibility for harms for which the action of some person was a condition.	RISK: Health, Safety & Environment
[83]	1998	Risk is a situation or event where something of human value is at stake and where the outcome is uncertain.	Journal of Risk Research
[84]	2001	The statistical probability that an undesirable event—disease or death—may strike.	Scandinavian Journal of Primary Health Care
[85]	2001	Risk as feelings.	Psychological Bulletin
[86]	2002	RISK = Replaces Incomplete Scientific Knowledge.	Toxicology
[87]	2002	Risk has two components: the extent of the damage and the probability or likelihood that such damage will occur.	Safety Science
[88]	2002	Risk is seen as a concept that human beings have invented to help them understand and cope with the dangers and uncertainties of life.	Regulation of Toxic Substances and Hazardous Waste
[89]	2003	What is to be considered a "risk" depends entirely on cultural settings and assumptions; risks are culturally defined and selected.	Ethnos
[90]	2005	Risk is a measure of the probability of adverse effects on health, property, and society, resulting from the exposure to a hazard of a given type and magnitude, within a certain time and area.	Natural Hazards and Earth System Sciences
[73]	2009	Risk refers to uncertainty about and severity of the events and consequences (or outcomes) of an activity with respect to something that human value.	Journal of Risk Research
[64]	2013	Risks are always situated in a social context and are necessarily connected to actors' activities.	"Essentials of Risk Theory"
[91]	2015	The selection of risks reflects social and political relations within groups.	Health, Risk & Society
[92]	2018	Risk is a state of uncertainty, s.y. there is a possibility that it involves loss or other undesirable outcome for an exposed actor.	Proceedings of the Central European Cybersecurity Conference
[93]	2019	Risk = Hazard $\times$ Exposure $\times$ Susceptibility	Natural Hazards

Table 1. *Cont.*

Reference	Year	Descriptions, Definitions, and Understanding of Risk	Source
[94]	2019	Risk = reality + objectives	Sustainability
[95]	2019	Risk + information entropy = k	Philosophy of Science
[96]	2020	Risk can be defined as the range of all possible, but uncertain, outcomes from positive (most optimal) to negative (most suboptimal) in terms of both reward magnitude and probability.	Current Opinion in Behavioral Sciences

4.1. Economics and Decision Sciences

There are three main categories of definitions of risk in economic and decision sciences: risk = objective uncertainty, risk = variance, and risk = expected utility.

The definition of risk has evolved over time. By 1920, the dispersion of a relative frequency distribution had been clearly identified as risk [26]. However, this definition faced scrutiny since the late 19th century, particularly among authors in the insurance field [74]. They observed that not all risks have reliable historical relative frequencies or statistics. Thus, risk is still present even if quantifiable statistics are not. If risk is measured by relative frequency, then some risks are unquantifiable, which creates uncertainty. Although scholars recognized the distinction between probability and risk, few scholars are able to specify the nature of the term by definition. Willett [97] was the first scholar to separate and distinguish the various aspects of the problem of explaining the nature of risk. He thinks it is necessary to define risk with reference to the degree of uncertainty about the occurrence of a loss, not with reference to the degree of probability that it will occur. In his definition, risk is the objectified uncertainty as to the occurrence of an undesired event. However, he did not make an explanation about the term "uncertainty". Knight illuminate the ambiguities concealed in the notion of "risk" and "uncertainties" by employing the terms "objective probability" and "subjective probability" to designate the risk and uncertainty, respectively. Risk is defined as "objective uncertainty" to make a distinction with "subjective uncertainty" (uncertainty). In Knight's definition, risk could be calculated precisely with certainty (the relative frequency) [27].

Financial economics is formed on the foundation of modern portfolio theory (MPT). MPT is an investment model that describes how investors may balance risk and return in constructing investment portfolios [98]. The basic principle of risk and return trade-offs is that the riskier the investment, the greater the required potential return. In Portfolio theory, risk is synonymous with volatility, representing the chance that the actual return on an investment will be different than expected [30]. The two most common ways of measuring volatility or risk are the calculation of the variance of an expected return and the standard deviation from an expected return. It should be noted that in investment context, a decision under risk must be understood as a joint function of the expected return and variance. Sometimes, investors will choose to bear greater risks in order to achieve higher returns.

Economics and decision science risk studies are closely related to the question of "how people should make decisions". Rational choice theory is essential in modern economics. It defines that a rational individual would seek utility maximization when faced with various alternatives [57,99,100]. Normally, the premise underlying pure rational choice theory under risk is that decision-makers do not know the precise outcome but have perfect knowledge of the likelihoods of various outcomes [101]. Additionally, the EU theory acknowledges that real life scenarios are a mixed risk and uncertainty. If individuals are risk-neutral, expected values can replace the definition of probability and utility [102]. Compared with other economics definitions, it has the merit of encompassing people's subjective preference and attitude towards risk in the risk concept [103].

4.2. Engineering and Science

The quantitative definition developed by Kaplan and Garrick profoundly influences how risk is conceptualized, especially in engineering settings [80]. Engineers and scientists prefer quantitative approaches that focus on "operationalization" and "measurement". From the engineering and science point of view, risk can be interpreted from a systems-based perspective as a function of system states [104]. They believe that risk could be defined and measured mathematically and free from subject bias. Different from the economics system, engineering risk assessment is often associated with systems where data is insufficient or absent. Actuarial approaches are inappropriate for engineers. Risk calculations in engineering have to handle various uncertainties. Hence, experts have to judge the probabilities based on their experience and knowledge. The illustration of system-based definitions is shown in Figure 3.

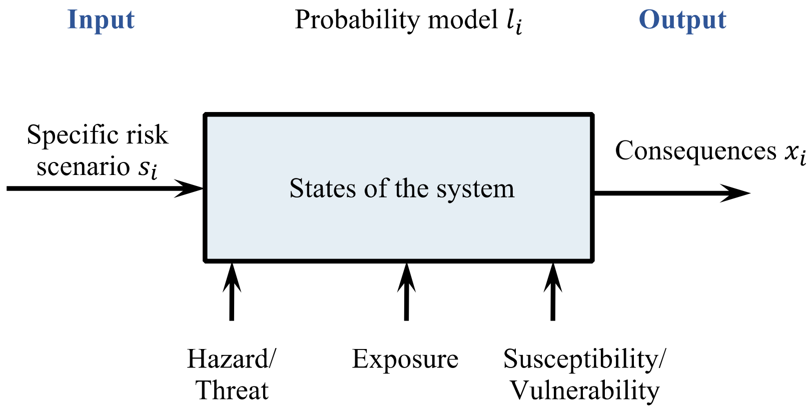


Figure 3. The illustration of quantitative "set of triplets" definition of risk: $R = \{< s_i, l_i, x_i >\}$; s_i denotes scenario ith risk scenario, l_i is the likelihood of the scenario, x_i denotes the potential consequences. Susceptibility/vulnerability represents the inherent states of a system to adapt and respond to hazards; threats could be seen as specific interruptions outside the system; exposure can be defined as assets and values exposed to certain threats.

There are three main discourses in defining risk in engineering and science literature: probability-based, uncertainty-based, and moral-based. This probability-based definition still plays an important role in today's engineering risk management.

The probability-based definition has two branches. One is from safety and reliability engineering, in which risk is defined as probability and consequence. In the other, risk is defined as a combination of "exposure", "susceptibility/vulnerability", and "consequence". This is because safety and reliability engineering are primarily concerned with probability of failures in the operating system itself. The second type of definition is commonly seen in environmental and security science fields. In contrast, in the field of environmental and security science, risks are caused by factors external (natural disasters, terrorist attack) to the reference system. This is what leads to the subtle difference in definition. But in "exposure", "susceptibility/vulnerability" are all calculated in the form of probability. Regardless of what variables are used to define risk, probability and the severity of consequences are two indispensable elements.

In the past decade, scientists with engineering backgrounds have paid attention to debates and discussions on the concept of risk. Scholars have focused on the distinction between risk concept and risk characterization and how to represent uncertainty accurately. They pointed out "probability" is just a way of characterizing "uncertainty", however, not the only way. Particularly, fruitful results have been yielded by introducing the "knowledge" dimension in characterizing the "uncertainty" component of risk [105,106]. The concept of risk is shift from probability-based to uncertainty-based. Furthermore, the acknowledgment of the "time" scale of risk concept provides support for resilience works [107]. According to the uncertainty-based definition, risk as a concept exists objectively and when risk is assessed it is dependent on the assessor—it becomes subjective.

Influenced by economic, science and engineering, psychometric, and social risk studies, Gardoni and Murphy proposed a synthesized risk ranking framework and applied it to dam risk assessment. The framework expands the two-dimensional risk definition to three-dimension with the addition of "source of risk" that emphasizes the moral differences between individuals. Specifically, voluntariness, distribution of consequences, and causation are incorporated to represent equity and intentionality [72].

4.3. Social Sciences

Risk does not have a precise definition in social sciences, unlike fields such as economics, decision science, engineering, and science. In social science literature, risk is a disputed concept that has comprehensive meanings. Social scientists argued that all human activity, including the physical sciences, relies on social, cultural, and political construction [108]. Based on how "risk" is constructed, different disciplines can generate different interpretations in the social sciences field.

According to anthropologists, statistical probability is a mathematical concept that quantifies the chances of an event or occurrence, and it has limited relevance for explaining how people think and act in situations where there is an element of uncertainty. For example, the cultural theory assumes that risk is a cultural phenomenon, and what constitutes "risk" is entirely dependent on cultural settings and propositions [89]. Risk is decided by a collective belief system. Thus, it varies with culture and social context.

From a psychologist's view, especially social psychology, risk could be defined by any individuals who may be influenced (e.g., experts employ risk assessment to evaluate hazards, and laypeople rely on intuitive judgments) [88,109]. However, cultural theory does not take into account individual differences in perceptions of nature. What is essential for anthropologists is to understand how groups select and frame risks. For example, some social misperception of risk studies concludes subjective attributes that influence individuals' view of acceptability of risks, voluntariness, benefits [59], dread, and familiarity [110]. The subsequent studies of risk-seeking behavior studies in economic and psychology literature also explain that risk can have a desired outcome. Depending on the value actors attributed to the manifold issues at stake, an outcome can be positive and/or negative [111].

The sociology of risk evolved from psychological and anthropological perspectives. Works on the sociology of risk generally focus how the social and cultural factors that influence the selection of "risk". In that sense, risk is also dynamic, continually modified by the societal environment. There are two major viewpoints of risk in sociology. The social construction of risk theory denies the "objective" elements of risk and regards risk as purely being shaped by social environment. Nonetheless, the SARF emphasize public perceptions can amplify the real dangers and leading to risk perception deviated from risk assessment.

In the context of law, risk is used to conceptualize and address social problems, and as an incentive to reduce individual claims on collective resources [112]. While the law demands positive statements by scientists that a risk does exist or does not exist [113], the results of risk research are often ambiguous. This makes translating scientific data into something that can be used to make decisions in a legal context difficult [114]. As such, studies in law do not emphasize probability as much as the field of engineering. Instead, the concentration of the lawyer is the causation and liability of risks [82,115].

4.4. Philosophy

Philosophy provides a new perspective for risk definition research from the perspective of epistemology and ontology. Ontology denotes the state of reality, while epistemology represents the creation of knowledge and understanding. Ontology focuses on whether risk exists objectively independent of risk observers. There are many discussions on the ontology of the concept of risk. For instance, Shrader-Frechette proposed a scientific proceduralist approach that assumes risk is neither a social construct nor purely objective [69]. Solberg and Njå maintained that all risk claims are subjective. risk as a possible state of affairs is a confusion between ontology and epistemology. They believe that when people think of risk, they always link it with specific activities or hazards. Hence, risk is a concept that we used to cope with the logically possible future states of affairs and risk does not exist objectively [109]. Hansson [116], Blokland, and Reniers reasoned that when no value can be attributed to reality, there is nothing at risk and thus that the concept of risk is not valid [94]. Peschard et al. argued that risk is based on objective facts, but risk identification and risk estimates are value-dependent processes [117]. The epistemology of risk refers to the study of how we know and understand risk. From the epistemological aspect, risk is a state that something undesirable may happen, but we do not know whether or not it will. Risk is regard as a state of lack of scientific knowledge or information. It therefore has a strong component of "uncertainty" [118]. If uncertainty is not deemed as an element of risk, then it becomes fatalism.

5. Risk Assessment Methods

After reviewing the diverse understandings and definitions of risk, this section focuses on the different methods to measure and assess risks. We subjectively selected three standard risk assessment methods (quantitative risk assessment, multicriteria decision-making, and psychometric risk paradigms) and some ad hoc approaches that are tailored to specific cases or situations. Their scope of use, purpose, main methods, and advantages and some controversial points are discussed in the following context. An overview of main risk assessment methods, their advantages, limitations, and their primary fields of application is summarized in Table 2.

Table 2. Overview of main risk assessment methods, their advantages, limitations, and main application field.

Risk Assessment Method	Advantages	Limitations	Main Application Field
QRA	Help understand real damage and probabilities; Free from subject bias.	Neglect contextual issues; Data scarcity.	Engineering, environmental science, chemical engineering, energy, earth and planet science.
MCDA	Enrichment of risk assessment process; Simplicity; Transparent.	Results can be manipulated; Not suitable for time-sensitive situations; The simple algorithm may result in misleading results.	Environmental science, public policy, urban planning, energy management.
Psychometric risk paradigm	Understand public's concerns.	Public attitudes are prejudiced.	Social sciences, medicine, psychology.
Ad-hoc approach: Risk assessment framework (RAF) Person-Centered Risk Assessment Framework (PCRSF)	Comprehensiveness; Empowerment; Enhance risk awareness; Transparency.	Evaluation of these approaches are limited; Mixed information is not integrated well.	Medicine, nursing.

5.1. Quantitative Risk Assessment (QRA)

Quantitative risk assessment (QRA) is a widely used technique for identifying and estimating hazards, especially in engineering and technical fields. It relies on engineering and scientific knowledge to aid "rational" decisions when the consequences of alternatives are uncertain. It aims to provide detailed quantitative information on consequences of specific hazards under uncertainty to aid decision-making regarding risks [119]. By thoroughly examining how factors can interact, what scenarios can result, and what damage the scenarios can cause, QRA helps technicians apply quantitative approaches to handle risk aiming to provide actual values of probabilities and consequences. Through this process, QRA effectively answers three questions: "What can go wrong (scenarios)?", "How likely is it (frequency)?", and "What are the impacts?" (the process of QRA is shown in Figure 4).

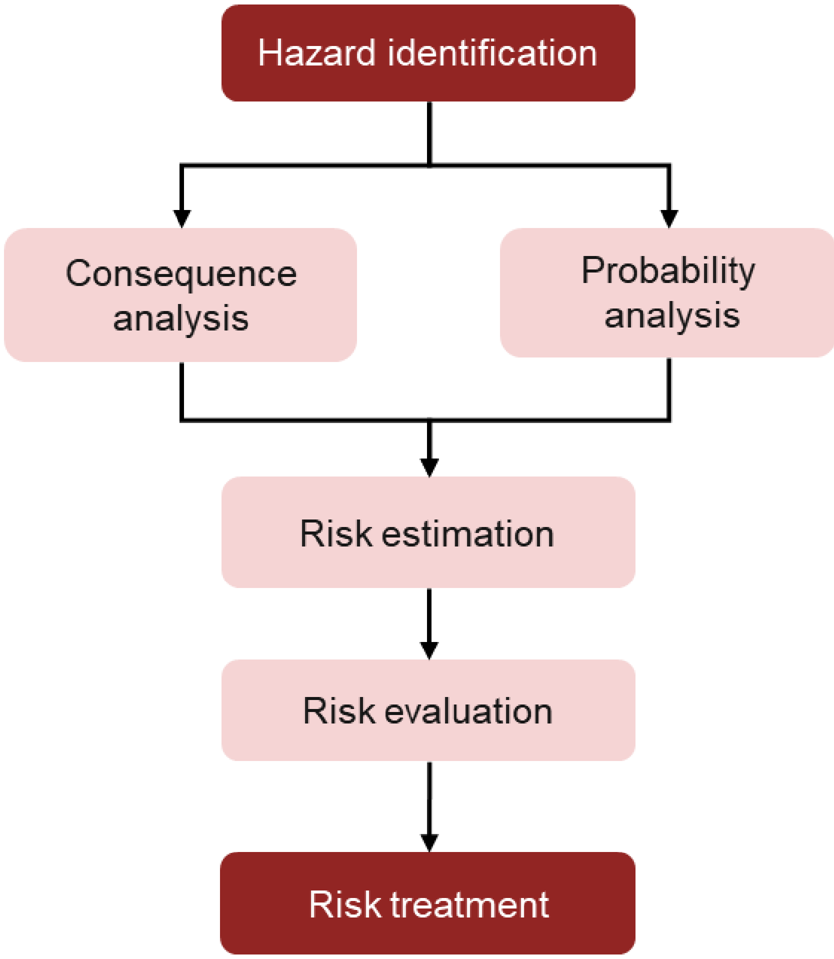


Figure 4. The basic process of quantitative risk assessment.

It should be noted that QRA was first developed in the nuclear engineering context. However, according to specific characteristics in other fields of engineering and science, such as chemical risk assessment and flood risk assessment, it may have different connotations and names. For instance, QRA in chemical risk assessment involves dose–response assessment, exposure assessment, and risk characterization [120]. QRA in flood risk assessment involves hazard identification, vulnerability assessment, and exposure assessment [121]. However, the similarities of these methods are that they all utilize quantitative approaches to estimate the level of risks.

Normally, the first step of QRA involves defining the scope and context of the analyzed system. Next, the possible hazards and potential linkage between causes and consequences are identified. After that, the frequency of the consequence is analyzed. The tools used for quantitative frequency analysis include historical data, fault tree analysis (FTA), probabilistic modeling, subjective judgment, and more. The fourth step involves the analysis of the outcome of the consequence. Tools for quantitative consequence analysis include subjective judgment, event tree approach, empirical physical model, experiments, and computational simulation. Next, the estimated risk is evaluated by probability-consequence diagram, i.e., F-N curves, risk matrix [122], etc. Finally, political, procedural, and technical control and mitigation measures are identified and applied to treat risks.

There are many disputes on utilizing QRA for risk assessment. On one hand, QRA has faced many criticisms on its proficiency of science. For example, QRA is questioned not deal adequately with data-scarcity scenarios with "rare" events, where there are substantial unknown elements in quantitative risk assessment [123]. Only caring about bottom-line numbers is not useful when they are highly uncertain, limited by risk analysts' knowledge [124], and include human error in risk estimation [125].

On the other hand, quantifications tend to reduce the complex nature of risk and cannot reflect key social, cultural, and political realities. For instance, this also leads to another criticism, as it concentrates on the direct impacts of consequences, such as physical harm to objectives, while ignoring the indirect social impacts [65]. Additionally, QRA may neglect emotional responses that importantly affect perceptions, judgments, and behaviors in response to real or perceived risks [126]. Some maintain that simpler and more popular techniques such as the precautionary principle should be used instead of or in addition to QRA [127].

Despite these, QRA does play a role in many real-world cases to help achieve preferred consequences. QRA is based on a rational idea of risk. Some studies have tried to address the limitations of risk assessment by introducing public values.

For example, Bohnenblust and Slovic proposed a framework to incorporate subjective factors such as risk aversion, willingness to pay, and voluntariness into a risk-based decision-making process [3].

$$R_m = \sum_{i=1}^{n} p_i C_i \varphi_i(C_i) \omega_i \quad (1)$$

where R_m is the monetary collective perceived risk, 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, $\varphi_i(C_i)$ is the risk aversion factor as a function of C_i, and ω_i is the marginal cost or willingness to pay (million SFr/fatality).

In addition, some scholars suggested including societal values and ethical principles in risk evaluation tools [128,129]. Reniers and Van Erp [130] proposed an integrated calculation formula for determining risk and obtaining risk prioritization by considering technical and non-technical factors.

$$R_i = \frac{p_i C_i^a}{\beta_i \left(E_i F_i^b\right)} \quad (2)$$

where β_i is policy factor that varies with the degree of participation in the risk due to event/scenario i is voluntary, E_i is a parameter representing equity principle, and F_i is a parameter representing fairness principle, a is aversion factor towards consequences, and b is factor representing the availability of combination. It contains several implicit assumptions.

5.2. Multicriteria Decision Analysis (MCDA)

Multicriteria decision analysis/making (MCDA/M) is a method that uses systematic analysis to evaluate and select alternatives based on diverse criteria to handle the uncertainty of diverse values and interests of individuals or decision-makers [131]. It is a sound analytical method for risk management where multiple and often conflicting criteria are considered. It focuses on addressing multi-faceted decision-making problems in complex scenarios, such as political or legal issues, social issues, project planning, etc.

The risk decision problem in MCDA is usually decomposed into a hierarchy of sub-criteria/indicators, and each criterion/indicator is called a "risk factor" which can be analyzed independently. It focuses on comparing the "risk factor" and calculate their rankings to identify risk management priorities. Generally, a MCDA analytical framework follows the serial process, as shown in Figure 5.

It starts with identification of the risk problem. The second step aims to identify risk determinants and potential choices. In some adapted MCDA approach for risk assessment, there is an additional step, "identification of stakeholders", between Step 1 and Step 2. Stakeholders are included to gather views from them in identifying criteria and elicit priorities of the criteria. After alternatives and criteria are determined, a synthesis of knowledge and approaches, such as survey, focus group, and consultation with experts, can be used to analyze the criteria. Then, the relative importance of criteria can be obtained through common approaches such as the analytical hierarchy process (AHP), outranking, etc. [132]. Finally, applying the MCDA decision rule as a tool to aid risk assessment has many advantages. First, an MCDA approach can take account into multiple dimensions of risk as well as various values of stakeholders simultaneously. Moreover, an MCDA approach can integrate various types of data. Additionally, in MCDA, all risk factors are represented using metrics, making the assessment process more transparent and accountable [133].

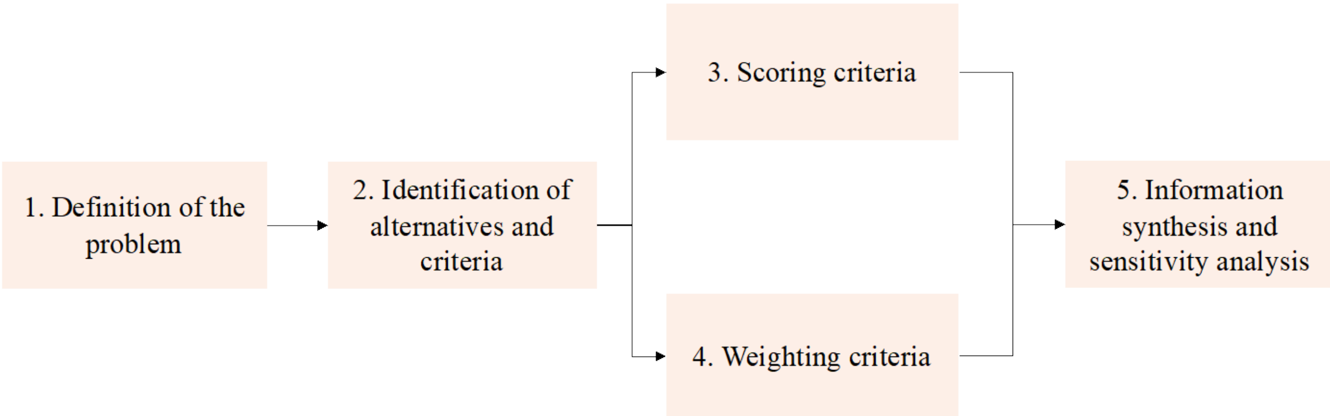


Figure 5. General steps of MCDA methods for risk assessment.

However, there are also a number of deficiencies of MCDA for risk assessment. One of the most crucial aspects is that the result of MCDA can be manipulated. Additionally, stakeholders' MCDA is only suitable for decision-making processes that have sufficient time. Furthermore, MCDA usually based on simple additive and multiplicative logarithms regarding criteria scores and weights. However, the proxy-based models might produce misleading results [134]. For example, in QRA, risk = probability × impact. The risk factors "probability" and "impact" are multiplicative. Then, an equivalent formula as in MCDA should be log(risk) = log(probability) + log(potential impact).

5.3. Psychometric Risk Paradigm

The "psychometric paradigm" is a method developed to understanding and quantifying laypeople's opinions and attitudes toward risks [60]. In addition to the pure aggregation of estimated likelihoods and consequences, risk assessments in psychology studies encompass more dimensions [126]. Psychologists are interested in intuitive risk judgments (perceived risk), for example, risk aversion to certain hazards, the discrepancies between experts and laypeople towards risks, and the factors behind the perceptions. Psychometric risk perception research is mainly focused on how laypersons' "perceived" risk is departure form "actual" risk. Through psychophysical scaling and multivariate analysis techniques, risk attitudes and perceptions are expressed by "cognitive maps" or quantified representations by consulting participants to rate the riskiness of hazards [60].

Fischhoff et al. hypothesized nine characteristics that influence judgments of risk perception. It includes knowledge about risk (To what extent are the risks known precisely by the persons exposed to those risks and to what extent are the risks known to science), control over risk, and the novelty of risks, among other factors. They determined that "dread" and "novelty" are the two main factors influencing people's perceptions of risk based on an examination of survey data [110].

The psychometric approach has been continuously expanded to include more perception factors. Bassarak et al. proposed that disputed risk and morality should be captured as additional dimensions of risk judgments in addition to dread and novelty [135]. Psychometric risk paradigm is widely used in various fields to study different group's perceptions of specific risks [136]. Psychometric risk studies usually use questionnaire surveys to rate possible hazards on various scales, e.g., voluntariness of risk (1 = voluntary, 5 = involuntary). Figure 6 shows an example of a psychometric risk questionnaire.

Qualitative dimensions	Description	Score (1-5)
Voluntariness	The extent to which exposure to the hazard is voluntary	
Immediacy	The extent to which the consequences are noticed immediately	
Knowledge of exposure	The extent to which a person knows if he has been exposed	
Expert knowledge	The extent to which experts know about the hazard.	
Controllability	The extent to which a victim can control the severity of consequences due to exposure	
Novelty	The extent to which the hazard is new to society.	
Catastrophic potential	How many fatalities occur at once	
Dread	The extent to which the effects of exposure are dreaded	
Severity	The extent to which the consequences of exposure are severe	

Figure 6. An example of psychometric risk paradigm questionnaire.

The qualitative dimensions in the first column on the left side represent attributes or elements on how individuals perceive different risks. Those elements may vary according to the specific contexts of various hazards investigated. Each dimension is presented in a short description, providing context for respondents. Respondents are asked to rate their perception of risk on a numerical scale (in this example, from 1–5). The combination of qualitative dimensions, descriptions, and numerical scoring provides a structured way to approach individuals' assessments of different risks. Psychometric approach is effective in identifying differences and similarities among groups related to their risk attitudes and risk perceptions of specific risks. However, the results of risk perception and the approach itself are seldom directly applied in the domains of risk management.

There are many criticisms on using public risk perceptions to influence policy making. The arguments include such as public perceptions are noise/bias, public attitudes are prejudiced, managing risk merely entails managing public perceptions. The public is not homogeneous in its risk perceptions [137]; some may worry that anything can become a determiner of risk perception [138].

By contrast, the advocates for risk perception research participatory decision process. Although lay people may have little knowledge about hazards, however, their basic conceptualization of risk can be far more extensive. These perceptions reflect the real concerns of people which technological analyses often miss [139].

For example, the group of Carnegie Mellon University proposed a deliberative risk ranking method. The method advocates gathering public input to help set risk management priorities. First, a set of risk attributes are identified by experts referring to risk perception literature. Then, risk is analyzed in terms of the attributes identified. After that, the selected participants are required to rank the attributes. Finally, risk ranking is obtained, applying the multi-attribute ranking procedure [140,141].

Plattner et al. [142] built an integrated model for natural hazard risk evaluation, including scientific risk analysis, economic perspective, social environment, values, and psychological characteristics. Plattner stressed the importance of risk perception, specifically perception-affecting factor (PAF) and objective risk e_{eff} (probability times consequences), in conducting risk assessment and management. Furthermore, applying "prospect theory" in dealing with irrational thinking regarding risks is suggested. Based on expressed preference theory in psychometric studies, Plattner et al. developed a perceived risk r_{perc}

formula with the integration of subjective deviation of risk perception and effective risk function e_{eff}:

$$r_{perc} = R_{eff} \frac{\sum_{i=1}^{n} (paf_i a_i)}{\sum_{i=1}^{n} a_i} \tag{3}$$

where paf_i [0.5, 2] is the value of the PAF, a_i [0, 1] is the weight of each paf_i, and n is the total quantity of relevant PAF. PAF includes voluntariness of risk-taking, individual reducibility of risk, knowledge and experience, endangerment, subjective damage rating, and subjective recurrence frequency perception.

5.4. Others

In addition to the three main methods mentioned above, there are other ad hoc methods that are tailored to specific situations but don't fit into conventional categories or lack formal recognition.

Risk assessment framework (RAF) is a method applied in hospitals and healthcare fields to deal with wrong medication, delayed discharge, patient claims, failure to comply with requirements, and other adverse events [143]. There are three main steps of RAF: risk identification, risk analysis, and risk treatment. The risk assessment result is summarized and documented in a risk assessment form (Figure 7).

Risk Assessment Form										
Assessor:			Ward/department		Date assessed:		Assessment no:			
1. descibe system to be assessed(aim, elements, interactions, boundary, context)										
2. Define undesired events	3.Determine contributory factors	4. Describe potential consequences	5. Examine current controls	6. Estimate severity	7. Estimate likelihood	8. Estimate risk level	9. Estimate risk tolerability	10. List required controls	11. Define required actions	

Figure 7. Risk assessment form, adapted from [143].

Different from the other risk assessment methods we mentioned before, RAF does not convert all the aspects of risk as a common unit. Instead, it keeps the result of risk assessment in their original form. This preservation of original units enriches the understanding of risk and enhances transparency.

Furthermore, recognizing the importance of potential emotional, psychological and spiritual harms of taking away meaningful activities that contribute to quality of life, a person-centered risk assessment framework (PCRSF) is developed. This framework addresses various risks, including falls, financial abuse, physical abuse, alcohol excess, unsafe driving and medication mismanagement or inability to manage selfcare, and more situations [144] (as shown in Figure 8).

Step 3 presents a heuristic representation of indicators of psychosocial need.

It has the merit of comprehensiveness as it not only considers physical safety risk, but also take account of psychosocial factors. Furthermore, the PCRAF is designed to empower patients, allowing them to actively participate in care planning by expressing their subjective perceptions and feelings. Moreover, PCRSF can act as a communication tool to increase awareness of existing risks among clinic team members. However, the PCRAF is not widely used due to the limited capability for patient and/or caregiver to recognize risks. Some participants have expressed that completing numerous forms can be challenging and suggest that the PCRAF needs better integration into the overall assessment process.

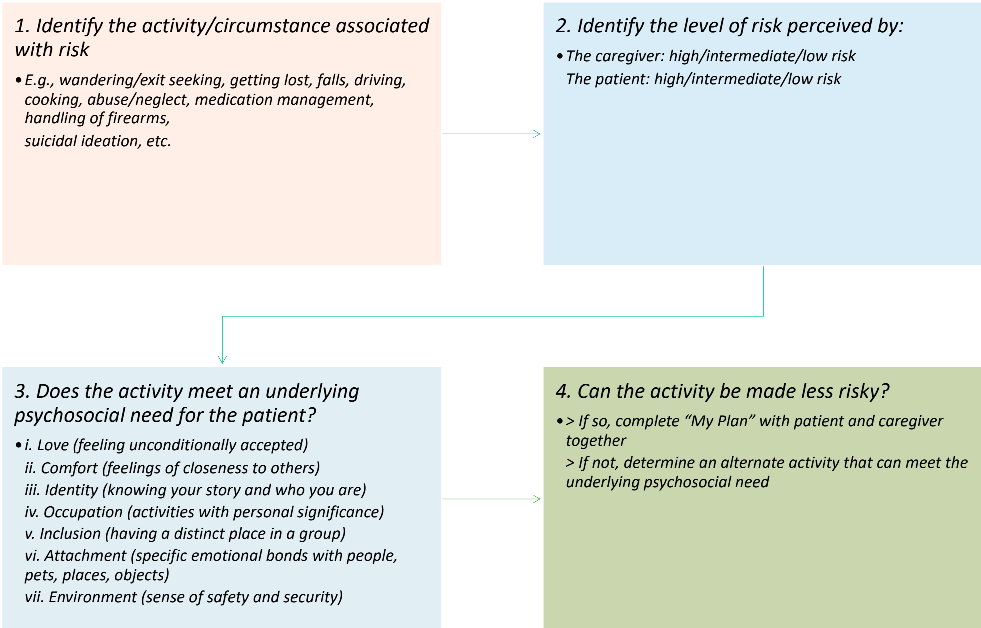


Figure 8. Person-centered risk assessment framework (PCRSF), adapted from [144].

6. Discussion

6.1. Current Research Status

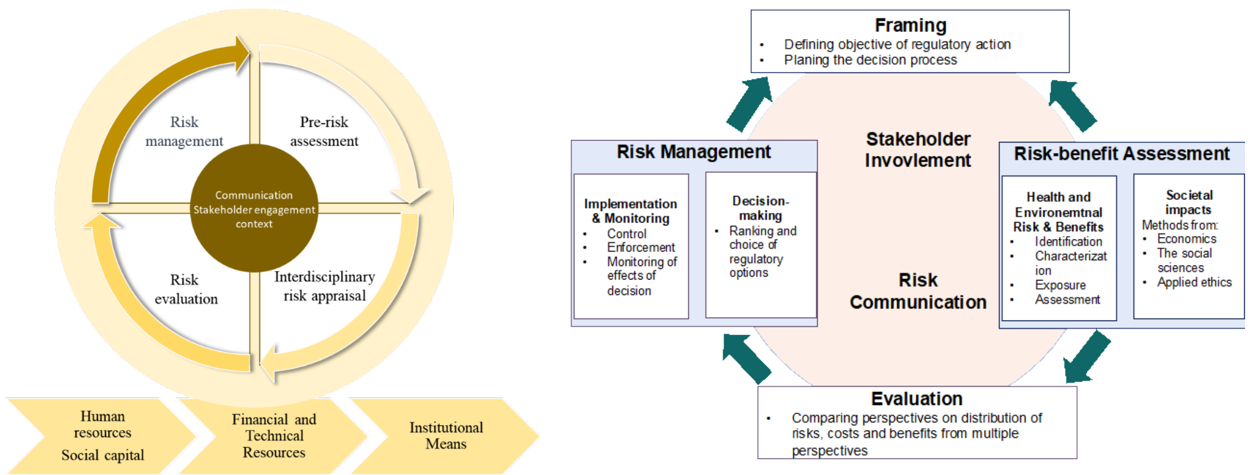
The concept of "risk" was first used in gambling and has now become part of our society. Its definition and connotation are constantly enriched with the development of society and science. There are many contradictory categories in interpretation and usage of risk, regarding objective or subjective, rational or irrational, and more. However, after reviewing the literature from various disciplines, the emergence of these controversial points is mainly due to the different starting points for looking at risks and the different context settings they made.

Engineers primarily focus on the adverse consequences of malfunctions of the technical system, often neglecting human activities within the system. In contrast, social scientists emphasize risk management, risk perception and risk communication, social acceptance of risk. Despite the presence of these contradictory elements, many socio-cultural approaches recognize the importance of techno-scientific approach to risk. The emphasis in social sciences is to broaden the scope of technical risk assessment by incorporating more societal factors, making it more meaningful to view those socio-cultural approaches to risk as an extension of risk.

In recent decades, the growing body of risk research in philosophy has introduced ethical and moral challenges to the study of technology risks, which often overlook societal dimensions [145,146]. Our rapidly changing society is rife with disputed risk problems that necessitate the inclusion of economic, moral, and ethical aspects in risk assessments [147]. Effective risk management should not only aim to reduce the frequency and negative impacts of accidents but also promote justice and democracy [148,149]. The COVID-19 pandemic has highlighted the tension between risk decision-making and public acceptance, underscoring the need to consider not just the consequences and likelihood of risks but also their distribution and the importance of building trust among the public, institutions, companies, and governments [150]. Responsibility should be prioritized as a fundamental aspect of risk management rather than a secondary concern. This calls for the development of a novel integrated risk management paradigm that takes social, ethical, political, and economic aspects into account.

Over the past three decades, numerous efforts have been made to achieve this objective. Engineers and natural scientists continue to absorb social scientists' perspectives and improve current risk assessment approaches by encompassing public values, moral principles, and utilizing deliberative process. However, these approaches have yet to be fully integrated into risk management frameworks with established procedural steps.

Recently proposed integrated risk management frameworks, such as the one developed by the International Risk Governance Council (IRGC) [151] and the SAFE FOODS framework for the governance of food safety [152], emphasize transparency, inclusive communication, stakeholder involvement, and the consideration of broader economic, social, and political contexts. These frameworks represent significant steps toward inclusive risk governance (as illustrated in Figure 9).



(**a**) (**b**)

Figure 9. Integrated risk management framework. (**a**) IRGC risk governance framework, figure adapted from [151]; (**b**) The SAFE FOODS risk governance framework, referred to in Ref. [152].

Both risk management frameworks show an irritative decision-making process with four main stages: framing (pre-risk assessment), risk appraisal (risk–benefit assessment), risk evaluation, and risk management. They both start with pre-risk assessment/framing that focuses on framing risk and identification of involved stakeholder groups. Then, risk appraisal/risk–benefit assessment is conducted to characterize risk. However, these frameworks diverge in their focus during this stage. The IRGC risk governance framework not only includes technical risk analysis but also gathers stakeholders' concerns and opinions. In contrast, the SAFE FOODS risk governance framework emphasizes the importance of societal impacts within the risk assessment process. Following the risk appraisal, the outcomes of risk assessment are compared to specific criteria to determine the significance and acceptability of the risk. Based on the results of risk evaluation, tolerable risks are then subjected to treatment. Despite these structured processes, several unresolved issues persist within both frameworks.

- How can public concerns be effectively measured or assessed, and in what ways do these concerns influence policymaking?
- What methods can be employed to rank risks while taking into account non-rational factors?
- How should decisions be made when conflicts arise between technical risk analysis assessments of public concerns?

6.2. Recommendations for Future Works

Based on the literature review results and current research status, some recommendations for future research are given.

6.2.1. Expanding Risk Dimensions for More Informed Decision Making

Social sciences and philosophy studies help to identify and explain public concern, economic, and psychological factors. A number of non-rational elements have been identified. For example, emotions such as voluntariness, distribution of risks and benefits, available alternatives [153], fear, happiness, anger, and surprise are positively correlated with risk aversion [154]. However, the results of these studies have rarely been applied in the formal risk management model. Methods of selecting and combining these aspects with the current technical concepts of risk need to be explored.

In future studies, it is necessary to expand the definitions of risk instead of focusing on one or two aspects to better cope and manage risks.

6.2.2. Need Integrated Approaches to Risk Assessment

Prior studies have proposed various methods for assessing concerns and ethical issues separately as a supplement to the main risk assessment process. These qualitative assessments based on expert judgment are also called concern-driven risk management [127]. For example, Hansson [155] introduced ethical risk analysis (ERA) to assess ethical related decisions on risk. The method covers ethical issues such as agency, interpersonal relationships, and justice. Malsch et al. [156] developed an innovative safety decision support system with the integration of ethical impact assessment into risk governance framework, in which social (e.g., equity, gender), economic, and environment-related values are included. Additionally, the UK Treasury method proposed additional scale-based assessment methods to take public concerns, such as familiarity, trust, dread, equity, and management, into account [157].

Generally, these contextual factors are assessed using non-quantitative methods. Given that quantitative approaches dominate current risk management frameworks, further investigation is needed to explore how to synthesize various types of information and data to aid decision-making.

6.2.3. Lack of Normative Procedures of Stakeholder Involvement in Risk Management

The cultural approach, psychometric approach, and moral philosophy all advocate people who may affected by risk should have input in risk management. A fair decision-making process that incorporates stakeholder participation can lead to procedural justice [158,159]. Stakeholder pressure is a significant factor influencing risk management strategies [160]. Over the past decade, there has been a growing interest in involving stakeholders in natural hazard risk management in Europe, particularly concerning flood risk management [161,162].

While there have been attempts to introduce stakeholders in the MCDA method, the approaches vary significantly from study to study. Despite many risk-related standards stressing the importance of stakeholders, systematic procedures for integrating stakeholders in risk management remain lacking [163]. A normative model that can systematically incorporate stakeholder involvement is necessary. Furthermore, scholars should explore ways to better manage diverse stakeholder opinions regarding risk, the interrelations between risk management and stakeholder management, and stakeholders' responsibility and roles in the risk management process.

7. Conclusions

This paper presents a comprehensive review of the historical development, theories, approaches of risk concept used in domain sciences when studying, discussing, and managing risks. The main conclusions are as follows.

1. There are wide variations and even competencies between and within disciplines regarding the notion of risk. However, many of the contradictive perspectives between the concept of risk are due to different standpoints. From a holistic point of view, the social science approach extends the concept of risk. The concept of risk in modern risk science has a deep technical background that emphasizes the scientific nature of

risk. However, risk resulting from a technical system is not isolated and may bring indirect impacts to the broader social system. Risk can not only be identified through scientific methods but also constructed from social activities.

2. The concept of risk has never evolved in isolation; its development has been shaped by the integration of theories from various disciplines. For instance, early probability theory in mathematics has long served as the foundation for quantitative risk assessment. In recent years, more and more risk management studies tried to integrate "hard" and "soft" approaches and provide meaningful results. However, a normative procedural integrated risk management framework still needs to be explored.

To conclude, a comprehensive risk perspective with the integration of diverse values, including technical aspects, social and cultural response, individual cognitive processes, etc., may have the potential to deal with risks in a sustainable and responsible way.

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