A comparative study of risk and resilience and their affiliation in maritime safety research

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Abstract: System safety is a general concept that includes identifying and controlling the hazards of the system during its whole life cycle in a systematic and foresighted way by adopting required technical and managerial means. In contrast with the traditional risk theory in safety science, resilience emphasizes the full-cycle system performance, including the phases before, during and after disruptions. This paper gleans the main results and advances in the two thoughts of study and sketches the theoretical structure of risk study as well as the difficulties it confronts, which sheds light on the motivation and trajectory of the development of the theory. The positions and relations of the two theories have been analyzed, and a comparative study is conducted on the two theories regarding similarities and differences in research methods. Afterward, this paper investigates the current resilience study in the maritime safety and tries to elaborate why resilience study seems more difficult and less appealing in maritime safety research. This paper also tries to point out some bottlenecks in the maritime safety research. The paper calls for a shift of paradigm and combined application of risk and resilience in maritime safety research.

Keywords: system safety; resilience engineering; risk analysis; modelling method; system theory

1. INTRODUCTION

System safety is a general concept that includes identifying and controlling the hazards of the system during its whole life cycle in a systematic and foresighted way by adopting required technical and managerial means. For a long time, research on system safety has mostly been carried out from the perspective of risk to obtain more detailed and quantitative analysis results. The risk is often termed as an opposite concept to safety, i.e., meanwhile, safety is the condition that the risk is acceptably low [1]. However, controversy exists in the definition and connotation of risk as the socio-technical system is turning more and more complex[2]. The discussion of the concept of risk in the academic community has rarely stopped [3]. At the same time, severe disasters and accidents in the real world seem never to be extinct, and the outbreak of these destructive events is continuously challenging and updating people's understanding of system safety or risk. Since entering this century, various types of vicious accidents or disasters have repeatedly caused heavy losses of human life and property. These have prompted safety science researchers to constantly reflect on whether there are new research perspectives beyond the traditional risk assessment perspective and can be more pragmatic.

Resilience has become an emerging research paradigm in safety science for the last ten years and has gradually formed a sophisticated theoretical framework. In contrast with the traditional risk theory in safety science, resilience emphasizes the full-cycle system performance[4], including the phases before, during and after disruptions[5]. This paper gleans the main results and advances in the two thoughts of study, and sketches the theoretical structure of risk study as well as the difficulties it confronts, which sheds light on the motivation and trajectory of the development of the theory. On that base, the positions and relations of the two theories have been analyzed, and a comparative study is conducted on the two theories regarding similarities and differences in research methods. Afterward, this paper investigates the current resilience study in the maritime safety and tries to elaborate why resilience study seems more difficult and less appealing in maritime safety research. This paper shows that these two theories are neither mutually exclusive nor substitutable. Furthermore, the paper anticipates the research trends of the two theories and their joint impact on the maritime safety. This paper also tries to point out some bottlenecks in the maritime safety research if we rely solely on the perspective of risk. The paper calls for a shift of paradigm and combined application of risk and resilience in maritime safety research.

Maritime activities enable the continuous growth of international trade, and play an important role in connecting economy around the world and driving economic prosperity. Although great achievements have been made by using the risk-based analysis framework in engineering practice during the past decades, considerable changes of maritime safety have been taken place at the same time, especially in quantification analysis of hazards and risks. In recent years, resilience theory and engineering has attracted attention of maritime and is hoped to bring new solutions to traditional maritime safety by introducing relevant theories.

The rest of this paper is organized as follows: Section 2 is the overview of risk analysis studies. On the base of analyzing the bottlenecks in risk research and summarizing the research on risk, the concept of resilience is introduced in Section 3. Section 3 introduces the emergence of the resilience concept in safety engineering, the mainstream definition of resilience and the characteristic parameters of system resilience. The further research methods of resilience theory are discussed at the end of section 3. Section 4 discusses the evolutionary relationship between the traditional concept of risk and the resilience and proposes that the dynamic of the analysis perspective is the internal driving force of the concept development. Section 5 makes a comparing between the resilience and risk, and also discuss the advantages of resilience in maritime. Section 6 discusses the affiliation of risk and resilience in maritime safety research. Some conclusions are discussed in Section 7.

2. OVERVIEW OF RISK STUDIES

2.1 Bottlenecks in Risk Research

The purpose of risk research is to serve various engineering practices in the social economy. On the one hand, people recognize the objective existence of risk, and on the other hand, they still feel incapacity to measure the risks precisely. Therefore, the quantitative research of risk has become the most important issue in academia, and the commonly used formulation is Quantitative Risk Assessment (QRA). The risk analysis in the engineering field needs to face greater challenges. The existence of these challenges is fundamentally determined by people's understanding of more basic issues. List the main issues as follows:

(1) Unlimited scene space
The classical risk representation is based on the specific accident scene (adverse event), but in a highly complex system, the accident scene cannot be accurately conceived in advance, and it is more difficult to enumerate and exhaust [6]. Research in the Kaplan era was also aware of this and took the completeness of adding "other" scenarios to achieve logic. However, under the complex conditions of modern social-technical systems, the scenes maintain the flow and transition, and the static scene division in traditional risk analysis is difficult to implement [7].

(2) Uncertainty
The modeling of uncertainty has always been a core issue in risk research [8]. Similar to objective probability (frequency) and subjective probability (faith measure) in probability theory, uncertainty is also divided into aleatory uncertainty and epistemic uncertainty [9]. As mentioned before, there are plenty of methods to measure certainty, including probability theory, random set/possibility theory, evidence theory and fuzzy theory, etc. Among these, probability theory has formed a strict axiom and a complete theoretical system due to it has strong support from basic mathematics. Therefore, it obtains the most application and results in the Probabilistic Risk Assessment (PRA) have become a method of quantifying risk assessment. However, in the actual risk analysis, "uncertainty" will

manifest itself in different degrees. For example, Walker et al. divide it from weak to strong into four levels [10]. Stronger uncertainty is classified as “deep Uncertainty." Under the increasingly complex social and technological conditions, deep uncertainty is a real problem that researchers need to face. The above-mentioned modeling methods for weak uncertainties are often difficult to achieve in the depth of uncertainty, which directly weakens the reliability of risk analysis.

(3) Failure of statistics.
For the adverse events that have occurred, people's experience and data obtained from them are constantly updated into the existing public knowledge base, and a statistical risk assessment is formed, such as the F-N curve [11]. Although there are schools in risk research that refuse to admit the existence of "objective risks" this public knowledge still provide stakeholders with objective implications. However, statistical probabilities or frequency values are derived from large sample data and can be misleading if applied to a specific system object. For example, there are no precedents for the occurrence of many serious accidents [12], or there are very few precedents within a certain time and space. However, if the risk analysis relies solely on historical statistics, the new accidents are difficult to take into account the concept of adverse scenarios.

(4) subjective/objective dual properties of risk and semantic ambiguity
The knowledge of the risks and the uncertainty also determine the orientation of risks on the subjective/objective issues. Academia has proposed concepts such as "absolute risk" and "objective risk" concept, but a growing number of researchers also acknowledge that risk depends on the analysis of subjective judgment, that is, risk analysis personnel knowledge condition (state-of-knowledge) [13]. It should be noted that the bipolar understanding of subjective and objective will be in trouble. The fundamental differences between them are how to view the stability (objective risk) shown by long-term statistics of large sample got from historical data, and the future unknowingness of small individual samples (subjective risk). For the risk analysis in the actual engineering field, the descriptions of risk entities and adverse events/scenarios are full of semantic ambiguity; the analysts cannot (or do not want to) make accurate instructions for the adverse scenarios and possibilities for the future[14]. As a more secure approach, comparing the relative likelihoods of different negative scenarios can avoid giving absolute values of probability (such as event probability, confidence, etc.) In this sense, "relative risk" becomes an alternative method.

2.2 Summary and review of the research on risk

The discussion on the concept of risk has not stopped in academia. It will put risk analysis into a situation that is neither verifiable nor falsifiable if always stick to quantitatively assess scenarios and pursue specific "risk values." However, the ultimate purpose of risk analysis is to reduce or to seek solutions for the risk. Therefore, from a practical point of view, if a reasonable and feasible strategy is found through risk analysis, it will be an attempt to avoid losing the substance. For example, in the field of navigation, the Risk Control Option proposed by the International Maritime Organization can be seen as an explanation of risk analysis at the operational level [15].

3. DEFINITION AND CONNOTATION OF RESILIENCE

3.1. The emergence of the Resilience Concept in Safety Engineering

Safety engineering is an application that provides technical and management methods according to engineering requirements to offer practical support for system security. As an early researcher on the resilience study in the field of safety engineering, Hollnagel gives a perceptual description of resilience [16]. In this research, resilience is regarded as a process that the system requires some core abilities which depend on each other and work together, including monitoring, anticipating, responding and learning, as shown in figure 1. Monitoring is to incorporate the abnormal performance into the scope of the surveillance, that is, the system "knows what to find." Anticipating is to early detect the possible risks and disasters based on perceived information and knowledge, that is, the system should "identify and anticipate what will happen." Responding is to integrate the perception and the predicted information into the cognition and take further action to mitigate the consequences of adverse events, that is, the system should "know what to do." Learning is a system that accurately judges the current state of the system by forming experience and cognition from events that have occurred in the past, that is, the system "knows what has happened." Hollnagel's model also refers to the part outside the system boundary as "environment." Both the system and the environment need to be "Monitoring," and the "responding" behavior affects both the built system and the environment.

As a representative point of view, Hollnagel's conceptualization of resilience has an obvious "proactive safety" interpretation. The system is regarded as a large agent, which able to adapt and respond to internal and external conditions so that the whole system can "seeking profits while avoiding harms." Hollnagel's views are more idealistic and have a certain impact on the interpretation of the concept of resilience. But it should also be seen that in recent years the mainstream understanding of resilience in academia has shown some differences from that of Hollnagel.

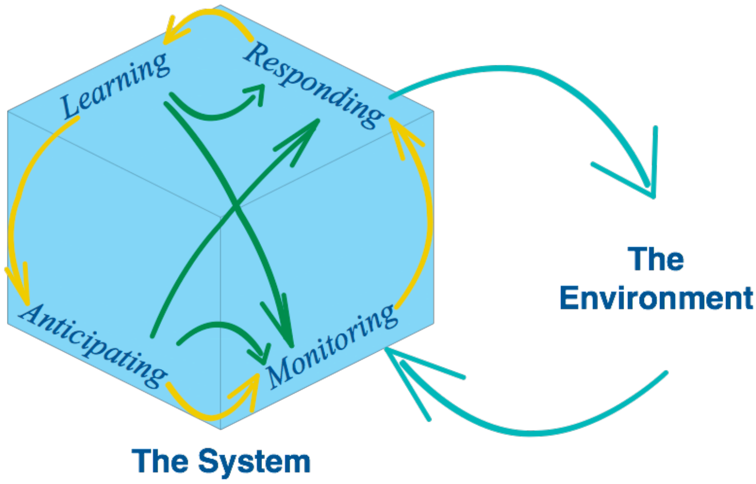

Figure.1 A typical presentation of resilience paradigm[16]

3.2 Mainstream definition of resilience

Many researchers have done a lot of in-depth discussion on the definition of resilience in their respective fields. Like most terms in the field of safety engineering, resilience still exists in academic research in a consensual conceptual form. The definition given by several authoritative institutions or scholars is as follows:

The American Academy of Sciences (NAS) believes that resilience is an ability to prepare, plan, absorb, recover and adapt to adverse events [17]: The research report of U.S. Department of Homeland Security (DHS) pointed out that resilience is an ability that can make the system to resist, absorb and recover from the negative impact of adverse events, this ability should run through before, during and after the events, Haimes[18] believes that resilience expresses system state changes with the aid of time-varying vectors. It is used to reflect the system's ability to withstand damages, including the performance of the system after being damaged to be degraded within an acceptable level, and recovers in an acceptable time, cost, and risk[19].

The above definition of resilience indicates that there are three common understandings of resilience. First of all, emphasis on resilience is a kind of "ability" of the system. Second, resilience is designed to depict the process performance of the system. Third, resilience focuses on the recovery of the system. In this range of this conceptual framework, resilience includes a series of features of the system, as shown in table-1. Among them, "robustness," "redundancy," "resourcefulness (resource abundance)" and " rapidity" were regarded by Bruneau[20] as the four most important resilience attributes (4R), getting a lot of identities.

Tab.1 Features of system resilience

Features	Descriptions
Pre-event measures	The ability of individuals, organizations, and systems to act before adverse events, including forecast challenges, plan and prepare for effective responses to risks or threats.
Situation awareness	In an emergency, people, organizations, and equipment maintain the ability to perceive and create operational scenarios, provide knowledge and understanding of the operating environment to decision makers at all levels.
Withstand	The ability to redirect, hinder, or weaken a threat, risk, or destruction before or when it arrives, including inherent design and positive or negative strategies.
Buffering	The ability of the system to absorb shocks and slow down the degradation in case of adverse events.
Robustness	The inherent strength or ability of the system to withstand internal and external pressures and maintain critical functions.
Redundancy	The ability to not depend on any key sub-system entirely, emphasize options and substitutions, diversify and decentralize of key assets and resources purposefully
Resourcefulness	The ability of an individual or organization to respond to risk and change promptly, including flexibility and adaptability.
Recovery	The ability of the system to operate at a lower or higher performance level after adverse events, which depends on actual needs, constraints, and learning capabilities.
Rapidity	The length of time required for a system to recover to a certain level of performance after adverse events.
Learning capacity	The ability of the system and organization to apply the experience learned in the previous events to improve the performance in the future
cost & feasibility	By analyzing the economic feasibility and practicability of the disaster, the system can maintain the system function at the cost threshold level, within this threshold, system failure or state change can be allowed.

3.3 The characteristic parameters of system resilience

In addition to the above-mentioned qualitative description of the system resilience, the research of resilience also formed an integrate quantitative research framework, the premise of this framework is to assume that people can get a system performance curve [21, 22]. Figure 2 shows this conceptual curve, referred to as the resilience curve, with the horizontal axis as time T and the vertical axis as normalized system performance F(t). Through the intuitive representation of the resilience curve, people can build a series of characteristic parameters that represent the resilience of the system, and the basic importance is undoubtedly the measurement of resilience. Different researchers have proposed their methods of resilience measurement, in which to measure the resilience of the system by area (integral) or distance gain more recognition due to it meets the public intuition.

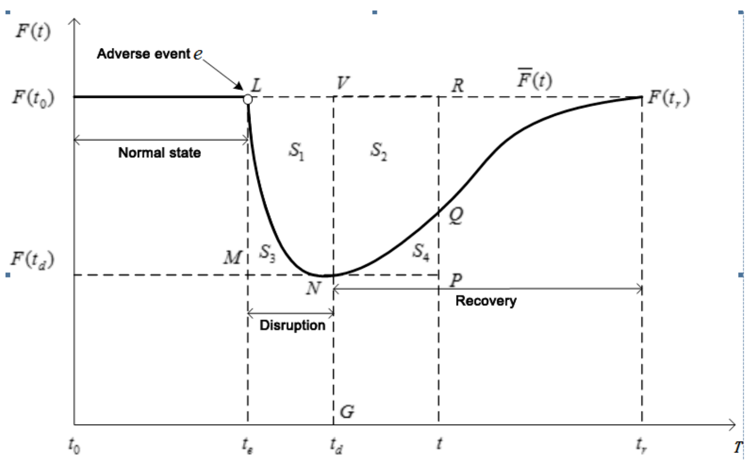

Fig.2 Conceptual curve indicating the system resilience

3.4 Further research methods of resilience theory

After the basic work of resilience research was prepared, some advanced modeling methods of measuring resilience continued to emerge to achieve further quantitative results, which could be divided into several types:

(1) Method of network structure.
The network structure is used to describe the "social-technical" system, which can effectively express the interactive dependencies among various elements in the system. Around 2000, the research boom of complex networks began to sweep the academia. Since then, network resilience has become an important research issue in complex networks [23, 24]. Although the concept of "resilience " in the early research of complex networks is conceptually inconsistent with the resilience of modern security engineering, the methods, and means in complex networks undoubtedly greatly shape the research on resilience in the field of security engineering. Ganin, et al. [6] tested the network performance of multi-layer, undirected graphs, and double-coupled undirected graphs, aiming to find out how the main network characteristic parameters affect the shape of the resilience curve. The Ramirez-Marquez research group's series of papers measure the network performance using the width of the path between the origin and destination nodes in the network[22, 25].Fang, et al. [21] measured the importance scale of nodes in the network model based on the resilience of the network system, in which the importance of the nodes was reflected in the priorities of repairs. The above research shows that the use of network models is an effective research approach for computing the resilience of critical infrastructures such as transportation, communications, and power[26].

(2) Method of the dynamic equation
The dynamic performance of system resilience has always been a very challenging issue, and the traditional dynamical system based on the differential equation is undoubtedly the main tool for this issue. Gao, et al. [27]added an item on the traditional dynamic system to describe the behaviors between system components, revealed the mutual influence between components by constructing the correlation matrix, and observed the bifurcation chaos of the system's resilience curve cluster by changing the value of key parameters. Cimellaro, et al. [28] consider the system's ductility curve as a kind of harmonic oscillator's damping behavior and use a second-order linear differential equation to represent it. The change of equation parameters will result in over-damped or critically-damped curves. The basic hypothesis for using system dynamics to study system resilience is that the recovery performance of the system after impact is governed by a set of rules, and this set of rules can be further expressed through higher-order derivatives of the performance curve.

(3) Method of uncertainty
The study of system resilience based on uncertainty methods involves various means including the use of stochastic, fuzzy, and subjective scoring. These means all recognize that the various characteristics of system resilience cannot be accurately obtained. Therefore, the range of easy estimation is given in the form of "probabilistic." Chang et al. Chang and Shinozuka [29] proposed a probabilistic model for evaluating resilience, which mainly measures the loss of system function and the length of recovery time. Francis and Bekera [30] introduced the entropy weight as a component factor of resilience, to describe the judgment of multiple experts on adverse events. The occurrence and duration of multiple hazard events in the system are also handled by using random variables. Azadeh, et al. [31]used fuzzy Cognitive Map (FCM) to evaluate the factors of engineering resilience and described the reasoning between the nine factors. The attention of the academia of uncertainties in system resilience and the corresponding modeling also reflect the most fundamental challenge in safety engineering, which is the prediction of unknown scenarios[32].

4. FROM RISK TO RESILIENCE: THE DYNAMICS OF CONCEPTUAL EVOLUTION

4.1 The limitations of risk in the perspective of security

There are two main limitations to assess system safety from the perspective of risk: (1) Risk is a “prospective" pre-analysis before the event to find as many threats to the system as possible and find reasonable solutions for that, it ignores the system's resistance to damage. (2) The risk adopts the "Cause-Effect" logic and stops at the edge of thinking on the destruction of the system by adverse events. It does not pay enough attention to follow-up incidents that have been damaged by the system. In general, risk does not pay attention to the "during" and "after" stage of system security.

The theory of risk essentially embodies the idea of “preventing problems.” In the process of system safety development, this more intuitive way of thinking is well in line with people's understanding of social-technical systems and has become one of the most important components of system safety theory. In practical application, the above limitations will lead to two difficulties in risk analysis: (1) Unforeseen events are unpredictable and can only be classified as "residual risks." For residual risks, it is difficult for QRA to provide effective evaluation; (2) the time scale of the risk is ignored, and the adverse events conceived are not considered the time attribute. Therefore, the risk analysis itself does not reflect the dynamics of the system, but can only be realized by the external repeated implementation of risk analysis. These difficulties in the theory of risk are the deeper challenges in the system safety research, which uses the limited knowledge of the past to speculate on the infinite possibilities of the future.
People are constantly trying to break through these limits of risk theory. To achieve this goal, it is particularly necessary to jump out of the old theory of risk and change the perspective of research.

4.2 Requirements and internal causes of resilience research

Since the beginning of this century, the occurrence of series of serious accidents has prompted researchers to further examine and supplement traditional security theories. In this context, a great deal of work has been done on the accident model in the field of safety engineering[33]. These studies show that, to a great extent, the impact of accidents (disasters) on the “social-technical” system is unavoidable, and the current level of technology cannot predict, contain, or circumvent all accidents (disasters). Contrary to the traditional way of thinking, it is assumed that a system will inevitably be attacked by unexpected events, and it will prepare and have a strategic way to reduce the impact of adverse events on the system. When a hazard occurs, striving for a more favorable situation and taking prompt measures to repair the damaged system has gradually become a new concept for enhancing system security, and “resilience” is a representative idea in this context.

Compared with the traditional risk analysis, measuring system safety using resilience reflects three changes: (1) the focus of the study is from scanning adverse events (scenarios) to the system itself, which is from external to internal. (2) focus on the whole process of adverse events, to investigate the system's ability to withstand adverse events in a relatively complete cycle; (3) pay more attention to the dynamic behavior and performance of the research system, rather than the static property of the system [34].

5. THE COMPARISON OF RISK AND RESILIENCE

5.1 The positioning and relationship between the two

Since the beginning of this century, the resilience theory has developed rapidly, and the risk theory has also been in the process of self-improvement. Therefore, the relationship between the two theories has gradually been concerned by the academia. Based on this, there are three viewpoints [35]: (1) resilience is the goal of risk management. Risk-informed system can be more resilient. (2) resilience is a part of risk management; it can take over the management of "residual risk" in risk management; (3) resilience is another alternative to risk theory.

It is not difficult to see from these attitudes that the contribution of the resilience theory to safety engineering has been recognized by the academia, but the risk theory is still an irreplaceable basic theory in the field of safety engineering.

5.2 The difficulties faced by both theories

As mentioned above, the resilience theory has achieved some evolution in the concept compared with the traditional risk research, but this does not mean that resilience solves the difficulties faced by risk theory. In fact, not only the main challenges in risk theory still exist in the resilience theory, but the resilience theory also comes with new problems:

(1) The setting of the initial adverse scenarios.
One of the most reviled areas of classical risk theory is that the scenario is not exhaustive, which still exists in the theory of resilience. For a resilience curve, it portrays people's estimates of system performance during a given adverse event. In other words, resilience depends on the performance of the system under a given scenario. Therefore, a lot of researches have been made to improve the resilience curve's shape of specific scenarios as the optimization objective. At the same time, the system performance value (index) in the resilience curve is designed to depict the basic characteristics of the operating condition of the system; however, the use of a single scalar is often difficult to fully characterize that.

(2) The evolutionary track of adverse scenarios.
The traditional risk theory does not involve the performance of the system after adverse events. It can be argued that the emergence of the resilience theory can undertake the deficiency of risk theory in this respect. However, the performance of the system after adverse events is still a difficult point in the study. For a given scenario, to construct the deduction mechanism to provide a reasonable estimate for the process and trend afterward, the existing research methods mainly include dynamic event tree, dynamic Bayesian network and so on. Among them, the former is an outward-oriented derivation, which is based on the derivation of rules, and the latter belongs to an inward derivation.

(3) Modeling of human factors and organizational factors
The most prominent complexity of the social-technical system is that the behavior of people and organizations is closely interwoven with natural conditions and engineering systems. The existing safety engineering theory believes that more than 70% of accidents are caused by human factors. However, the modeling of human factors and organizational factors is more complex and uncertain than the modeling of natural and physical systems [36]. Traditional risk theory does not touch human factors and organizational factors. However, for the study of resilience theory, the modeling of human factors and organizational factors is no longer a problem that can be avoided.

5.3 Study route comparison

Although risk and toughness research faces some common problems and difficulties, a large number of studies on risk and resilience for practical application has been implemented in different engineering fields. An important difference between risk and resilience is that risk analysis is used to make sense beforehand, and resilience can be used for pre-assessment or retrospective analysis.

Apart from the discussion of theoretical frameworks and conceptual connotations, the existing quantitative research work does not differ greatly in the research tools used in the research of these two theories. This also indicates that the major difference between risk and resilience for a given safety-critical activity or system is the orientation of the evaluation criteria or decision goals. Table 2 summarizes the application methods in the study of risk and resilience according to the main technical options. It is not difficult to see that when various tools are applied in resilience theory, more emphasis should be placed on giving a time-varying model. For example, dynamic Bayesian networks, dynamic event trees, etc. which also put forward higher requirements for such more basic model research.

Table.2 Comparison of widely-used technical treatments in risk and resilience study

Technical options		The emphasis on application in both theories	
		Risk studies	**Resilience studies**
Data Driven	Historical accident statistics	Extract the types and likelihood of occurrence (frequency) of adverse event	Extract the typical toughness model, including the performance characterization of "before," "during" and "after."
	Event Correlation Analysis	Establish numerical or quantitative characteristics of independence/ association between events	Establish a time-dependent model of the sequence of events in a specific scenario
	Loss analysis	Estimate the consequences of similar adverse events based on large sample data	Estimate the recovery process for similar adverse events based on large sample data
Simulation method	Discrete event simulation	The damage degree of adverse events is simulated based on the outbreak of adverse events and their impact on the system.	Overall function of simulation is restored, according to the recovery mechanism of each component of the system after self-repairing or receive external resources.
	Monte Carlo simulation	Simulate accidental randomness of adverse event triggers	Simulate accidental randomness of constraints in the repair of adverse events
Expert survey	Indicator selection	Identify risk factors and identify risk sources	Determine the real-time performance value of the system and its meaning to draw the roughness curve.
	Experience estimation	The subjective possibility of adverse events (trustful)	Build unfavorable scenario event tree
	Fuzzy Semantic Analysis	Extract fuzzy causal rules triggered by adverse events	Modeling the dependency relationship between elements of adverse events, such as building fuzzy cognitive maps
Uncertain methods	Bayesian network	Dependency (topology) and conditional probability tables for designing adverse events and other related events	The dynamic Bayesian network is used to model the time-varying characteristics of the system state.
	Fuzzy reasoning	Analyze the cause by reasoning, extract the risk factors and induced conditions for the set of adverse events	Predictive evolution of events following rules

6. AFFILIATION OF RISK AND RESILIENCE IN MARITIME SAFETY RESEARCH

6.1 Affiliation of risk-based studies in maritime safety research

In recent years, the maritime risk analysis method has attracted more and more attention and has been well developed. The International Maritime Organization (IMO) has formulated corresponding specifications or recommendations for the use and development of maritime risk analysis and management tools [37, 38]. In parallel, the basic scientific issues related to maritime risk analysis have also been developed, and further research has been conducted on issues such as the application of terminology, analysis and management of risk principles and perspectives [39-41].

With the arising of new challenges, maritime risk analysis also has new developments in theory and application. There are several trends worth noting, for instance, the use of new uncertainty modeling methods to deal with the uncertainty of risk to approach insufficient historical data, introduction of FSA into the shipping safety analysis framework system, and developing new HRA methods for maritime affairs, the further quantified and analyzed tools for human error and factors in the maritime operation, and opening up new areas of maritime safety research, etc. These works have achieved different research results, and the latest risk analysis and quantitative tools have been introduced to bridge the gap between the maritime industry and the high-tech sector by using formal methods to quantify risks.

6.2 Affiliation of resilience in maritime safety research

The infrastructures and structures of the maritime system have the characteristics of a fast rate aging and deteriorating and a high rate of damage due to its challenging working environment. However, given the important role of these systems playing in advancing the global economy, the challenge for decision makers is to maintain a balance between safety, sustainability, and resilience ability of system from various operational uncertainties[42]. These severe operation environments bring a lot of uncertainties, as there are so many incidents that are vague and inaccurate. This brings many difficulties when design and analysis of the systems because many of the available data are highly uncertain and difficult to obtain. This requires a new systematic approach to dealing with quantitative and qualitative data, as well as ways to update existing information when new knowledge is acquired. Resilience, the ability of to recover quickly after severe damage has been widely recognized as an important feature of maritime operations and is used as one of the key factors in system design and analysis[43].

Rational modeling of the system can achieve useful insights about the propagation and principles of failures, as well as provide a basis for developing robust frameworks and methods. In turn, these frameworks and methods can also be used for system analysis[44]. Building resilience in maritime structures and engineering requires the ability to create system models that are sufficiently sensitive to the various factors involved in their operation. Also, scholars and industry acknowledge that the efforts of improving safety and reducing risks will always bring about a reduction in revenue. Therefore, a more realistic thought to optimize the system's ability to defend against risks is to incorporate resilience into design, analysis, and operations to adapt, respond to, and recover to the required functional level.

The system design, analysis, and operation methods that emphasize resilience can provide the system with flexible and collaborative modeling ideas, and enhance the system’s ability to proactively handle the various risks of disruption, especially when new risks and threats are constantly changing. Besides, studies related to resilience in the maritime field are still inadequate, and the need to establish a safe and resilient maritime engineering system is very urgent. Mostashari, et al. [45] introduced resilience-based theory into the traditional maritime engineering modeling method. Mansouri, et al. [46] approached an intelligent decision-making tool which can provide decision-makers with recommendations based on the resilience theory to optimize the effectiveness of maritime engineering system performance.

7. CONCLUSIONS

From risk to resilience, it reflects the change of research concepts in the field of security engineering. Compared with traditional risk research, resilience theory emphasizes studying the impact of adverse events on the system from the whole process. Through the comparative study of risk and resilience, the following conclusions can be formed:

(1) The resilience theory has remedied some defects that in the traditional risk theory, but some fundamental problems in the risk theory also cannot be overcome in the resilience theory. So resilience is not a "more perfect" theory to replace risk. Many researchers are also trying to expand the resilience theory into a more general business continuity theory [47].

(2) Resilience and risk will develop into two theories that can learn from each other. The research of resilience theory promotes the development of risk model to combine dynamic and adverse scenarios. The risk decision will be optimized at each transient time point of the resilience theory.

(3) In the context of the deepening of big data to scientific research, risk and resilience need to focus on solving unexpected or extreme events that cannot be reflected by big data. This incident, which is known to foreign researchers as "the black swan," will place the risk and resilience in an iterative learning process.

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