Some reflections on pre- and post- accident analysis for water transport: A case study of the Eastern Star accident

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ABSTRACT: In the literature, research on pre-accident and post-accident analysis has been reported extensively. The former falls into the category of risk analysis to identify the potential hazards and the consequences, so that decisions can be made to take appropriate preventive and mitigation measures. The latter amounts to accident investigation for learning lessons and finding solutions. This paper uses the catastrophe of Cruiser Eastern Star in 2015 as a case study to analyze some typical accident models, including the Swiss Cheese Model, AcciMap, Stamp, FRAM, etc. By comparison, pros and cons of each perspective are identified. Overall common challenges for all methods are pointed out and a reflection is offered with respect to the added value of complementing the analysis under a resilience perspective, to enhance preparedness for unknown adverse events.

1 INTRODUCTION

Water transport is a traditional industry that can date back to the most ancient human activities. Despite the fast transition of the world's socio-technical being, waterway remains the essential means of transportation, accounting for over 90% of the world's trade (Rodrigue et al. 2013). During its long course of development, water transport has been always considered potentially hazardous and dangerous. Regardless of the truth or falseness of such consideration, records of numerous maritime accidents, such as Costa Concordia, Sewol and Eastern Star disasters, definitely show that waterway transportation is an industry intrinsically associated with risk.

In view of this, there has been a large volume of academic research work devoted to safety analysis for water transport (Goerlandt et al. 2014). Apart from the risk analysis studies (Li et al. 2012), the study on accident analysis, as the other side of the coin, is equally receiving ardent interest from the researchers. Apparently, the study of risk and accident analysis in the field of maritime transportation mainly draws its ideas, concepts, models and approaches from the general study of risk and accident analysis (Yang et al. 2013, Goerlandt & Montewka 2015), which is within the domain of safety research. In another sense, the study of general risk and accident analysis can find its application and validation by the data and cases in the maritime transportation (Zhang et al. 2014a, b, Montewka et al. 2014).

In the literature, ad hoc research on pre-accident and post-accident analysis has appeared extensively (Wang et al. 2013). For the majority of the pre-accident study, the risk-based perspectives and methods dominate the perception (Goerlandt & Montewka 2015); for the typical post-accident study, statistics or data of the past accidents are exploited to find the pattern of accidents, and these refined findings can in turn cast risk indications for accident prevention.

The risk-related study encompasses a broad spectrum of academic perceptions. In its most naïve form, risk can be interpreted as the product of likelihood and the consequences of adverse events (Rausand 2011). Nevertheless, there have been different understanding about the rigid definition of risk (Aven 2011, Haimes 2011). A sophisticated definition may contain uncertainty, knowledge, or system state vectors etc (Haimes 2009).

Accident models are the mainstream problems as well as methodologies in the ex-post study of accidents. The main categories of accident models include the sequential model, the epidemiological model and the systemic model (Hollnagel & Woods 1999). There have been numerous variants developed to interpret the causes, effects and reasoning of the accident process. AcciMap, system-theoretic accident model and process (STAMP) and functional resonance accident model (FRAM) emerge as the prominent methods to analyze accidents (Underwood & Waterson, 2014). It can be envisioned that the study of accident makes a stepping stone to the study of safety issue in water transport.

This paper conducts a case study on the catastrophe of Cruiser Eastern Star in 2015 to acquire a more comprehensive understanding about the domain-specific accident analysis. Typical accident models, including the Swiss Cheese Model (SCM), AcciMap, STAMP, FRAM and risk-based perspective are utilized to yield multi-angled views. By comparing these accident models, pros and cons of each perspective are identified, and challenges for them are pointed out. Based on these results, reflections are made with respect to the added value of complementing the analysis under a resilience perspective.

The remaining of the paper is organized as follows. Section 2 introduces the maritime accidents used for the case study. Section 3 analyzes the five relevant accident analysis methods. Section 4 discusses the strengths and weakness of the five methods. Section 5 concludes the research findings.

2 THE EASTERN STAR ACCIDENT

While the disasters in water transportation can always arouse the sensation of people, some of the stakeholders may show great scrupulousness to release the informative accident reports. Research on the foundering of Costa Concordia in 2012 began to appear shortly after the accident (Schröder-Hinrichs & Hollnagel 2012). Although the loss caused by Costa is much less than that of the TITANIC in 1912, it is somehow compared with the latter for introspection. Two years after the accident, the capsizing of Sewol in 2014 once again outreaches the scope of the experiential safety knowledge (Hyungju & Stein 2016).

Each occurrence of a distress will widen human's knowledge on safety/hazard, and correspondingly, the knowledge base of the researchers and the practitioners will be monotone increasing. The ideal hypothesis is that, with the ever growing knowledge base of accidents, the ability of foreseeing or coping with the accidents should be strengthened consequently, and that the tendency of accident occurrence will decline asymptotically.

Unfortunately, the actual situation is by far worse than the idealized envision. In 2015, the inland passenger ship, Eastern Star, once more interrogates the theory and practice of risk or resilience in water transport. Eastern Star is a cruise ship who operates the itineraries along the Yangtze River, featuring the Three Gorges sightseeing. The length of the ship is 76.5 meters, the beam 11 meters and the capacity 534 passengers.

The ship departed from Nanjing at the time 1300 hours (GMT+8, the same below) on 28th May, and the destination was Chongqing in the upper reaches of the Yangtze River. At the time 1930 hours on 1st June, 2015, the ship entered the JianLi waters, with heading nearly to the north. At this time of the trip, the regional waterway was being struck by a severe rainstorm. The ship rushed into the central area of the strong convection at the time 2119 hours, and was hit by the fierce northwest linear gale to the port. The ship swerved to the left during the time 2120 to 2121 hours, with heading jerked from 23° to 342°, aiming to counteract the gale. Approximately at the time 2132 hours, the ship capsized to the starboard within 1 minute, and was drifting downstream afterwards. The last AIS signal was broadcasted at the time 2131 hours at 29°42'N, 112°55'E.

The sinking of the Eastern Star cost 442 lives, making it the most fatal maritime accident in China since 1949. Only 12 persons on board survived from this accident, including the master and chief engineer officers.

3 ACCIDENT ANALYSIS VIA DIFFERENT MODLES

3.1 *The barriers and defences*

From the perspective of SCM (Reason 1990), several layers of barriers are placed to hedge an accident. As for the case of Eastern Star, the four defensive layers are described in Figure 1.

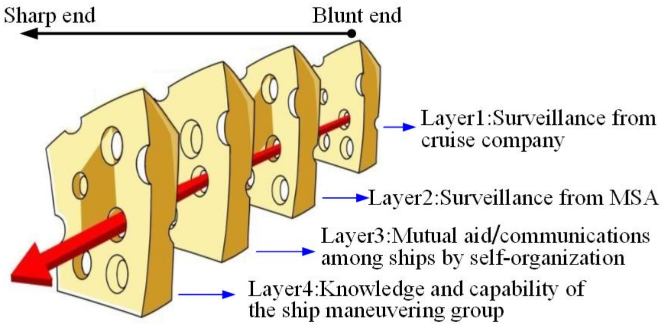

Figure 1. A SCM-style analysis.

The realization of the accident means that the holes in the barriers do exist, and cause the failures of the defensive layers, as follows:

- Layer 1: The cruise company tacitly consents to adventurous sailing in treacherous environment at night.
- Layer 2: The early warning messages dispatched by the maritime safety administration (MSA) come out too late, and there is a lack of decisive and strong intervention in the vessel traffic at the time of hazardous weather condition.

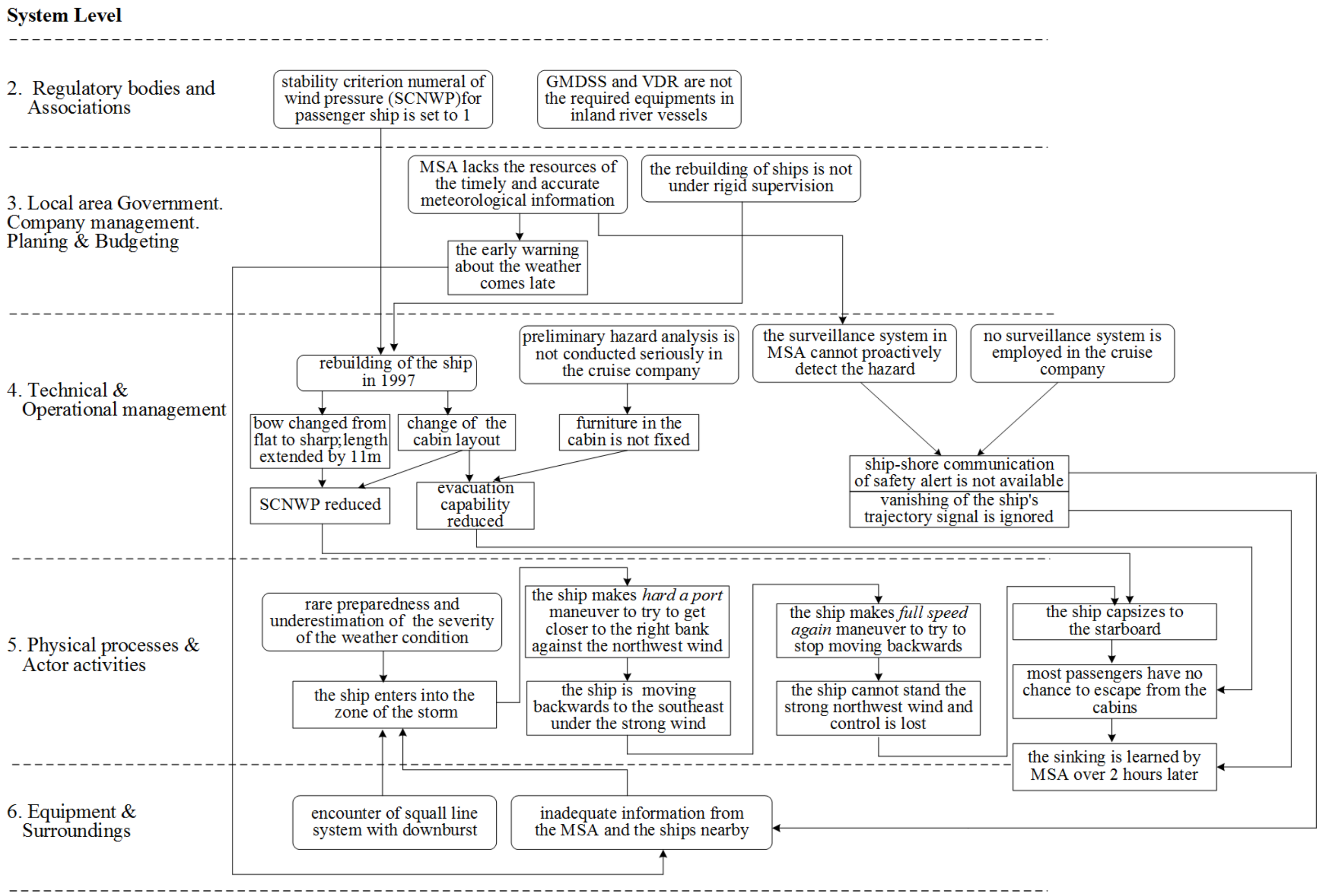

Figure 2. An AcciMap-style analysis.

- Layer 3: Poor information about the hazardous weather condition is shared over the VHF communication among the ships near the area. Six ships are involved in the storm simultaneously, but the reciprocal communications and behavior is scarce.
- Layer 4: The maneuvering group underestimate the severity of the weather condition, and choose a venturesome strategy to break through, thus leaving the whole ship at stake.

3.2 *Socio-technical system and AcciMap*

To bring an accident in question into the socio-technical context therein will offer a wider panorama for the analytic treatment. In his seminal paper, Rasmussen (1997) introduces the dynamical boundary of the safe behavior. Inspired by this idea, the analysis of Eastern Star is illustrated in Figure 2. In the case of waterway transportation, the accident analysis should specially consider the multiple actors within the scenrios whose actions can have joint impact on the evolution of accident.

Figure 2 presents an AcciMap-style analysis of the Eastern Star (Rasmussen & Svedung 2000). The original AcciMap model has six system levels, but in this analysis, the top level is omitted because the relevance is less direct and the omission will cause no loss of the essence. By AcciMap model, the accident analysis is placed in a panorama of socio-technical context.

3.3 *System-theoretic accident model and process*

With the ideas of STAMP, systems are viewed as interrelated components that are kept in a state of dynamic equilibrium by feedback loops of information and control (Leveson 2004, Licu et al. 2007). The three bedrocks of STAMP are safety constraints, hierarchical levels of control, and process loops.

Through the lens of STAMP, the major casual factor of the Eastern Stars accident is the constraint failure, which does not prevent Eastern Star from entering the wrong place at the wrong time. And this failure is mainly due to the block of some control loops that are supposed to take effects over time.

Figure 3 depicts the STAMP-style control structure of the accident scenario. The cruise company does not employ any surveillance infrastructure to trace the ship, which means no link with the ship; MSA does not obtain the adequate information about the meteorological conditions, and does not maintain a peer-to-peer supervision with the ships involved in the foreseen dangerous situation; the communication among the ship is not functioning well due to noise or disturbance of the storm.

From Figure 3, we can see that the Eastern Start bears few control loops from other components of the system. This suggests that the ship is subject to no constraint or control in the extreme environment. And finally, the unfortunate encounter of the traversing squall line becomes the last straw.

For simplicity, the further qualitative process delineation in line with the STAMP template is omitted.

3.4 *Functional resonance accident model*

Using the language of FRAM, the system is viewed through a functional abstraction rather than structural decomposition. The interaction among the functional entities governs the behaviors the system. In this regard, the context of Eastern Star is expressed by three functional entities as can be demonstrated with the three hexagons in Figure 4. The relations among the functional entities depicted by the arrows reflect the normal behaviors and performance variability in a routine sense.

In FRAM, function resonance refers to the high performance variability of a functional entity, which is deemed as a sign of a potential accident. Setting the damping factors is the practical way to curb the function resonance, and the accident in the end. However, the FRAM shows certain drawbacks in analyzing accident due to extreme events, as in the case of Eastern Star, where the extreme event usually cannot be manifestly reflected by a functional entity in the FRAM diagram.

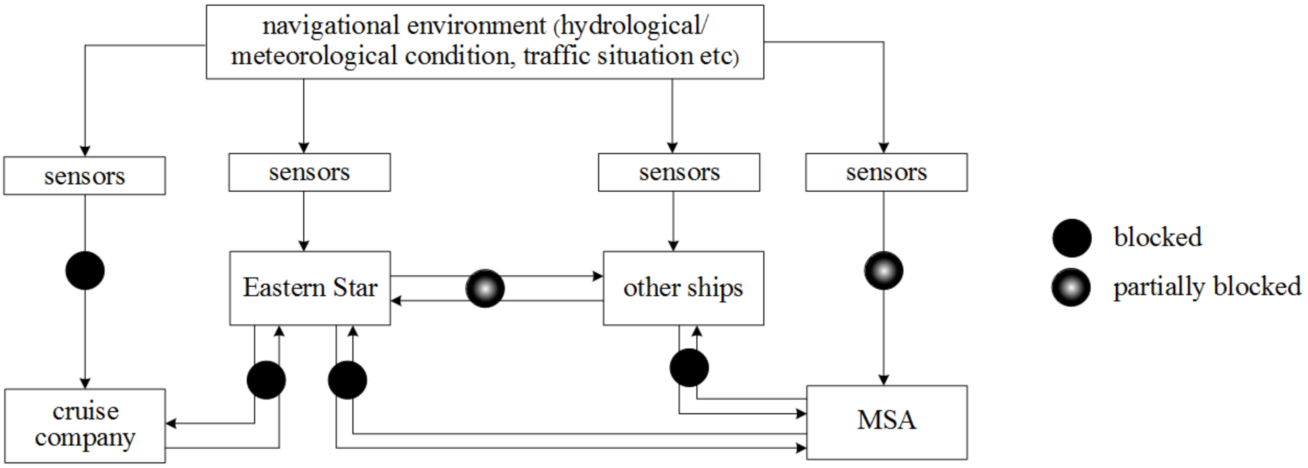

Figure 3. A STAMP-style safety control structure analysis.

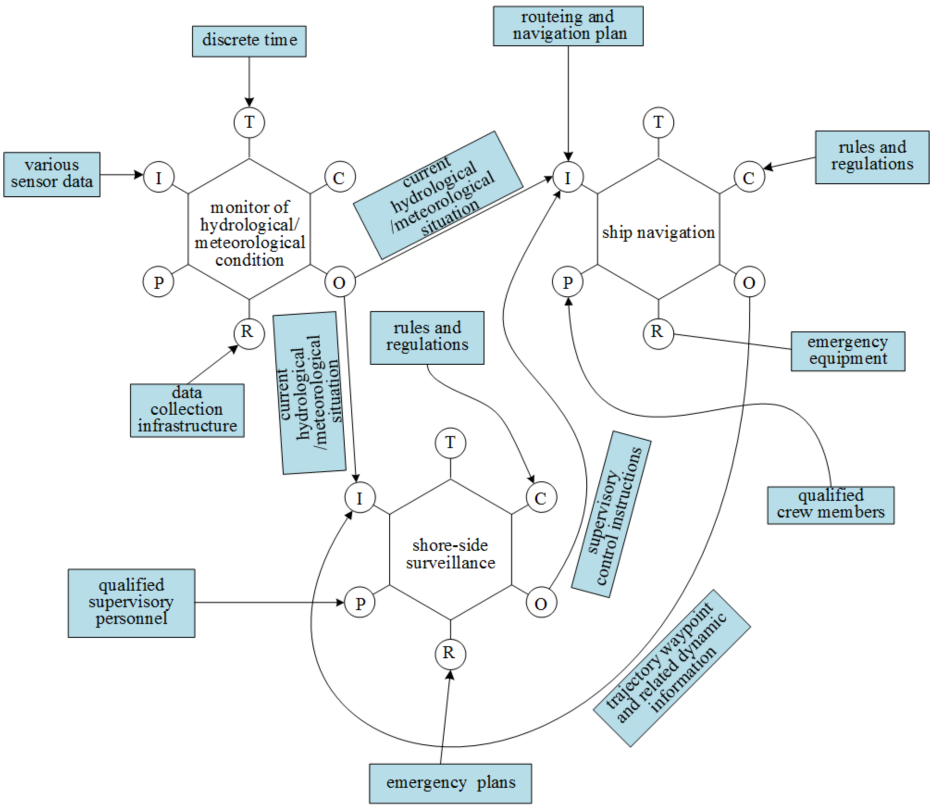

Figure 4. A FRAM-style function entity diagram.

3.5 *The risk analysis in hindsight*

Risk analysis is normally conducted a priori to prevent or mitigate risks (Zio 2007, 2016). As for the case of Eastern Star, we explain to what extent the risk analysis can yield meaningful results. This can help us understand the gap between the current theoretical presentation and the accident-prone activities in the real world. Here, again, the attempt is to set out from the practical and engineering angle.

We follow the widely accepted conceptual risk description (C, Q, K) (Aven & Krohn 2014), with the three elements standing for the event/ consequence (C), quantitative measure of uncertainty (Q) and background knowledge (K), respectively. We assume that the following analysis is carried out as if we were at the time prior to the Eastern Star accident.

A broad spectrum of hazard events can be involved and investigated in the navigation of Eastern Star, at the time she starts the journey. For instance, windstorm, collision, contact/grounding, fire/explosion are main hazard sources (Mazaheri & Montewka 2014). The variety of root causes makes it difficult with selecting or exhausting the “relevant” events. Even focusing on a certain type of hazard event, the variance in time and space will still cause a considerable variety of events.

The measure of uncertainty is largely a technical problem, in which there are alternative tools, such as probability theory, Bayesian Network, D-S theory and possibility theory (Zio & Aven 2013). These tools are backed by their own theories with concrete mathematical foundations. It is worth noting that the measure of uncertainty is the direct reflection of the background knowledge. In most quantitative risk assessment (QRA), the measure of uncertainty and the knowledge share the same theoretical kernel, once the knowledge is represented with a specific formalized model. Although the Q and K have very close affiliation, the risk description regards them as separated input to better denote the various knowledge from different sources.

In the case of Eastern Star, if we could apply the knowledge-featured risk description to the ship prior to her last journey, we shall have to confront the additional challenges as follows:

- The actual accident is *unexampled* in several aspects with respect to the accident data base during the past 15 years, including the location (Damazhou waterway), the root cause (entering the center of a storm), the ship type (the cruise ship) and the master’s competence (highly experienced master). If the knowledge relies too much on the frequency or probability of similar accidents based on the historical dataset, the risk analysis may give false negative results.
- The knowledge about the Eastern Star journey can be classified into open knowledge and private knowledge. The former represents information that is publicly available, such as the meteorological and hydrological parameters; the latter represents the information that is only available for a few insiders or professionals, such as the foreseen squall line, the past rebuilding record and the SCNWP(Stability Criterion Numeral of Wind Pressure) of the ship. This disparity in knowledge will result in disparity in risk assessment from different analysts.
- For the cost-effective purpose, the risk analysis would be conducted with less sufficient knowledge and for more abstract objective, e.g., at a higher scale. For instance, it is more likely for MSA to analyze the risk of navigation of a specific range of waterway during a specific period, instead of the risk of a specific ship like Eastern Star, and this leads to the lacks of discriminatory information for individual ships. In this manner, the risk analysis is often reduced to a less informative form, i.e., the early warning message.

4 DISCUSSION

Based on the above conventional treatments of the Eastern Star analysis, two questions are of special interest for the discussion:

- Is the Eastern Star case truly an inevitable accident? Or otherwise, where is the least modification that can prevent the misfortune if everything could be repeated?
- Apart from the latter-wit, how can we distill something from these conventional methods that can make the system more immune to accidents, even though we are blind about when, where and, how the next accident will occur?

The first question is equivalent to finding the cause of accident. The root cause can be ascribed to the irresistible natural force. However, it is more pertinent to categorize this accident into human factor and organizational factor. It is due to human factor that the crew fails to make the right decision to prevent the accident; it is due to organizational factor that the navigational information and warning from the shore-side administration is inadequate and untimely. Other factors, such as the degrading of the ship’s resistance against wind pressure, are not the dominating factors.

The second question is rather ambitious, and there may be no off-the-shelf answers. Table 1 summarizes the limitations of the aforementioned treatments for accident analysis. It has to be acknowledged that most of the existing analytical approaches are post-hoc study, meaning that we have already known the incident and try to make a backward analysis. However, it is purely a paradox that we could know something about the future accident and take precautions.

As has been mentioned previously, one of the key characteristics of accidents is the unpredictability. The unpredictability can relate to the time, the space/location and the causation etc. Although human's knowledge is broadened with each occurrence of accident, and we endeavor to take preventive measures based on the accumulating knowledge, we still can see no extinction of accidents.

The reason can be interpreted by Figure 5, which illustrates the space of causal element. With each occurrence of accident, the number of hollow dot increases and the circled area around them expands.

However, with the ever-growing precision, compactness and complexity of large systems, the number of unknown causal elements (the solid dots) may be rising at even faster speed over time. In other words, what we know about the casual elements of future accidents is much less than the potential casual elements which we don't know or are out of our anticipation.

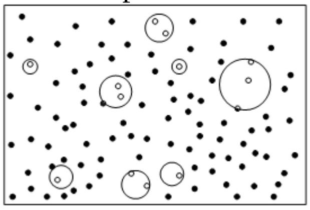

Figure 5. A space of causal element.

Returning to the Eastern Star case, despite the limitations listed in Table 1, we are in the position of making the most out of the existing theories and methods. To this end, we resort to a resilience view to find a partial solution to the second question (Hosseini & Barker 2016). Regarding resilience, the most salient shift from traditional risk analysis (or assessment, management) lies in the holistic thread for adverse event responding (Baraldi & Zio 2008). The main limit for risk study, as we can think of, is the relatively short run-length of consideration span along the time dimension for the adverse possibility. The reaction and recovery cycle of the adverse situation disposition, is less covered in the conventional risk study while it is the cycle that the resilient study places emphasis on.

Table 1. Comparison of the aforementioned treatments for accident analysis.

Method		*Limitations*
Swiss Cheese Model	*1*	Mono-threaded assumption of accident process development
	2	Lack of logical interdependence among multiple causal factors
	3	The pre-configured barriers are based on stereotyped knowledge derived from past experience, and may be by-passed by unknown accident thread
AcciMap	*1*	Lack of chronological relation among multiple causal factors
	2	A more of *post hoc* view and delineation of accident analysis
	3	Lack of the capability to describe the dysfunctional interaction between agents
STAMP	*1*	Lack of the capability to describe the impact of *external* disruption or surprises
	2	A mostly *post hoc* view and delineation of accident analysis
	3	Inadequate capability to model the weak control and feedback among loosely coupled components
FRAM	*1*	Lack of the capability to describe the dynamical and interactive behaviors among multiple real/physical components over time
	2	It is difficult to define and identify the abnormal performance variability for the functional entity
	3	The spatial and temporal interdependence cannot be manifestly described
(C,Q,K) Risk Analysis	*1*	Disruptive events can hardly be exhaustively enumerated
	2	Subjective knowledge differs significantly among multiple analysts
	3	Statistics on historical data may lose effect for the foresight of extreme events such as catastrophes due to their low frequencies
	4	Post-disruption situation is usually beyond the boundary of the current risk study

5 CONCLUSION

The diversity of accident models provide multiple angles to gain insights into the cause path and mechanism of the accident, whereas the risk analysis is supposed to help stakeholders evaluate the potential hazard before accident.

The innate difficulty for these methodologies is also very straightforward: what will these methodology bring forth for the decision-makers when no accident occurs?

Obviously none of the above methodology can act as a fortune-teller by foretelling when, where and which type of accident will occur. Nevertheless, these methodologies can show their values by enhancing the consciousness of safety, including the following aspects:

(1) Understanding the structure, function and interplay of the components to know the trajectory of any

potential accident in terms of time, space and logic dependence.
(2) Being aware of the potential hazards according to the dynamic status of the system;
(3)Paying more attention to the human factors and the organizational factors in human-intensive systems such as waterway transportation.

With the growing complexity of the modern socio-technical development, it is ever difficult to exhaust the potential casual factors to guarantee an accident-free system. This paper uses the catastrophe of Cruiser Eastern Star in 2015 as a case study to analyze five typical accident models, including the SCM, AcciMap, STAMP, FRAM and risk-based perspective for accidents analysis. These methods generally fall into the categories of pre- and post- accident analysis. Based on the comparison, it is shown that all the conventional methods demonstrate some limitations in dealing with extreme events. For the safety of a complex system like the water transport, the utmost difficulty to tackle is the unknown or the unpredictable hazard, and this makes a paradox for researchers. With this understanding, this paper finally tends to favor a more practical paradigm of thoughts, i.e., resilience, as a promising perspective. More work is anticipated to incorporate the traditional point of view into the new mindset, and this will be the direction of our future research.

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