Models and Computational Algorithms for Maritime Risk Analysis: A review

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Abstract

Due to the undesirable implications of maritime mishaps such as ship collisions and the consequent damages to maritime property; the safety and security of waterways, ports and other maritime assets are of the utmost importance to authorities and researches. Terrorist attacks, piracy, accidents and environmental damages are some of the concerns. This paper provides a detailed literature review of over 180 papers about different threats, their consequences pertinent to the maritime industry, and a discussion on various risk assessment models and computational algorithms. The methods are then categorized into three main groups: statistical, simulation and optimization models. Corresponding statistics of papers based on year of publication, region of case studies and methodology are also presented.

Keywords: Maritime Risk Analysis, Literature Review, Risk Assessment, Risk Models

1. Introduction

With more than 90% of the world's international trade traveling by sea, the importance of maritime transportation to the world economy cannot be over-emphasized. As such, global economic inter-dependency among nations is largely reliant on the success of the maritime industry. Unlike other modes of transportation, maritime transportation has proved to be the most cost-effective way of transporting bulk goods, petroleum products, food supplies, manufactured goods, containerized cargo, etc., over long distances. According to an IMO (International Maritime Organization) document, maritime vessels can be broadly classified as tankers, general cargo ships, bulk carriers, passenger ships, containerships and fishing vessels.

The shipping safety regime consists primarily of international safety codes and regulations issued by the IMO, and the rules for the construction of ships are issued by independent clas-

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sification societies. Marine safety regulations have grown in a more reactive way, in which the regulations get revised after an accident occurs. This approach has been successful for large fleets of similar ships where past experiences helped form a good basis for safety management. However, it has been less effective for the rapidly changing designs such as many offshore installations and various types of ships. Because of this, the shipping industry has begun developing more formal safety assessments as a proactive approach to regulation. The advantage of marine regulations help to encapsulate the accumulated experience from past accidents as well as the contributions of many experts world-wide who have helped to refine and improve them. The disadvantage when performing a risk assessment is that the accident experience and anticipated hazards that underpinned each rule are not recorded, making it very difficult to tell how safety-critical a particular rule may be for a particular installation.

It must be noted that maritime transportation can be dangerous due to different kinds of threats. Piracy, inclement weather conditions, natural disasters (tsunamis, earthquakes, etc.), narrow water ways, dangerous un-charted water ways and vessel collisions are some of the identified threats to the safety and security of vessels, commodity, passengers and seafarers. Though, international maritime regulations adopted by the industry have, to a great extent, improved safety and security in this industry ; decision making can be better achieved if risk exposures can be accurately determined ahead of time (and adequate measures proffered to mitigate the effects).

Based on this background, it is only natural that extensive research efforts should be focused on the safety and security of maritime transportation assets such as vessels, ports and waterways. In maritime port systems, accident data related to port operations are often non-existent. As such, estimation of accident probabilities in ports usually necessitates analysis of the opinions from individuals with domain knowledge on important maritime operations and mathematical models. Also, maritime port situations are constantly evolving due to changing traffic patterns, different traffic rules and environmental conditions such as visibility and wind. Our literature review reveals that simulation, mathematical modeling and expert judgment elicitation play important roles in modeling maritime security and safety risks in ports and waterways.

Risk assessment is an aid to the decision-making. An appropriate analysis of these risks will provide information that is critical to good decision making and will often clarify the decision to be made. The information generated through risk assessment can often be communicated to the organization to help impacted parties understand the factors influencing the decision.

Risk assessment is performed in a systematic way. The steps include: 1) hazard identification, 2) frequency assessment, 3) consequence assessment and finally, 4) risk evaluation. The level of information needed to make a decision varies widely. Figure 1 illustrates this idea. In some cases, after identifying the hazards, qualitative methods of assessing frequency and consequence are sufficient to enable the risk evaluation. In other cases, a more detailed quantitative analysis is required. There are many different analysis techniques and models that have been developed to aid in conducting risk assessments. A key to any successful risk analysis is choosing the right method (or combination of methods) for the situation at hand. This study reviews the common methods used in risk assessment for maritime traffic.

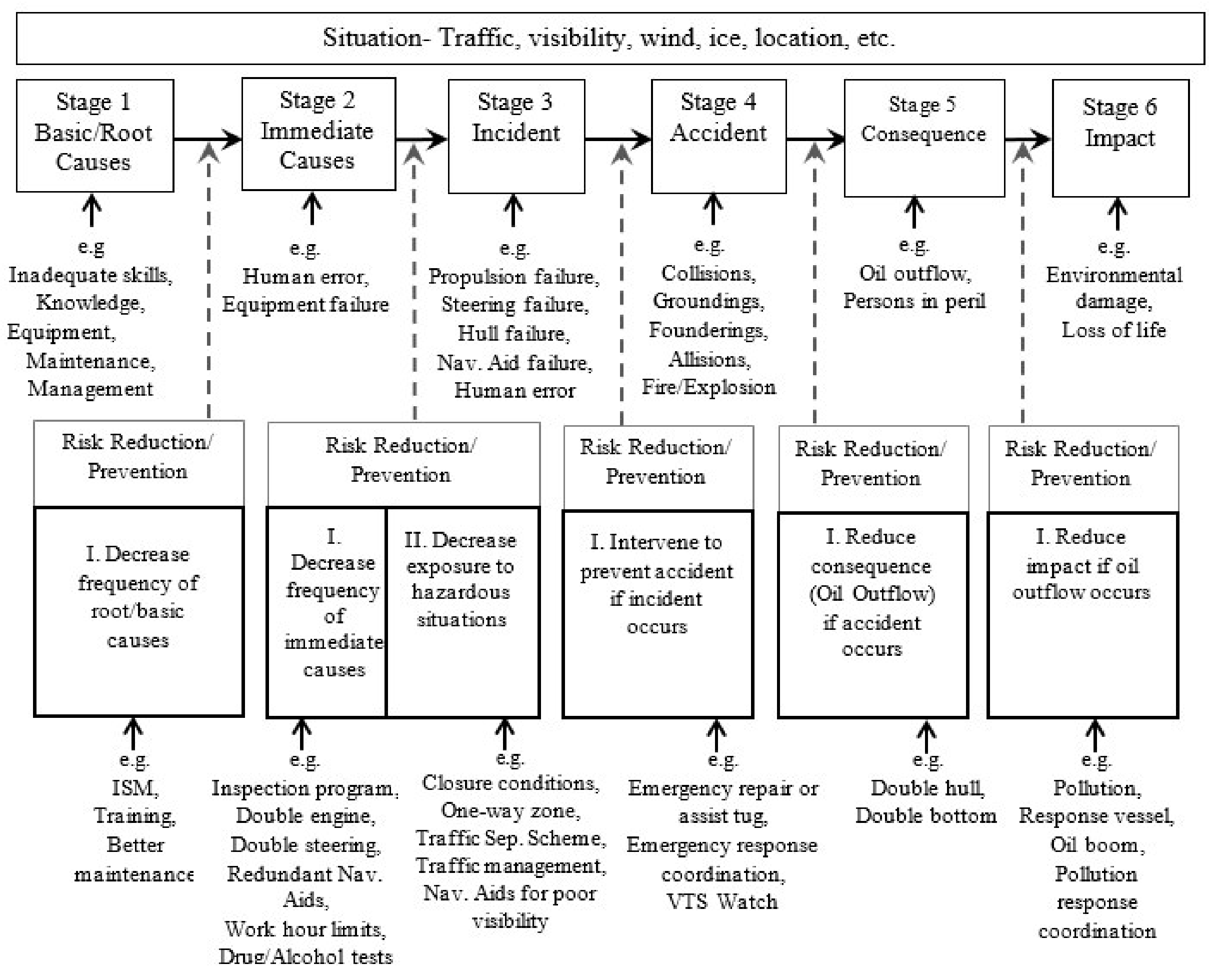

Figure 1: Framework for maritime risk assessment and risk reduction interventions Harrald et al. (1998)

In this paper, we present a literature survey of research on maritime risk analysis (MRA) for the past three decades. To our knowledge and research, the first notable study on MRA was conducted in 1986. Our study comprises of over 180 papers published between 1986 to present date with the goal to reveal important gaps in the observed literature as well as suggest possible future research directions. Our approach to this review paper is based on Galindo and Batta (2013), who offered a survey of OR/MS papers applied to disaster operations management (DOM), which includes a detailed descriptive analysis of the papers as well as classification scheme.

Beginning from the year 2000, the studies on MRA have increased significantly. We wanted to identify the trend and the progress in this field (Figure 2). Gaps, trend, challenges and opportunities are identified relevant to MRA to glean thoughts about future research directions. We believe that by having a clear and unified picture of the past and present studies on MRA, as well as its most crucial needs, researchers will be able to conduct future related research in more effective way.

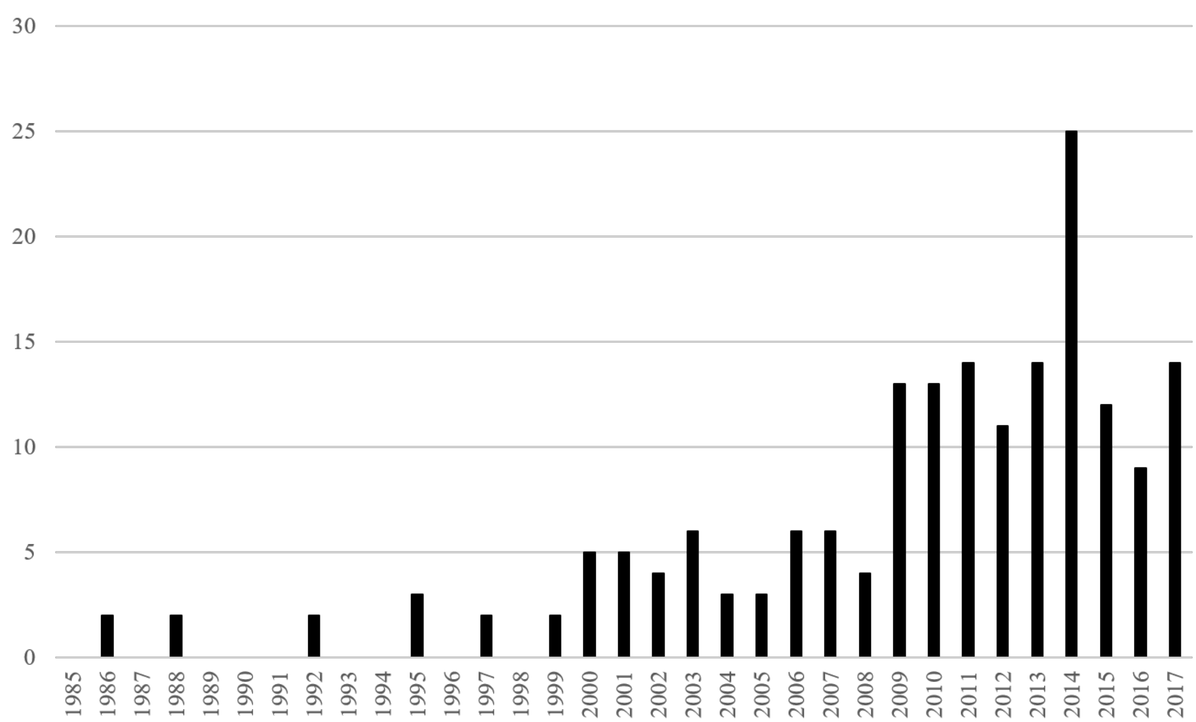

Figure 2: Number of publications on MRA

Since the year 2000, recent review papers have surfaced in MRA. For example, Grabowski et al. (2000) explores the challenges of risk modeling and gives a framework for a risk modeling approach (which is utilized on an example study). The authors conclude by discussing the limitations and what can be done in the future for risk modeling approaches. Soares and Teixeira (2001) present different approaches to quantify risk in maritime transportation. Early studies in the probability of ship loss by foundering and capsizing are reviewed. The approaches used to assess the risk of structural design are addressed. Also, there is brief mention of recent development of suing formal safety assessments to support decision making on legislation applicable internationally to maritime transportation. Pedersen (2010) presents a review on prediction and analysis tools for collision and grounding analysis. They outline a probabilistic procedure where these tools can be used by the maritime industry to develop performance based rules to reduce the risk associated with human, environmental and economic costs of collision and grounding events. They conclude by indicating the main goal of this research should be to identify the most economic risk control options associated with prevention and mitigation of these events. Most recently, Li et al. (2012) provides a detailed review and assessment of various quantitative risk assessment models for maritime waterways. The review presents analysis of the frequency and consequence estimation models separately.

Clearly, there is an increasing trend of literature in MRA in recent years. Therefore, the time is right to understand the evolution of different studies conducted in this area of research, to report the recent progress of the field, and to highlight potential future needs in MRA.

2. Search methodology and scope of the study

In this section we discuss the search methodology and the boundaries of our survey. Our study focuses on published journal papers and proceedings that relate to maritime security. There was no limitation on the databases used. The keywords employed were **maritime, risk, safety, security, collision, grounding, navigation, port and marine** to search for articles published in English.

The scope of our survey include mathematical models and computational algorithms in maritime risk security and risk analysis. Therefore, the boundaries of our survey depend on the definition of maritime security. According to the United States Coast Guard, maritime security activities include port, vessel and facility security. The maritime domain faces threats from nation states, terrorists, unregulated fishing, natural and environmental disruptions and piracy. However, it must be noted that there is no legal definition of these terms.

Having defined the boundaries of our survey, we proceeded to verify the identified papers that fit into our scope. Our screening process can be divided into two levels. First, there were results that could be rapidly eliminated by inspecting the titles of the papers and their abstracts, this provided clear evidence that these papers were not related to maritime security and risk analysis. After passing the first screening test, we used a second and final filter to inspect the papers. To do this we read the introduction of the paper as well as the problem description to determine whether the paper would be included in our list. Then, we performed a forward reference search based on the papers that had been selected. We used the two-filters approach (Galindo and Batta (2013)) to screen the papers obtained from the forward reference search.

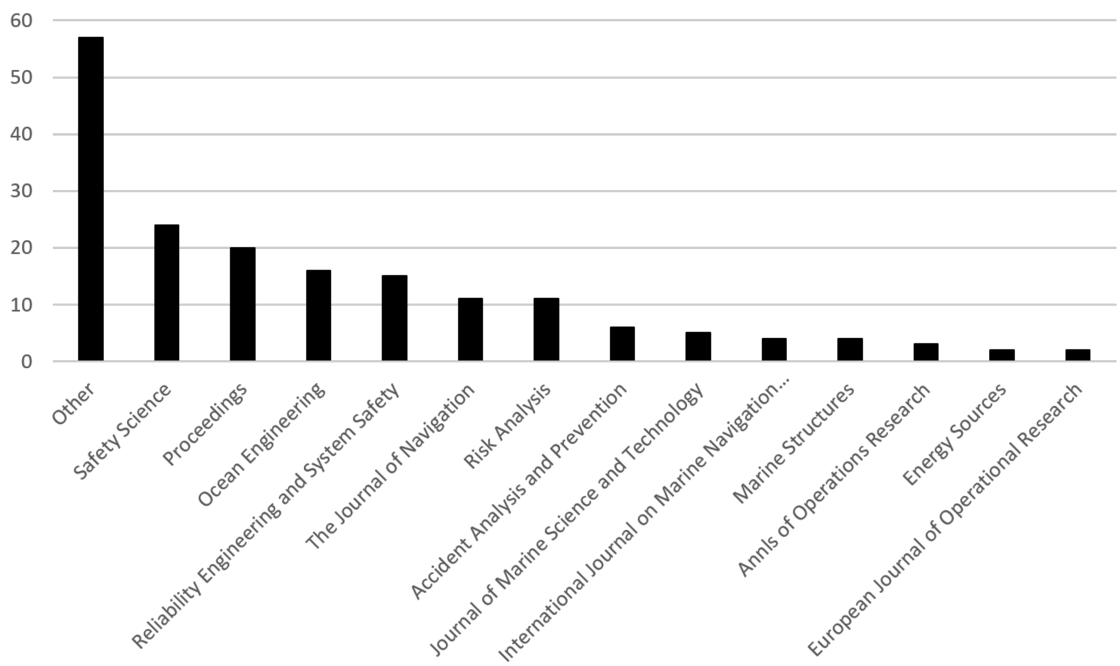

Figure 3: Number of relevant papers appearing in different journals.

3. Characteristics of the articles and comparative analysis

As an attempt to conduct an exhaustive bibliography on maritime security research, a collection of over 180 journal and conference proceedings papers are included in our survey. Figure 3 shows the number of papers found in different journals and proceedings overall. The Journal of Navigation, Risk Analysis, Safety Science and Reliability Engineering and System Safety are the most frequently used venues of journal publications on maritime risk analysis. This survey result indicates the operations researchers may have not fully engaged in research on this topic, or they may prefer journals that are more focused on risk analysis and reliability rather than the traditional journals in Operations Research (OR). Table 1 provides the statistics from our

Table 1: Summary of statistics of literature on MRA (180 articles).

Authors nationality	%	**Focus**	%
Asia	22	Frequency	17
Europe	57	case	21
USA	12	safety	25
Other	9	consequence	7
		more than 1	30
Methodology	%	**Security concern type**	%
Bayesian	14	collision	27
Regression model	3	waterway security	13
Fuzzy logic	9	grounding	4
Simulation	20	human safety	9
Risk model	9	port security	5
Mathematical modeling	6	Grounding	8
Probability and statistics	15	More than 1	33
Literature review	5	Other	4
Decision analysis	3		
Other	15		
Research contribution	%	**Denizel et al. classification**	%
Model	40	MC1	56
Application	30	MC2	10
Theory	30	MS2	6
		MS1	12
		ME1	9
		ME2	7

review. In the following subsections we will discuss each of the categories listed. Furthermore, we also offer an analysis about the appropriateness of the model assumptions most commonly made in the recent literature.

3.1. Authors affiliation

The world map displaying the incident zones between 1999 and 2011 by Butt et al. (2012) is shown on Figure 4. As shown, most of the cited incidents are centered around Europe and Asia. Similarly, the nationality of authors involved with MRA studies are mostly from Europe and

Asia as well (Table 1). When the authors are broken down to specific countries, USA, Turkey and Finland are leading as the majority (Figure 5). The Baltic and the Bosporus are among the regions with high vessel traffic, which makes it more likely for maritime incidents to occur. On another note, as seen in many other fields, researchers affiliated with USA happens to be more involved with MRA than researchers from other countries.

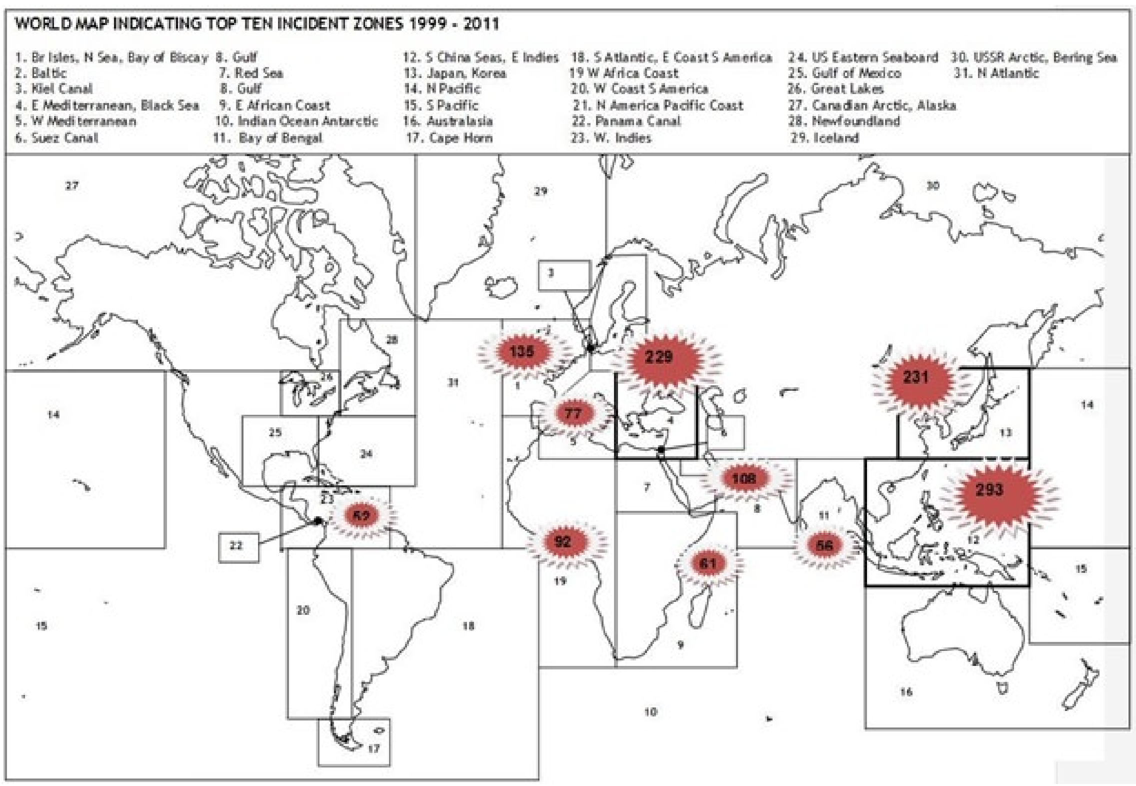

Figure 4: Maritime incident zones Butt et al. (2012)

3.2. Methodology

The methodologies used in the surveyed MRA papers are similar to the general methods used for risk analysis (Figure 6). Simulation came as the most frequently used tool followed by Statistics. This is because there are many probabilistic factors involved in modeling. Simulation is a versatile and effective tool in solving complex problems such as the ones discussed in this paper. Many uncertain conditions (i.e., weather conditions, traffic, etc.) can greatly affect the outcomes of the model due to the random nature of these parameters. Hence, many researchers rely on analytical methods that are based on probability and statistics. As stated in the beginning of this article, historical data is not always available and in order to have a complete risk

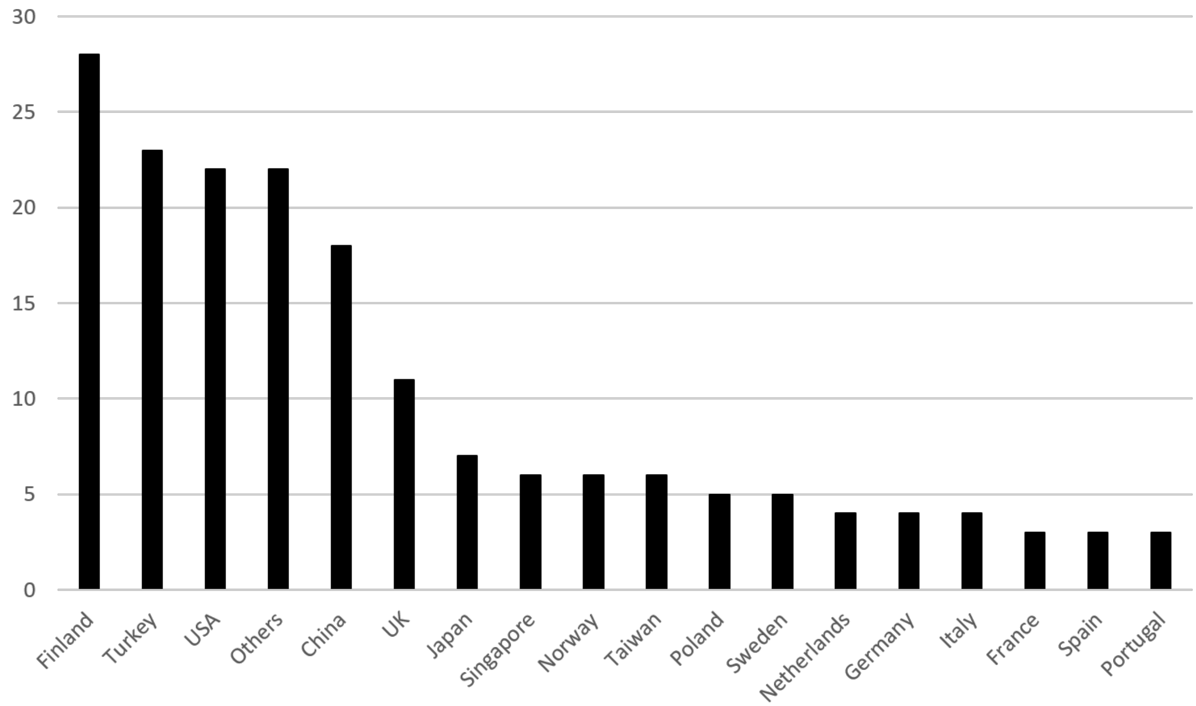

Figure 5: Number of MRA publications by country of first author

assessment, knowing the probability of occurrences of undesired events is important. Capturing these random events is also possible using stochastic models or robust optimization models. However, solving the resulting optimization models can be computational challenging and even impossible to solve. We have also observed that most of the MRA studies were motivated by a case study.

3.3. Research contribution

We use the three classification categories proposed by Altay and Green (2006), which is based on their type of contributions: theory, model and application. Among all categories of maritime risk analysis, developing models was the most common type of research contributions observed (Figure 7). Theory came in second, and product development for applications was the least frequently observed. For an obvious reason, application based studies were observed to utilize multiple categories of research contributions. Although the development of models is valuable in MRA, research in the other two categories (theory and applications) should not be disregarded. Theory is relevant for a better understanding of MRA problems and can serve as a base for developing more accurate models. The importance of application related studies is that

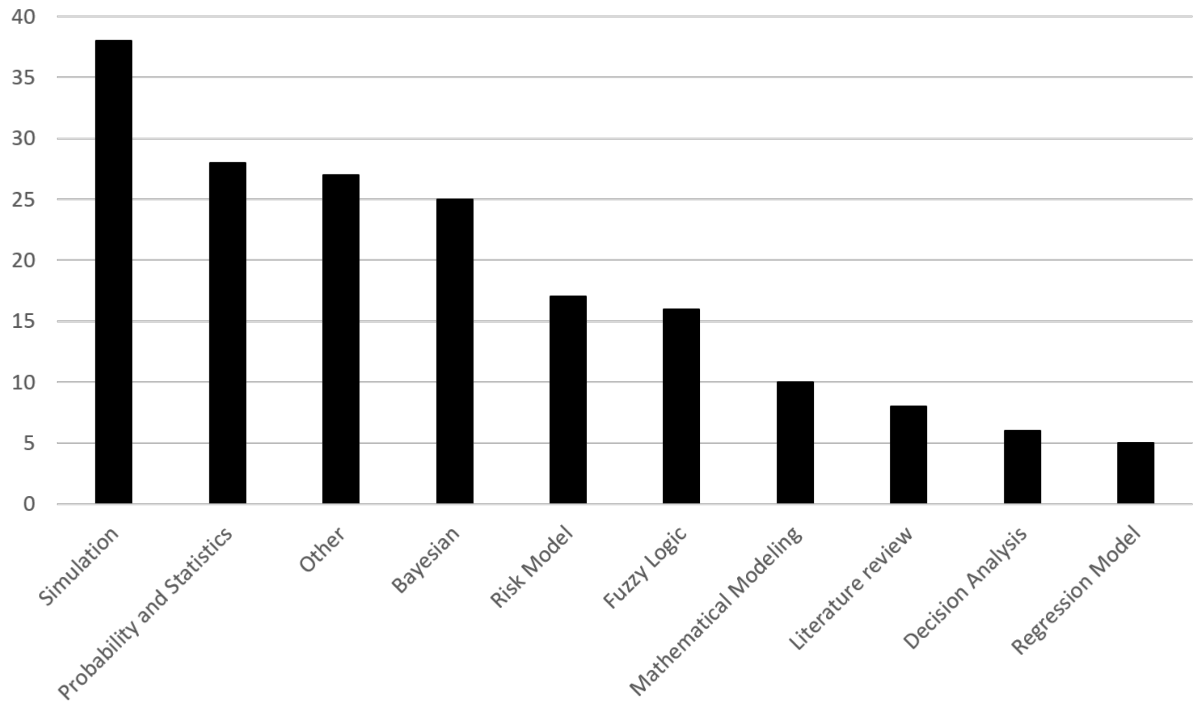

Figure 6: Methods used in MRA

they provide tools for taking theoretical and analytical research into practice. MRA requires tools that support the process of decision making in a more precise and efficient way. Therefore, more research in decisions support systems and other applications would be of great value for future contributions.

3.4. Security concern type

Review on the type of security concern shows that collision was the commonly studied subject followed by waterway security (Figure 8). Studies that deal with more than one aspect were the next popular subject. From the point of research contributions discussed in Section 3.3, model development was the most common contribution whereas applications were the least.

3.5. Denizel et al. classification

An interesting dimension considered by Altay and Green (2006) is based on a classification framework given by Denizel et al. (2003), which is in turn based on Corbett and Van Wassenhove (1993). The authors Corbett and Van Wassenhove (1993) provided a classification framework that categorizes research into three main groups:

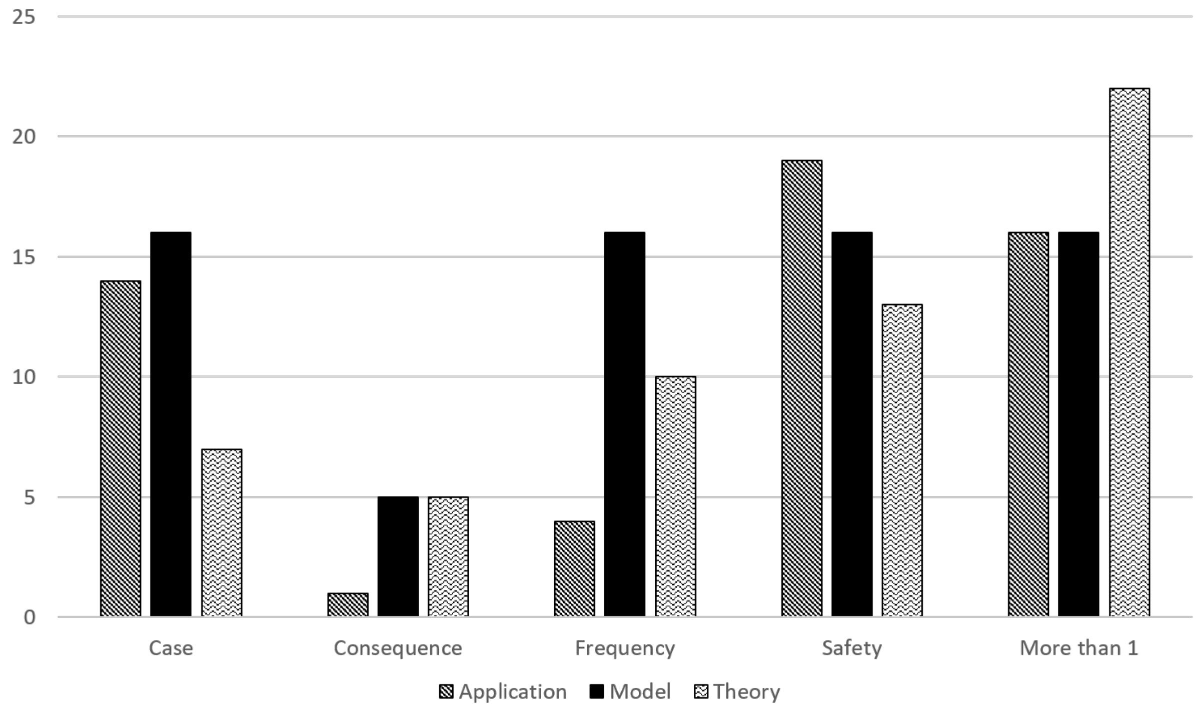

Figure 7: The breakdown of contribution areas of survey papers

- MS (management science): which contains papers whose objective is to contribute to the body of knowledge of a given research area;
- MC (management consulting): which covers research where a practical problem is solved by standard methods; and
- ME (management engineering): which refers to research that uses existing methods in a fundamentally novel way to solve practical problems.

Denizel et al. (2003) proposes six categories: MS1, MS2, MC1, MC2, ME1, and ME2 (see Figure 9). The attributes considered by Denizel et al. (2003) are problem setting (real, hypothetical or none), source of data (real, random or no data), situation (novel or widely studied in OR), approach (novel or widely studied in OR), results (specific or general), and further research implications (existent or nonexistent).

We further refine the Denizel et al. (2003) classification scheme as follows:

1. Settings and data are considered real only if the authors make an explicit comment about it;

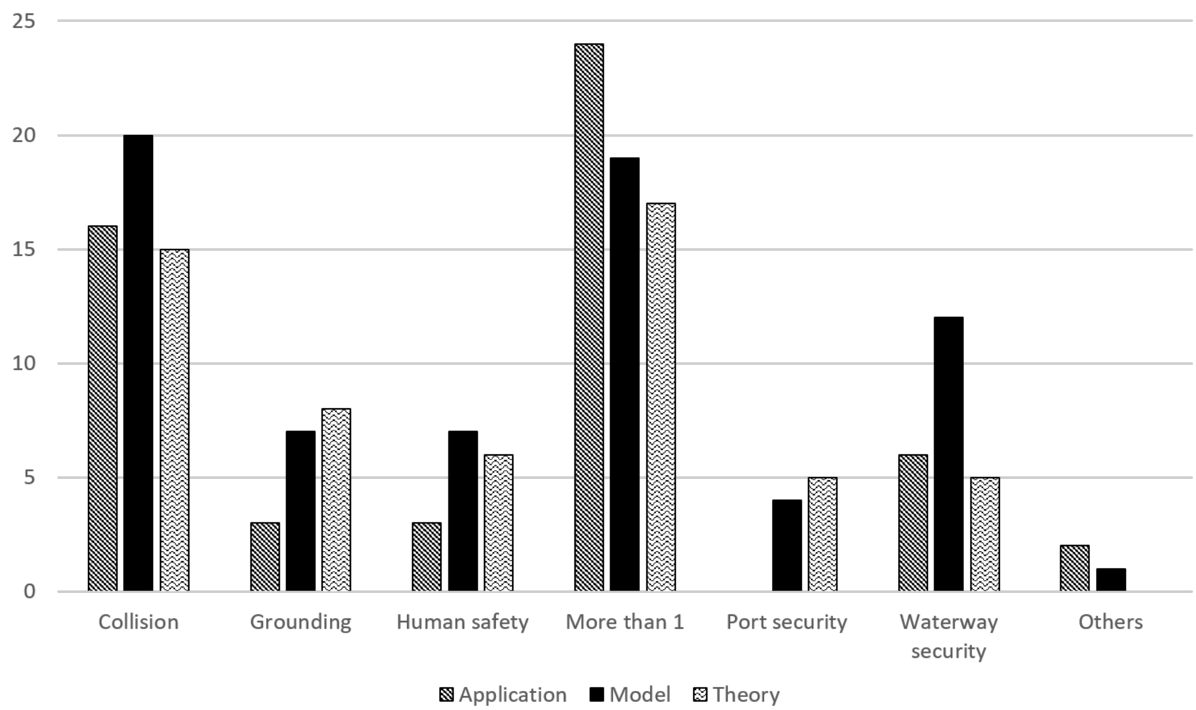

Figure 8: The breakdown of contribution of papers based on security concern

2. The novelty of the situation and approach is defined based on the literature review offered by each article;
3. Results are considered specific if the authors develop a study for a specific setting (e.g., a particular simulation model used) and they do not explicitly mention the possible extension of their outcomes to other scenarios; and
4. Further research implications are considered existent only if they are explicitly mentioned by the authors.

Review and survey papers are treated as special cases and their classification is performed following the procedure proposed by Denizel et al. (2003). According to this, if a paper reviews the state of the art in a particular area of research, it is coded as MS2. If it summarizes and states the relevant issues from previous work, it is classified as MC2. Finally if the review paper proposes future research implications based on its observations, it is categorized as ME2. As a result, the most frequently observed category was MC1, followed by MC2, MS1, and then ME1, ME2 and MS2. Our review found that more than 50 percent of the publications used real data as seen in Figure 10. Overall, model development studies were observed most frequently with

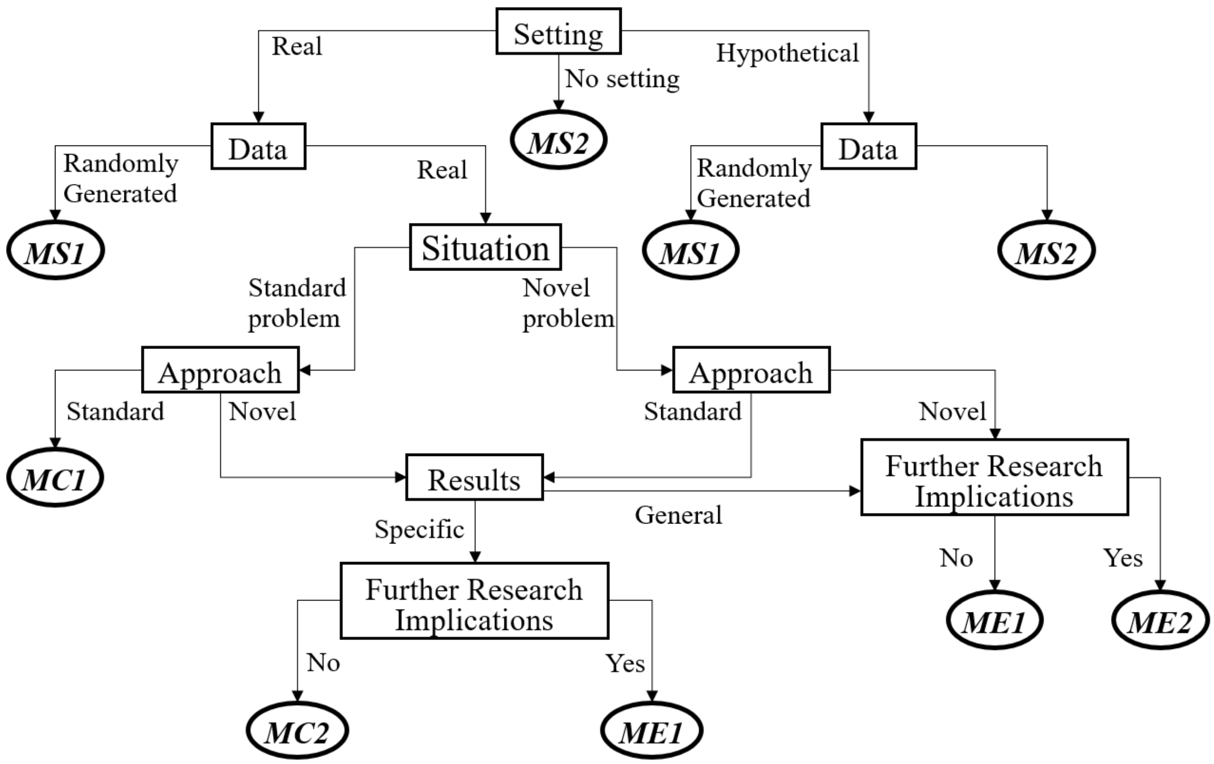

Figure 9: Classification scheme by research type Denizel et al. (2003)

an emphasis on management consulting. Management engineering was the least studied subject as well as applications.

3.6. Research assumptions

Assumptions for models and theoretical development are common. We have also observed that some assumptions were made more frequently than others in the reviewed papers. Table 2 gives a short list of common assumptions mentioned in the papers, where comments were added on the validity of these assumptions and an explanation. As in the paper by Galindo and Batta (2013), we use three categories: realistic, limited and unrealistic. Papers with realistic assumptions provide results that are applicable to relevant problems. Papers with limited assumptions are those with findings that are not applicable to every problem setting, but work well under specific problem settings. Thus, future research is needed to take care of the limitations on the conditional settings. On the other hand, unrealistic assumptions provide results that are not really applicable in real world situations. Either the setting is severely constrained to be practically useful or the assumptions contradict heavily with the way things work in maritime

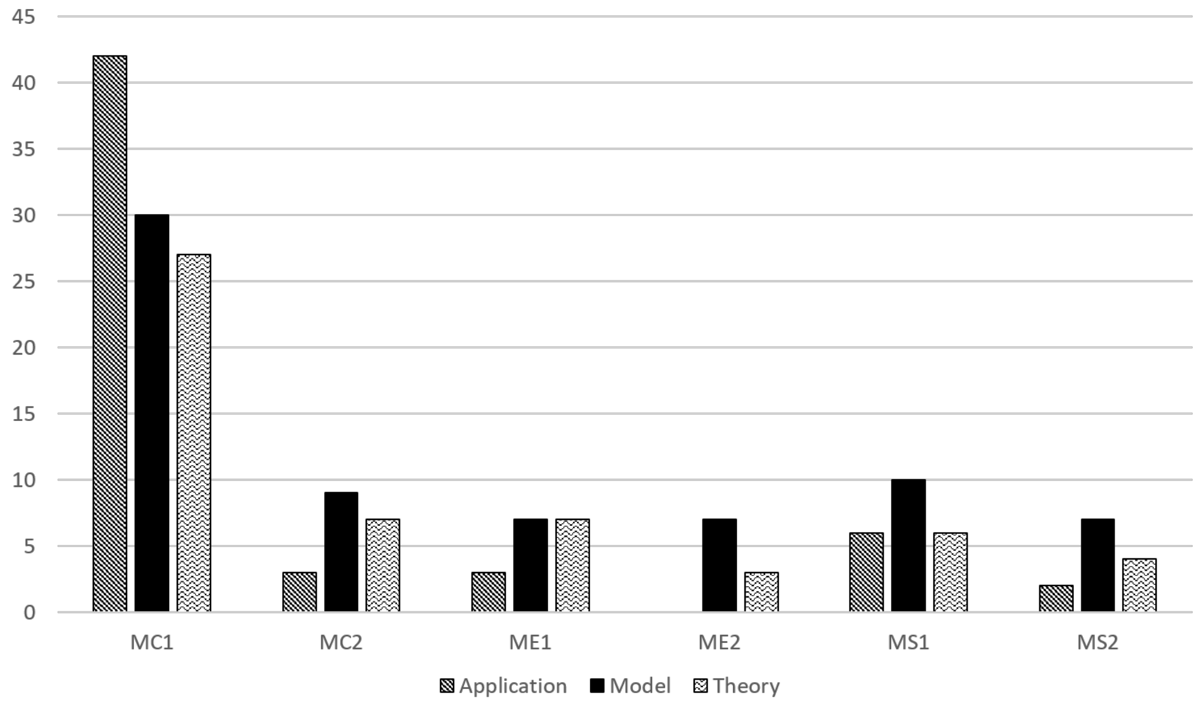

Figure 10: The breakdown of contribution of papers based on security concern

environment.

4. Future research directions

To define our future research directions, we focused on what we consider as the main components for addressing MRA. Based on the papers in our survey, these components can be defined as actors, technology and the MRA problem itself. The latter component includes the following three major categories: (1) data handling, (2) assumptions and (3) solution approach. We list the future research directions under these categories in order to close gaps in the literature. These findings are primarily based on our observations from Section 3.

4.1. Actors

We have identified two research directions that involve the actors. First, researchers should start working on ways to improve communication between different parties involved; such collaboration would reduce the likelihood of accidents to occur. In addition, in case there is an accident, its associated consequences can be minimized. Secondly, the historical data available is not always useful. As the number of regulations on maritime traffic increased over the years, some of the data has become either obsolete or no longer accurate. When there is no available data or the data itself is no longer good, researchers usually resort to opinions of experts and make their models accordingly. The domain experts are usually involved with maritime activities on a day-to-day basis and their input should be carefully used to develop models, tools or policies that can help make better decisions.

4.2. Technology

As mentioned earlier, sole application related studies are limited in numbers compared to theoretical and modeling studies. As a result, there are ample opportunities for future research in MRA. In general, human factors are the hardest to incorporate into a model for any risk analysis study. As such, they were often disregarded in many reviewed papers. However, humans as instigators play a key role at every stage of a risk analysis study. Therefore, there is a need to develop technologies that incorporate human behaviors in maritime operations. Another application field that needs urgent development is real time decision making tools. With more advanced technologies becoming available in the modern world, it is very easy to access online data such as AIS (Automatic Identification System). However the analysis and decisions still needs to be made by human operators. Tools must be developed in assisting authorities in this decision making process.

4.3. Solving maritime risk analysis problems

4.3.1. Data handling

In case of lack of data, expert elicitation is the most common method used. However, expert elicitation may not be the best option if new information will become available in the near future which may affect or diminish the uncertainty at hand. More focus should be put into making use of expert elicitation along with available data to satisfy all needs for the problem at hand. Also, other methods should be investigated and their validity analyzed.

4.3.2. Assumptions

We have identified some gaps for improvement in the way incidents and consequences are handled on risk analysis. Especially, in terms of consequences of a disaster, realistically modeling the impact of a disaster can be often difficult due to possible domino effects from the incident.

The lack of modeling considering this cascading effect is one of the shortcomings. In most cases, only a limited number of organizations are involved with and/or affected by an accident and the impact of the accident is confined within a limited region. As for the assumptions related to incidents, not all incidents are independent of each other whether they are situational or organizational. The relationship between these factors should be studied and analyzed in more detail so that better risk analysis models can be developed. As a result, better preemptive measures can be taken to reduce potential risks. Another possibility for future research is based on the assumptions of how accidents such as collision and grounding occur. Many different models have been developed using different assumptions. Therefore, it is possible to get different results based on which model is used in the analysis. Researchers should evaluate the existing models and develop a unified model.

4.3.3. Approaches

Our review reveals that many research opportunities exist in methodologies. As mentioned previously, approaches considering human factors as instigators in maritime risk analysis have not been fully exploited yet. Another research direction is to develop mitigation strategies in maritime risk analysis. One can develop an effective response strategy framework to reduce the effects of an anticipated or already occurred disastrous event. Furthermore, there is a need to develop theoretical models for collisions and grounding that incorporate human behavior associated with an accident. How do people behave when a disaster is approaching to them? Models can be developed anticipating that maritime operators behave differently. Another area of research that can directly benefit practitioners is to build a class of models and case studies that can be widely applicable to different types of disasters in a maritime environment. The motivation for this suggestion is that many causes of incidents may share similarities and dissimilarities. Currently, many approaches are designed for a specific problem of interest using different assumptions and instigators. There is a need to review and analyze maritime incidents and cluster them into few categories. Then, one can develop a generic model that can be applied to different types of incidents within a category.

5. Conclusion

We have presented a review of MRA literature to show the trend and immediate needs of research in this field. We used the classification scheme presented by Galindo and Batta (2013) to review an existing body of literature and analyze the trend and evolution of studies on the field of MRA. Our review also identified the gaps in the literature. Suggested future research directions can include (1) to take human operators' behavior into account when a model is developed, (2) to develop more advanced technology (both devices and software) to monitor and detect any threats in real time, (3) to develop an efficient way of collecting and analyzing data, and (4) to develop a theoretical mitigation framework to reduce the effects of an anticipated or already occurred disastrous event. We believe that our results give an accurate perspective of current status of MRA literature. Our list of references is an exhaustive bibliography of the field. We hope that our review can help the researchers in selecting appropriate subjects to address existing gaps in the literature.

Acknowledgments.

This publication was made possible by the NPRP award [NPRP 4-1249-2-492] from the Qatar National Research Fund (a member of The Qatar Foundation). The statements made herein are solely the responsibility of the authors.

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Table 2: List of common assumptions found in the literature

ID	Assumption	Type	Comments on classification
1	Given a set of scenarios whose probabilities and behavior are based on expert opinion and historical data	Realistic	Scenarios should consider domain experts and historical data whenever available.
2	Trading marine traffic follows relatively well-defined shipping lanes that have a characteristic lane width, traffic frequency, and lateral distribution	Realistic	This follows the current regulations on maritime traffic.
3	Organizational factors have an impact on the occurrence of triggering incidents and that situational factors influence the occurrence of accidents, whereas both affect the consequences of an accident	Realistic	Risk frameworks have been structured like this since it was first suggested by Harrald et al. in 1998.
4	Inter-arrival times are assumed to be exponentially distributed	Realistic	The arrival times of vessels are independent from each other and therefore this is a valid assumption.
5	Statistical independence of events	Limited	Even though accidents occur independently of each other, auditing of the ongoing maritime activities increases when they occur. Therefore it would be less likely for undesired events to occur.
6	Assumptions on how incidents such as collision, grounding, etc., can occur	Limited	These assumptions vary from one model to another and mostly human intervention or weather conditions were not considered.
7	The triggering incidents are independent	Limited	In terms of the way, triggering incidents have been defined, this assumption usually holds. However, not all situational factors are independent from each other, which has led to some researchers start using fuzzy methods.
8	Not all vessels including an area of study are included	Limited	Based on the area of study, the types of vessels ignored usually are insignificant to the general flow of the maritime traffic. However, this exclusion may cause a bias on the study.
9	Actions to avoid collision are fixed, not scenario dependent	Limited	In modeling collisions, the actions defined to avoid a collision are based on expert opinion, which is the most appropriate approach available. However, there are always special cases and theoretical models that may not cover these cases.
10	No consequences for false alarms	Limited	False alarms do not occur frequently or even if they occur, sometimes no action is taken. However, stalling the ongoing operations based on a false alarm may have financial impact and other consequences.
11	Only the short-term consequences are considered when a disaster occurs	Limited	It is a challenging task to model or quantify the domino effect, therefore researchers tend to focus on short-term consequences.
12	Vessels are considered to collide, what could be a near-miss case in real life	Limited	Even though an accident may not be unavoidable when two vessels are approaching toward each other at a certain speed and angle, the consequence due to an incident can be reduced by human intervention. .
13	The consequences of a disaster only affect a limited region, or limited number of parties	Limited	Even though immediate consequences of a disaster may influence a limited region or limited number of parties, the domino effect should be also considered when the study focuses on consequences.
14	Human factors neglected in occurrence of undesired events	Unrealistic	With an increasing number of regulations on maritime operations, human factors have become one of the most significant components that trigger an undesired event. Therefore they must be considered.
15	Traffic movements are uncorrelated	Unrealistic	The local maritime traffic is affected by trade traffic especially in dense traffic areas.
16	Fire/explosion probabilities or their consequences are assumed to be independent of environmental conditions.	Unrealistic	Weather conditions such as rain and wind heavily affect the spread rate of fires. The rain would help with putting the fire out and the wind may cause fire to spread faster or prevent it reaching from a nearby settlement.
17	The statistics from past collisions and grounding events involving aged ships are adequate to be used to predict probabilistic damage distributions	Unrealistic	There have been many changes in the infrastructure of vessels. Also, the number of regulations regarding maritime traffic have increased over the years. Therefore, some of the existing models need to be revised.
18	Consequences are not correlated to each other	Unrealistic	When a consequence occurs as a result of an accident, the occurrence of other consequences may increase.
19	The striking vessel does not lose its cargo or fuel	Unrealistic	Both vessels may get affected the same way, or the striking vessel may be more damaged than the vessel that has been hit.