Half-century research developments in maritime accidents: Future directions

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ABSTRACT

Over the past 50 years, research in maritime accidents has undergone a series of fundamental changes. Understanding the evolution of these changes can help maritime communities to know what has been done in the past, how maritime safety can be improved in the future, and how to reduce or eliminate the risks to ships, the lives aboard them, the cargo they carry, and the marine environment.

This study conducts a comprehensive literature review on research in maritime accidents, comprising 572 papers published in 125 journals over the 50 years from 1965 to 2014. The patterns of evolution of the researchers, the journals, the disciplines involved, the research methods, the major issues and causes, and the data sources are identified, and the changes explained. We find that the main focus of research in maritime accidents has shifted over the past 50 years from naval architecture to human error, and may continue to expand into socio-economic factors. In addition, future research in maritime accidents will be multi-disciplinary, use multiple data sources, and adopt advanced research methods, to account for complex interactions between the natural environment, the development of naval technology, human behavior, and shipping market conditions.

1. Introduction

Maritime accidents, undesired abnormal events of a ship that often result in loss of life or major injury to any person on board and in various types of property damage, have been a major issue in the international maritime community since shipping began. As shown in Fig. 1, the number of maritime accidents decreased from a high of 3152 in 1979 to a low of 959 in 2001. However, it increased again in 2002, reaching a second peak in 2008. The overall number of maritime accidents over the past 36 years is 63991, an average of 1777 per year. According to the *Guardian*, about 2000 seafarers lose their lives each year.[1]

Huge effort has been expended on developing measures to improve maritime safety, through a better understanding of the marine/coastal environment, improvement of the technology involved in shipbuilding and ship management, more advanced navigation technology, and better crew training. In addition, international organizations such as the International Maritime Organization (IMO) and many national Maritime Safety Adminis-

trations (MSAs) have published extensive rules and regulations on safety standards, and various guidelines on the safe operation of ships (Baniela and Ríos, 2010). The development of these measures and regulations has largely been based on new findings regarding the major causes of maritime accidents, through detailed analysis and research in the possible causes of such accidents.

Research in maritime accidents grows on a fertile soil of increased awareness of the dire consequences of such events (Clingan, 1981), a connected pool of researchers with multi-disciplinary knowledge, the availability of rich data and information on maritime accidents, the development of new research methods for accident analysis and prevention, and new theories on the possible causes of ship accidents. Understanding how research in this area has developed in the past can help current researchers to target the right directions for their research. New findings can then be used to assist with the formulation of new policies and practices to prevent future maritime accidents.

To this end, this study collects maritime accident research papers published in various peer-reviewed journals written in English over the past half-century, and analyzes the evolution of these publications with respect to author location and field of study, the main topics, the dimensions of the analysis, the major causes of maritime accidents, the methodology, and the data sources. The main findings are that although research in maritime accidents

Nomenclature

ARMAX	Autoregressive moving average with exogenous variable
ARPA	Automatic radar plotting aids
BDS	Business dynamics statistics
CART	Classification and regression tree
CATS	Cost of averting a tonne of oil spill
CBA	Cost-Benefit analysis
CEA	Cost-Effectiveness analysis
CFD	Computational fluid dynamics
CHAID	Chi-squared automatic interaction detector
CPA	Closest point of approach
DCPA	Distance to the closest point of approach
DEA	Data envelopment analysis
DFLM	Dynamic fuzzy logic model
DNV	Det norske veritas
DST	Dempster-Shafer theory
EDN	Event decision network
FAD	Fuzzy axiomatic design
FCA	Formal concept analysis
FMEA	Failure modes and effects analysis
F-N diagram	Frequency-Number of fatalities diagram
FQSD	Fuzzy quaternion ship domain
FVA	Formal vulnerability assessment
G-BRB	Generalized belief rule base
GESAMP	Group of experts on the scientific aspects of marine environmental protection
GF-AHP	Generic fuzzy analytic hierarchy process
HOE	Human and organizational error
HOF	Human and organizational factors
HRA	Human reliability analysis
IQSMS	Integrated quality and safety management system
ISL	Institute of shipping economics and logistics
ITOPF	International tanker owners pollution federation
JCA	Joint correspondence analysis
MAFAD	Multi-Attribute fuzzy axiomatic design
MCMC	Markov chain monte carlo
MDTC	Minimum distance to collision
MHIDAS	Major hazard incident data service
MLE	Maximum likelihood estimation
MRRA	Model based on relative risk assessment
P&I Club	Protection and indemnity club
PCA	Principal component analysis
PRA	Probabilistic risk assessments
QERA	Quantitative ecological risk assessment
QMAS	Quality management assessment system
QRA	Quantified risk assessment
R-D diagram	Residual strength performance to the damage index diagram
ROC	Receiver operating characteristic
SARF	Social amplification of risk framework
SDSS	Spatial decision support system
SEM	Structural equation modeling
SHS	System of hierarchical scorecards
SMAS	Safety management assessment system
SPAR-H	Standardized plant analysis risk-Human reliability analysis
SYRAS	System risk analysis system
TCPA	Time to the closest point of approach
TOPSIS	Technique for order of preference by similarity to ideal solution
TQM	Total quality management
VCD	Variation of a compass direction
VSL	Value of statistical life
VTS	Vessel traffic service
WCSC	Water commerce statistics center

has mainly focused on naval technology, human error has been identified as the main cause of maritime accidents, and many new methods have been developed to accommodate human behavior. In addition, this study reveals the recent trends in maritime accident research: its multi-disciplinary nature and the use of multiple data sources. The condition of the shipping market has recently been identified as a new causal factor of maritime accidents in a few studies, which may require further development in this area.

This study makes two contributions. First, it summarizes the research publications over the past 50 years from different aspects, revealing the evolution of maritime accident research. Second, it indicates future research directions, including the involvement of new disciplines, emerging issues, new methods, and data sources.

The paper is arranged as follows. The method, data, and scope of the study are presented in the next section. This is followed by a description of the findings relating to the evolution of maritime accident research, in eight subsections. Finally, it summarizes the major findings and provides conclusions.

2. Method, data, and scope of the study

We collected papers on various aspects of maritime accidents from all of the academic journals written in English and categorized them according to aspects such as the location and affiliation of the author(s), the main concerns, major causes, dimensions, methods, and data sources. Examining the evolution of the research papers in this way allowed us to identify the trends in maritime accident research and directions for possible future research.

In total, 572 articles, published from 1965 to 2014, were collected from 125 academic journals in business, economics, engineering, and medical science. The topics focus on maritime accidents, accident risk, and safety. Papers on maritime security, piracy, hijack, and financial risk were excluded. Only papers written in English were collected. Technical reports, conference proceedings, book chapters, and regional journal papers in other languages were excluded.

The collected papers cover maritime accidents involving small fishing and leisure boats (O'Connor and O'Connor, 2005; Swett et al., 2011), Floating Production, Storage, and Offloading (FPSO) (Sii et al., 2005), merchant ships, fishing vessels, ferries and their passengers, cruise vessels, and offshore structures (excluding submarine and warship). Accident locations comprise rivers, ports/terminals, inland waterways, offshore, restricted waters, and the open sea. The vessels involved in accidents carry containers, dry bulk cargoes, oil and oil products, chemicals, or passengers, or are fishing vessels. Accident and risk analysis for the transportation of Hazardous and Noxious Substances (HNS) (Neuparth et al., 2011), dangerous goods (Ellis, 2010), and special nuclear materials (Bolat and Yongxing, 2013) were included.

Studies of management systems for accident prevention, mechanical analysis of the structural stability of ships, pollution from maritime accidents, and maritime regulations such as safety codes produced by national or international organizations were also included. Finally, papers dealing with databases of maritime accidents were collected as it is important for researchers to be able to find accident patterns and major factors involved in maritime accidents, so that appropriate policies may be developed to

Fig. 1. The number of maritime accidents from 1978 to 2013. (Data source: Lloyd's List)

prevent future accidents (Hassel et al., 2011; Oltedal and McArthur, 2011; Psarros et al., 2010; Sii et al., 2003).

3. Trends in maritime accident research

3.1. Overall trends

Table 1 presents the number of published papers and journals grouped in 5-year intervals for the past 50 years, and gives the average number of papers published per year. Both the number of papers and the number of journals has increased, especially in recent years. Although the maritime sector has a long history of maritime accidents and loss of life, the marked increase in research publications only occurred in the past two decades. This phenomenon may be due to the increasing number of maritime accidents, the greater consequences of accidents in terms of the higher values of the ships and cargoes affected, and the resulting effects on the environment. In addition, the increased availability of different types of data and greater computational power allow researchers to do much more today than 20 years ago. These factors may explain the increasing output of this research area.

Of the 572 papers, 208 (36.3%) were published during the most recent 5-year period, and 64.9% were published during the past 10 years. Before 1995, the paper generation rate was about 1.73 papers *per year*, while in the past five years this rate has increased to 41.6 papers *per year*, or 1.6 papers *biweekly*. After 1995, the number of journals covering maritime accidents and issues of risk in the maritime domain also increased markedly.

Table 2 lists the top 20 journals publishing papers on maritime accidents and risk/safety. Of the 572 papers, 413 were published in these journals, accounting for 72.2% of the total number of papers. Ranked first in Table 2, *The Journal of Navigation* published 61 papers in this area over the longest period. From the top three journals, it can be seen that navigation, safety, and policy and management are the three most important areas. In addition to the specialized maritime journals that are the normal outlets for maritime accident research, many other academic journals publish research in this field. Recently, journals with a general focus on safety and

risk analysis, such as *Safety Science*, *Reliability Engineering & System Safety*, *Accident Analysis & Prevention*, and *Risk Analysis*, have published articles on maritime accidents and safety/risks. Journals in the transportation field have published papers on water transportation accidents. All of these findings reflect an increasing awareness of the importance of research in maritime accidents in broader fields of study. It can be seen from this Table that engineering journals, such as *Marine Structures*, *Ocean Engineering*, *Marine Technology*, and *Ships and Offshore Structures*, have increased in number in recent years. This may be another trend in maritime accident research.

3.2. Evolution of the geographic location of maritime accident research

The popularity or capacity of research in maritime accidents in a particular country can be represented by the number of researchers in that country. Here we use researcher rather than author, as one researcher can publish more than one paper in a year. In the collected publications, the researchers were based in 43 countries determined by the location of their institutions. Fig. 2 presents the evolution of the number of researchers in each country in 10-year intervals over the past half-century.

Before 1995, research in maritime accidents was only carried out in a few countries in Japan, Europe and North America, and the number of researchers was very low. From 1995 to 2004, more papers were generated in North America and Europe and some were generated in Asia. Over the past decade, many researchers from Europe carried out risk analysis on maritime accidents. In addition, research in maritime accidents extended to China, Australia and South America.

Table 3 summarizes the evolution of the regional distribution of maritime accident research. North American and European researchers dominated this research area in the 1960s and 1970s. After 1995, African, South American and Asian researchers became new forces in the global research team. Of these, the number of Asian researchers grew especially quickly. The number of Asian

Table 1
The number of papers and journals on maritime accident research from 1965 to 2014.

	1965–69	1970–74	1975–79	1980–84	1985–89	1990–94	1995–99	2000–04	2005–09	2010–14	Total
Number of papers	4	12	6	15	5	10	44	105	163	208	572
Average number of papers per year	0.8	2.4	1.2	3	1	2	8.8	21	32.6	41.6	11.4
Number of journals	1	3	2	7	5	9	28	41	55	53	125

Table 2
Top 20 journals for maritime accident research from 1965 to 2014.

No.	Journals	1965–74	1975–84	1985–94	1995–04	2005–14	Total number of papers
1	The Journal of Navigation	14	14	1	12	20	61
2	Safety Science			1	12	44	57
3	Maritime Policy & Management		1	3	10	18	32
4	Reliability Engineering & System Safety				6	19	25
5	WMU Journal of Maritime Affairs				4	21	25
6	Accident Analysis & Prevention				1	22	23
7	Marine Policy				6	17	23
8	TransNav Journal					23	23
9	Marine Structures				9	10	19
10	Risk Analysis		1	1	6	11	19
11	Ocean Engineering				4	13	17
12	Marine Technology				7	7	14
13	Journal of Hazardous Materials		1	1	5	4	11
14	Transportation Research Record				2	9	11
15	Ships and Offshore Structures					10	10
16	Disaster Prevention and Management: An International Journal				6	3	9
17	Marine Pollution Bulletin					9	9
18	Transportation Research Part D: Transport and Environment				3	6	9
19	Journal of Loss Prevention in the Process Industries			1	3	4	8
20	Journal of Safety Research				3	5	8
Total		14	17	8	99	275	413

researchers has more than doubled from only 57 during 2005–2009 to 124 during 2010–2014.

Also shown in Table 3 is the spatial distribution of the researchers. The percentage of researchers in Asia has increased since 1995, while that for North America has declined over the same period. This indicates that although European institutions still have a leading position in this area, Asian researchers are catching up and are gaining importance over North American researchers. In the past five years, Asian researchers accounted for almost 30% of the world's researchers in terms of publication records. Furthermore, although research in this subject area has extended to Africa, South America and Oceania, the number of researchers from these regions remains relatively small, indicating a direction for further development.

3.3. Evolution of the disciplines involved in maritime accident research

Maritime accidents involve many factors, requiring researchers from different backgrounds to study the possible causes. The affiliations of researchers can reflect their field of study. Accordingly, observing changes in affiliations can help with understanding changes in disciplines within maritime accident research. Fig. 3 summarizes the evolution of authors' affiliations over time, in 10-year intervals.

Over the first 20 years, authors of maritime accident research papers were mainly affiliated with maritime-related centers or institutes such as Coast Guard, maritime institutes, and navigation centers (MN in Fig. 3). After 1985, authors from the social science

(a) 1965-1974   (b) 1975-1984   (c) 1985-1994

(d) 1995-2004   (e) 2005-2014
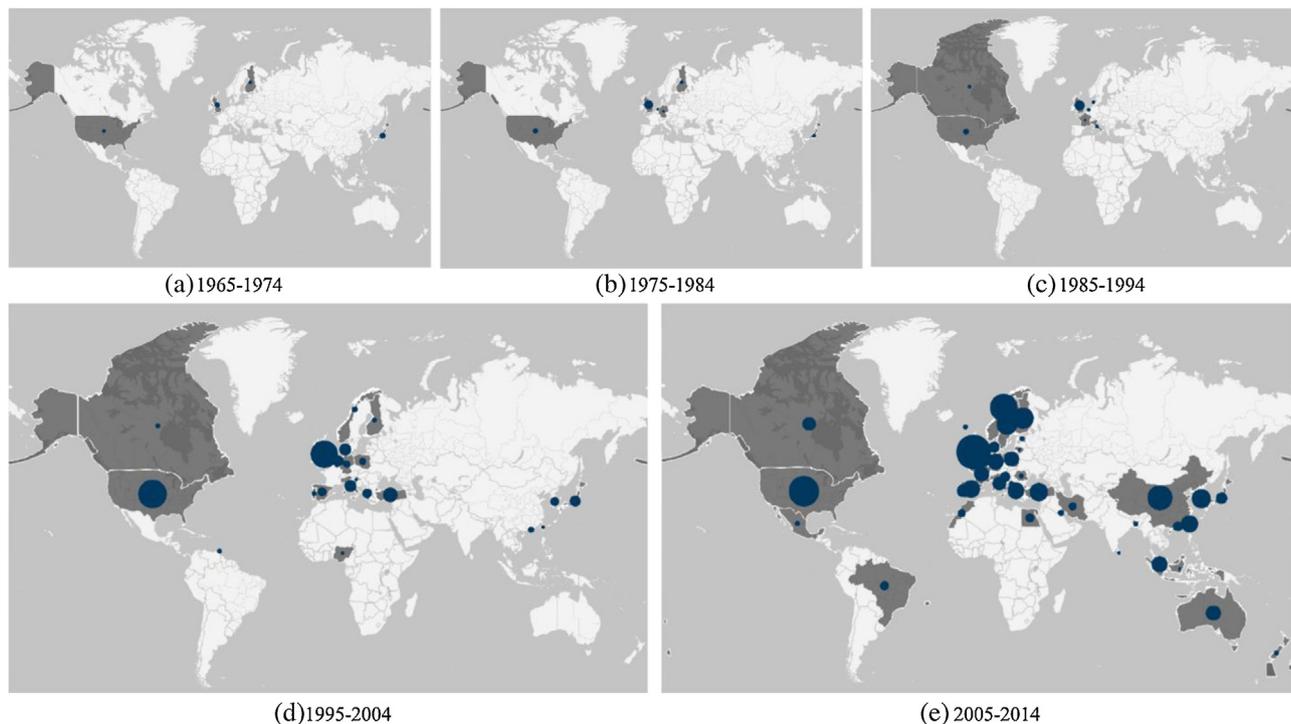
Fig. 2. Evolution of the popularity of maritime accident research in various countries over the past 50 years. Note: The size of the circles indicates the number of researchers.
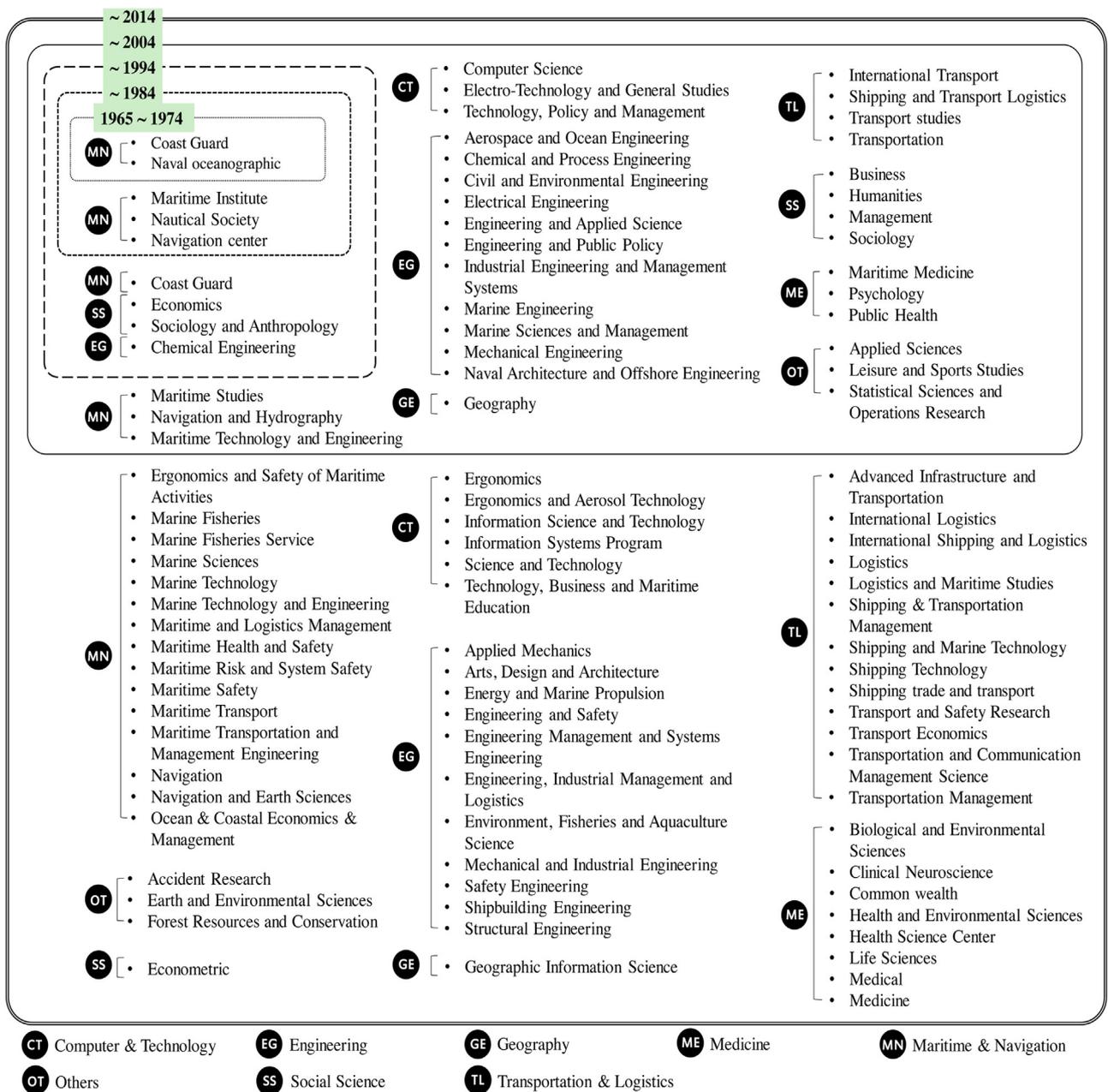
Fig. 3. Evolution of authors' affiliations.

(SS) and engineering (EG) fields began to study ship accidents from human behavior and ship structure perspectives. From 1995, many researchers from broader areas of engineering and social science joined the study of maritime accidents, and researchers from new fields of study, such as medicine (ME), computer and technology (CT), transportation and logistics (TL), and geography (GE), also contributed to the research in this area. In the most recent decade, the subject areas in each field of study have greatly expanded. This indicates that maritime accident research is becoming increasingly interdisciplinary and multidisciplinary, requiring cooperation between researchers from many different backgrounds.

3.4. Evolution of the main focus of research

Maritime accidents result from a combination of complex conditions (Fukushima, 1976). Research in different periods involves different concerns, reflecting an improved understanding of the possible factors contributing to an accident, or multiple viewpoints on the complex accident environment. Understanding the changing patterns of the main focus of past research can help to identify new research directions that will fill gaps and improve maritime safety.

As shown in Fig. 4, up until 1984 the investigation and analysis of navigation and traffic accidents were the most popular topics. Maritime safety and environmental issues related to spills and pollution gradually gained popularity from 1975 to 1994, probably due to increasing environmental awareness during that period. From 1995 to 2004, systematic risk management methods (assessment and analysis) also emerged as a major area of maritime accident research. It has become the most popular topic since 2005, providing decision support and assisting with the formulation of proactive policies for safety management in ship operations.

In the past decade, the human factor has become increasingly important in maritime accidents, as it has been widely acknowledged to be a major cause of maritime accidents (Roberts et al., 2014). In addition, environmental issues, such as the spillage of oil

Table 3
Evolution of the number of researchers by region.

	1965–69	1970–74	1975–79	1980–84	1985–89	1990–94	1995–99	2000–04	2005–09	2010–14
Number of countries	1	3	3	6	3	6	11	21	32	36
Number of researchers	4	15	7	17	14	15	70	169	303	416
Africa	–	–	–	–	–	–	–	1 (0.6)	4 (1.3)	8 (1.9)
Asia	–	5 (33.3)	2 (28.6)	1 (5.9)	–	–	8 (11.4)	28 (16.6)	57 (18.8)	124 (29.8)
Europe	–	6 (40.0)	2 (28.6)	13 (76.5)	12 (85.7)	9 (60.0)	26 (37.1)	97 (57.4)	185 (61.1)	227 (54.6)
N. America	2 (50.0)	–	3 (42.9)	1 (5.9)	2 (14.3)	5 (33.3)	34 (48.6)	39 (23.1)	39 (12.9)	50 (12.0)
S. America	–	–	–	–	–	–	–	2 (1.2)	–	6 (1.4)
Oceania	–	–	–	–	–	–	–	–	18 (5.9)	1 (0.2)
Unknown	2 (50.0)	4 (26.7)	–	2 (11.8)	–	1 (6.7)	2 (2.9)	2 (1.2)	–	–

Note: The numbers in parentheses represent regional percentages.

and hazardous materials, along with safety cultures and safety climates have also emerged as major concerns in maritime accident research.

A noteworthy trend in maritime accident research is work on the efficiency of policy and regulation in the prevention of accidents. Maritime safety administrations at both national and international levels have tried to apply regulations in the maritime industry. As previous studies point out, however, the shipping industry considers these safety provisions to be a necessary evil, due to the cost burden (Thai and Grewal, 2006), and a regulatory overload (Lappalainen et al., 2013). The appraisal of policy and regulation has emerged as a research topic.

In addition to major concerns, it is interesting to see that a much broader range of topics has been studied in the recent decade than in previous decades. This indicates that researchers are trying to analyze maritime accidents from many different angles. It also implies that future research in this area will be more multidisciplinary, requiring the collaboration of researchers from many different fields of study.

3.5. Evolution of research in the major causes of maritime accidents

To facilitate discussion on the evolution of research in the major causes of maritime accidents, we first examined how to categorize the major causes. Fukushima (1976) placed various conditions relating to maritime accidents into five groups: natural conditions, route conditions, ship conditions, traffic conditions, and navigation conditions. Reilly (1984) summarized major causes into three etiological categories: human (navigator), ship structure, and environment (subdivided into human environment and physical environment). Goossens and Glansdorp (1998) grouped a list of 45 initiating events of maritime accidents into six categories: one mechanical failure and five human failure (general human failure, strategic human failure, human observation failure, human processing failure, and human decision implementation failure). In a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis, Arslan and Er (2008) stated that maritime accidents resulted from three weaknesses (human-related factors, operational factors, and job-related factors). This study categorizes the past findings on the causes of maritime accidents into six groups: 1) Vessel and equipment conditions; 2) Environmental factors; 3) Traffic factors; 4) Navigation and operation; 5) Shipping market conditions; and 6) Human factors. The evolution of the major causes found in the published papers over the past 50 years is shown in Fig. 5.

Fig. 5 shows that research in all of the major causal categories except for shipping market conditions was published before 1995, reflecting the new direction in maritime accident research that takes into consideration the impact of market conditions. Such causal factors examined in the past publications include freight rate (Baniela and Ríos, 2010), economic activity (Heij and Knapp, 2014), and oil price (Anderson and Talley, 1995; Glen, 2010).

The area of human error, the most important factor in maritime accidents, has continuously seen new findings and new publications over the past 30 years, signifying the complexity of human interactions with maritime operations. Compared with human factors, the number of publications involving traffic and natural environmental conditions is relatively small, possibly because there is better understanding and control of these factors.

3.6. Evolution of the dimensions of the research

The 572 papers are categorized into seven dimensions according to the different aspects (subjects) of the research, and Table 4 presents the development in the number of papers in each dimension.

The general/overall analysis category involves exploratory or descriptive analysis of the general issues, policy assessment, problem description, and the explanation of preventive countermeasures. Such studies have been published throughout the half-century, and have mainly used the descriptive approach, case studies, or literature review.

The navigation/traffic area involves analyzing the effect of the navigation route and the traffic level in fairways on maritime accidents. Such research has usually been conducted using probabilistic/accident rate calculations (Fujii and Shiobara, 1971; Lighart, 1980; Ståhlberg et al., 2013), navigation pattern analysis (Bateman et al., 2007; Kemp, 1973; Silveira et al., 2013), or traffic analysis (Coldwell, 1981; Squire, 2003), and recently through analyzing AIS data and simulation (Goerlandt and Kujala, 2011; Goerlandt et al., 2012; Gucma and Przywarty, 2008).

Accident data analysis applies various statistical models to maritime accident data to find the causal factors of accidents. The methods used include descriptive statistics (Fricker, 1965; Jonse-Lee, 1990) and questionnaire surveys (Antonsen, 2009; Chang et al., 2014; Vinnem, 2011). Statistical reviews and econometric models were the most widely used in this dimension, with many published results using these methods. These three dimensions—general/overall analysis, navigation/traffic analysis, and accident data analysis—have a long history in maritime accident analysis to the present day.

Research on maritime risk and safety gained popularity from the mid-1990s. The most important method is the application of a Bayesian network (Eleye-Datubo et al., 2008; Faber et al., 2012; Hu et al., 2008; Li et al., 2014; Martins and Maturana, 2013; Montewka et al., 2014; Trucco et al., 2008), followed by Analytic Hierarchy Process (AHP), Fuzzy AHP (FAHP), and Formal Safety Assessment (FSA). Compared with research in other dimensions, the number of papers in this dimension is the highest since the 2000s.

Fatalities and occupational accidents analysis focuses on the death of or injuries to the crew aboard ships. Many fatalities and injuries can occur to seafarers on board ship (Hansen and Pedersen, 2001), and seafarers working aboard merchant ships have a high casualty rate (Li and Ng, 2002). With respect to methodology,
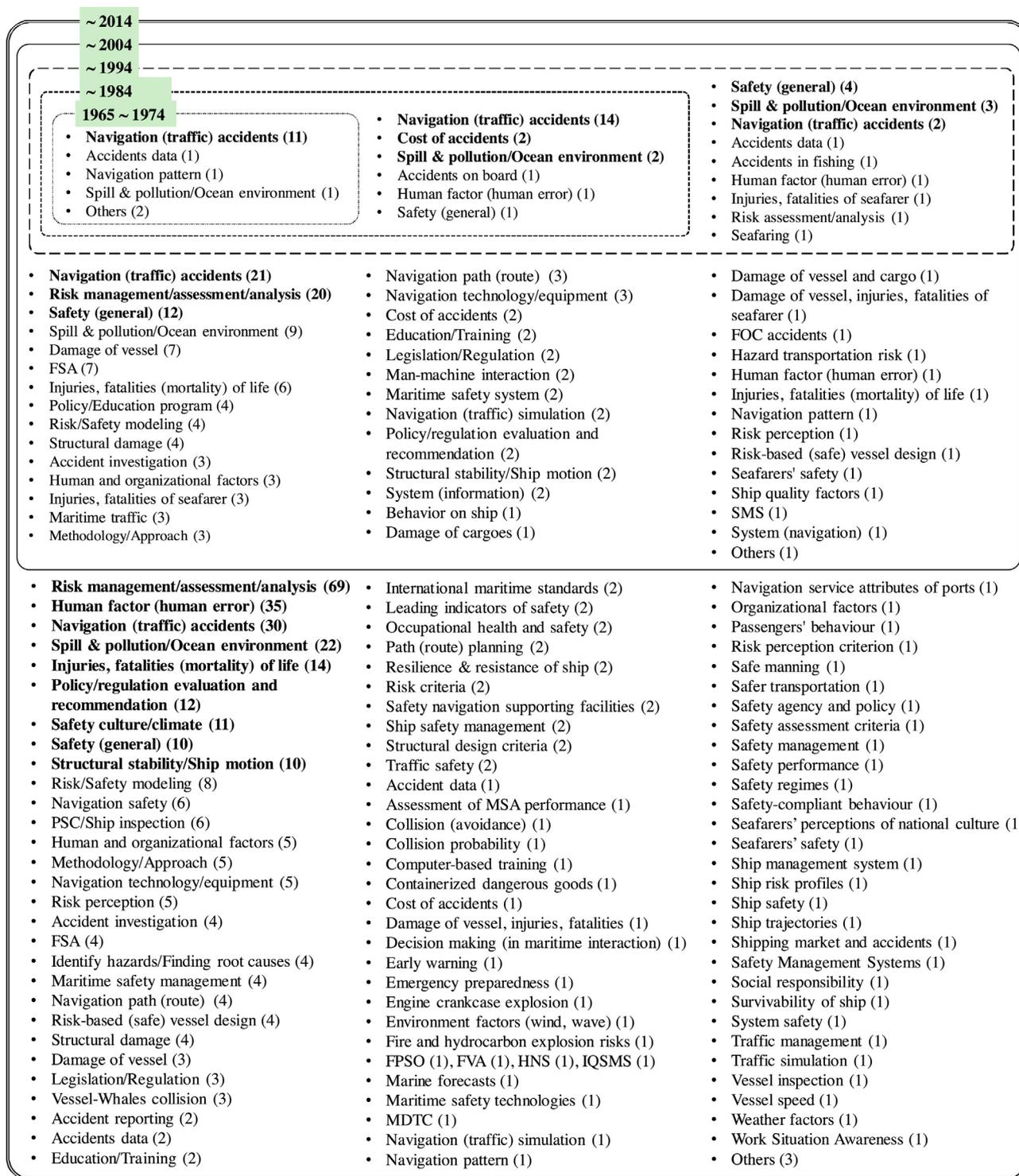
~ 2014
~ 2004
~ 1994
~ 1984
1965 ~ 1974

1965 ~ 1974:
- **Navigation (traffic) accidents (11)**
- Accidents data (1)
- Navigation pattern (1)
- Spill & pollution/Ocean environment (1)
- Others (2)

~1984:
- **Navigation (traffic) accidents (14)**
- **Cost of accidents (2)**
- **Spill & pollution/Ocean environment (2)**
- Accidents on board (1)
- Human factor (human error) (1)
- Safety (general) (1)

~1994:
- **Safety (general) (4)**
- **Spill & pollution/Ocean environment (3)**
- **Navigation (traffic) accidents (2)**
- Accidents data (1)
- Accidents in fishing (1)
- Human factor (human error) (1)
- Injuries, fatalities of seafarer (1)
- Risk assessment/analysis (1)
- Seafaring (1)

~2004:

Column 1:
- **Navigation (traffic) accidents (21)**
- **Risk management/assessment/analysis (20)**
- **Safety (general) (12)**
- Spill & pollution/Ocean environment (9)
- Damage of vessel (7)
- FSA (7)
- Injuries, fatalities (mortality) of life (6)
- Policy/Education program (4)
- Risk/Safety modeling (4)
- Structural damage (4)
- Accident investigation (3)
- Human and organizational factors (3)
- Injuries, fatalities of seafarer (3)
- Maritime traffic (3)
- Methodology/Approach (3)

Column 2:
- Navigation path (route) (3)
- Navigation technology/equipment (3)
- Cost of accidents (2)
- Education/Training (2)
- Legislation/Regulation (2)
- Man-machine interaction (2)
- Maritime safety system (2)
- Navigation (traffic) simulation (2)
- Policy/regulation evaluation and recommendation (2)
- Structural stability/Ship motion (2)
- System (information) (2)
- Behavior on ship (1)
- Damage of cargoes (1)

Column 3:
- Damage of vessel and cargo (1)
- Damage of vessel, injuries, fatalities of seafarer (1)
- FOC accidents (1)
- Hazard transportation risk (1)
- Human factor (human error) (1)
- Injuries, fatalities (mortality) of life (1)
- Navigation pattern (1)
- Risk perception (1)
- Risk-based (safe) vessel design (1)
- Seafarers' safety (1)
- Ship quality factors (1)
- SMS (1)
- System (navigation) (1)
- Others (1)

~2014:

Column 1:
- **Risk management/assessment/analysis (69)**
- **Human factor (human error) (35)**
- **Navigation (traffic) accidents (30)**
- **Spill & pollution/Ocean environment (22)**
- **Injuries, fatalities (mortality) of life (14)**
- **Policy/regulation evaluation and recommendation (12)**
- **Safety culture/climate (11)**
- **Safety (general) (10)**
- **Structural stability/Ship motion (10)**
- Risk/Safety modeling (8)
- Navigation safety (6)
- PSC/Ship inspection (6)
- Human and organizational factors (5)
- Methodology/Approach (5)
- Navigation technology/equipment (5)
- Risk perception (5)
- Accident investigation (4)
- FSA (4)
- Identify hazards/Finding root causes (4)
- Maritime safety management (4)
- Navigation path (route) (4)
- Risk-based (safe) vessel design (4)
- Structural damage (4)
- Damage of vessel (3)
- Legislation/Regulation (3)
- Vessel-Whales collision (3)
- Accident reporting (2)
- Accidents data (2)
- Education/Training (2)

Column 2:
- International maritime standards (2)
- Leading indicators of safety (2)
- Occupational health and safety (2)
- Path (route) planning (2)
- Resilience & resistance of ship (2)
- Risk criteria (2)
- Safety navigation supporting facilities (2)
- Ship safety management (2)
- Structural design criteria (2)
- Traffic safety (2)
- Accident data (1)
- Assessment of MSA performance (1)
- Collision (avoidance) (1)
- Collision probability (1)
- Computer-based training (1)
- Containerized dangerous goods (1)
- Cost of accidents (1)
- Damage of vessel, injuries, fatalities (1)
- Decision making (in maritime interaction) (1)
- Early warning (1)
- Emergency preparedness (1)
- Engine crankcase explosion (1)
- Environment factors (wind, wave) (1)
- Fire and hydrocarbon explosion risks (1)
- FPSO (1), FVA (1), HNS (1), IQSMS (1)
- Marine forecasts (1)
- Maritime safety technologies (1)
- MDTC (1)
- Navigation (traffic) simulation (1)
- Navigation pattern (1)

Column 3:
- Navigation service attributes of ports (1)
- Organizational factors (1)
- Passengers' behaviour (1)
- Risk perception criterion (1)
- Safe manning (1)
- Safer transportation (1)
- Safety agency and policy (1)
- Safety assessment criteria (1)
- Safety management (1)
- Safety performance (1)
- Safety regimes (1)
- Safety-compliant behaviour (1)
- Seafarers' perceptions of national culture (1)
- Seafarers' safety (1)
- Ship management system (1)
- Ship risk profiles (1)
- Ship safety (1)
- Ship trajectories (1)
- Shipping market and accidents (1)
- Safety Management Systems (1)
- Social responsibility (1)
- Survivability of ship (1)
- System safety (1)
- Traffic management (1)
- Traffic simulation (1)
- Vessel inspection (1)
- Vessel speed (1)
- Weather factors (1)
- Work Situation Awareness (1)
- Others (3)

Fig. 4. Evolution of the main topics in maritime accident research.

Table 4
Trends in research dimension for maritime accident research.

| Dimensions	1965–69	1970–74	1975–79	1980–84	1985–89	1990–94	1995–99	2000–04	2005–09	2010–14	Total
General/overall analysis	2	2	1	3	–	4	13	20	29	28	102
Navigation/traffic analysis	–	6	1	2	–	–	1	6	8	14	38
Accident data analysis	2	4	3	7	2	4	14	22	43	59	160
Risk analysis/safety assessment	–	–	1	3	2	1	12	38	63	84	204
Fatalities and occupational accident analysis	–	–	–	–	1	1	3	9	11	13	38
Mechanical analysis	–	–	–	–	–	–	1	9	9	6	25
Maritime database analysis	–	–	–	–	–	–	–	1	–	4	5
Total	4	12	6	15	5	10	44	105	163	208	572
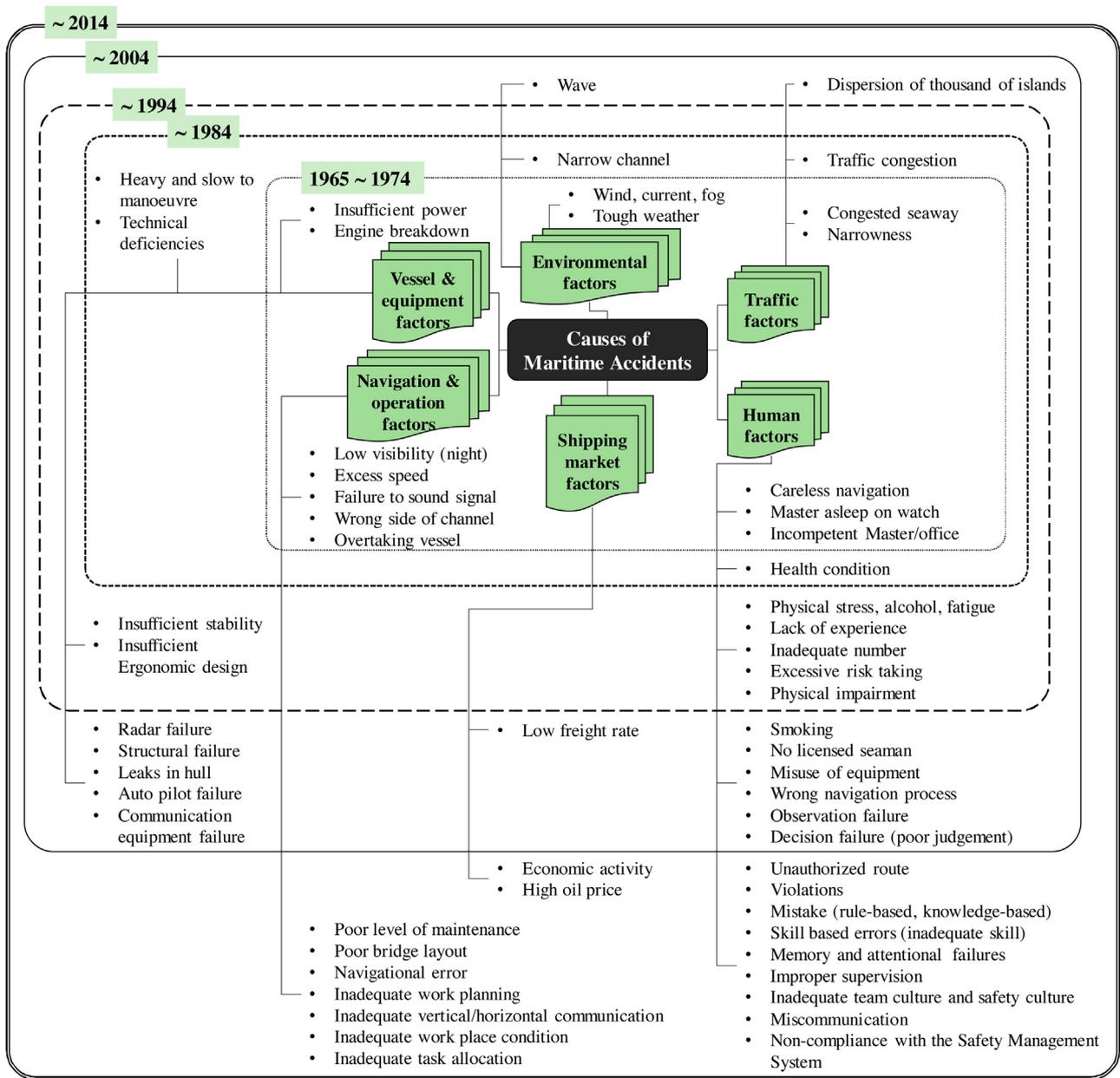
Fig. 5. Evolution of the major causes of maritime accidents.

most researchers used descriptive statistics, case studies, statistical reviews and surveys. In addition, econometric models were also used for analyzing seafarer accidents (Talley, 1999; Roberts et al., 2013).

Most studies on mechanical analysis were conducted by engineers, analyzing vessel safety, seaworthiness, and ship stability. Probabilistic/accident rate calculation, modeling, and simulation were the most common methods. Laboratory experiments and results were also used in this sector (Korkut et al., 2004, 2005; Silber et al., 2010).

Studies on the importance and limitations of maritime data have indicated problems of under-reporting in maritime accident databases (Hassel et al., 2011; Psarros et al., 2010). The causal factors determined from such databases may suffer from problems of under-estimation, affecting their usefulness for formulating policies to reduce the probability of future accidents (Oltedal and McArthur, 2011).

Of the seven dimensions, risk analysis/safety assessment and accident data analysis have the highest numbers of published papers. Using social network analysis of the co-authorship of these papers and the corresponding geographic location of the authors' affiliations enables identification of the regional development of such research and the leaders in these research areas.

Fig. 6 shows co-authorship and identification of the leader in the risk analysis/safety assessment dimension, which has 204 published papers over the past 50 years. Professor Jin Wang from Liverpool John Moores University is at the center of this research area. His co-authors are mostly located in the UK and China, and also in Korea and Turkey. The research methods include FSA, Bayesian Networks (BN), Artificial Neural Networks (ANN), AHP, FAHP, Fuzzy Bayesian Networks (FBN), Fuzzy Fault Tree Analysis (FFTA), Balanced Score Card (BSC), Evidential Reasoning (ER), Geographical Information System (GIS), Cognitive Reliability and Error Analysis Method (CREAM), and Why Because Analysis (WBA). Most of the
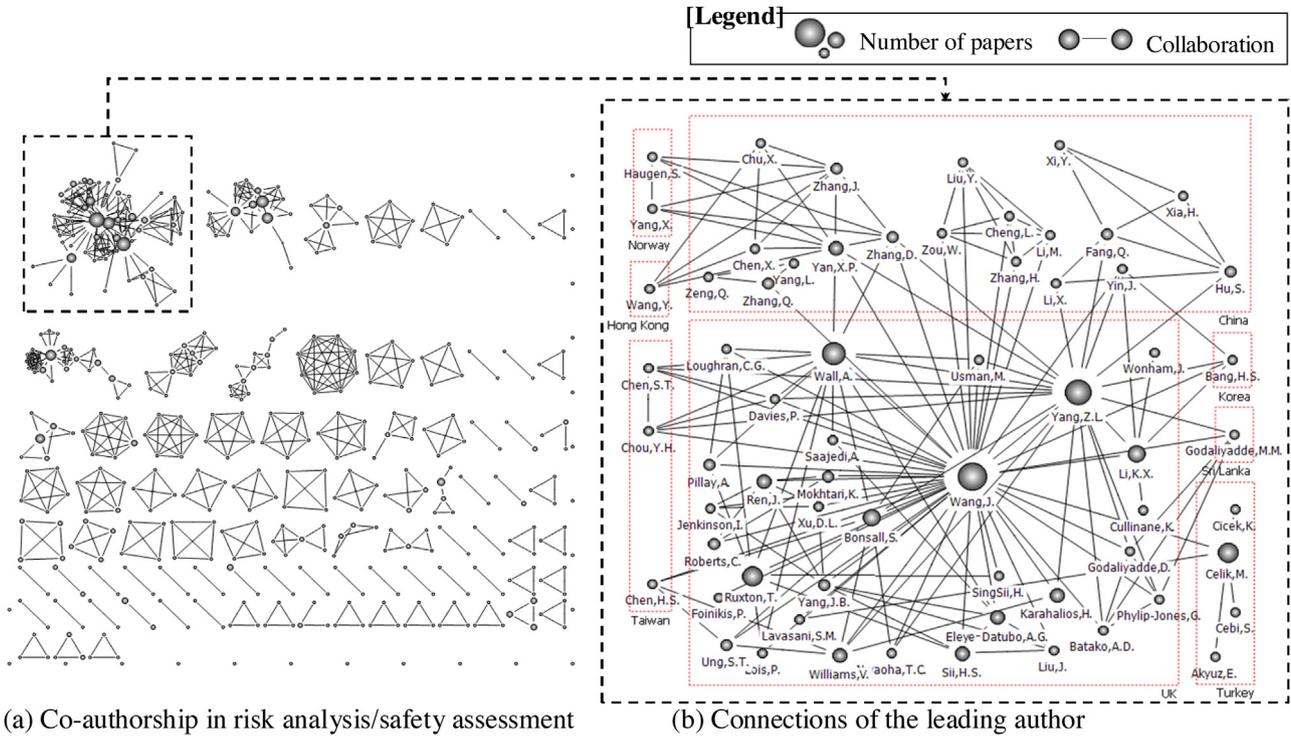
(a) Co-authorship in risk analysis/safety assessment   (b) Connections of the leading author

Fig. 6. Collaboration network in risk analysis/safety assessment.

papers that used these methods were published in the past five years, reflecting the trend toward risk analysis/safety assessment.

The second largest dimension is accident data analysis, with a total of 160 papers. The collaboration network is shown in Fig. 7. There are two main groups in this dimension, one led by Prof. Wayne K. Talley at Old Dominion University, USA, and the other by Dr. Sabine Knapp at Erasmus University, The Netherlands. Both groups have used various econometric models, such as Tobit and Probit, Poisson regression, negative binomial regression, ordered Probit and logit, and duration analysis.

3.7. Trends in methodology

The early studies in maritime accident research usually adopted very basic methods such as statistical and descriptive reviews, case studies and probability calculations, while recent studies often used multi-disciplinary approaches, comprehensive risk analysis, and system-width viewpoints (Fig. 8). After 1995, many studies adopted econometric methods to find causal factors (Anderson and Talley, 1995; Talley, 1996; Jin et al., 2001; Knapp and Franses, 2010; Talley et al., 2012). Econometric analysis has two major
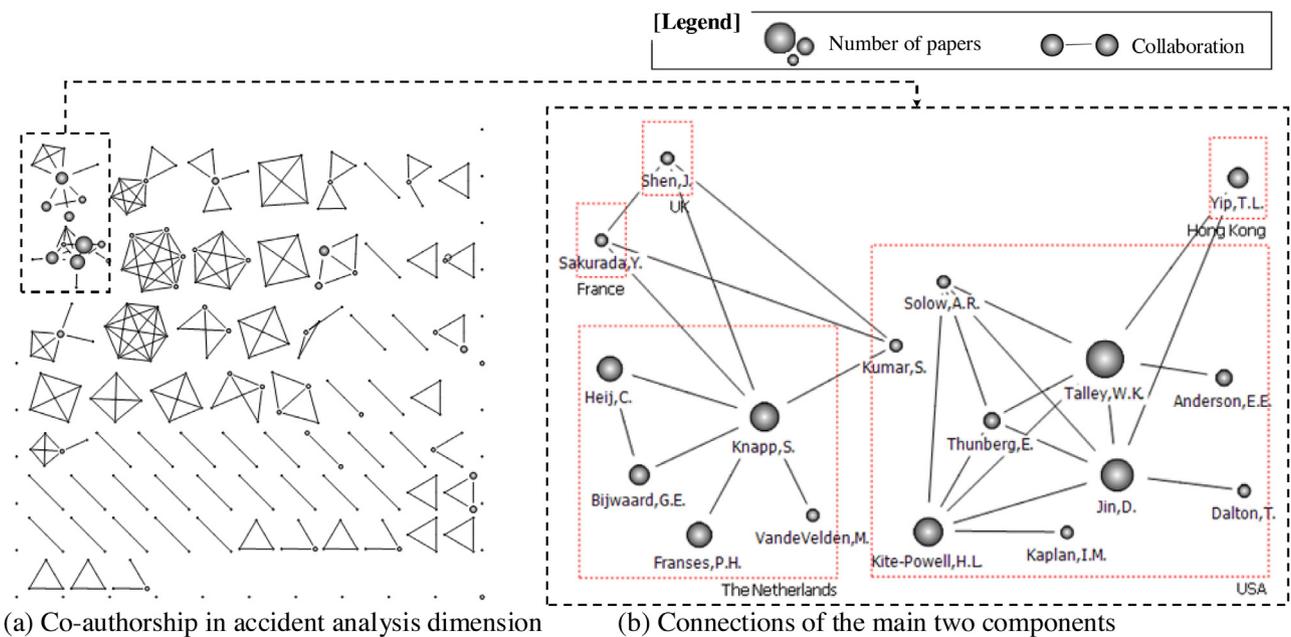

(a) Co-authorship in accident analysis dimension   (b) Connections of the main two components

Fig. 7. Collaboration network in accident data analysis.

~ 2014
~ 2004
~ 1994
~ 1984

1965 ~ 1974
- Accident rate calculation (6)
- Descriptive (5), Case study (1)
- Statistical review/Descriptive statistics (2)
- Navigation pattern analysis (1)
- Theoretical analysis, Case study (1)

- Statistical review/Descriptive statistics (7)
- Accident rate calculation (5)
- Descriptive (4), Cost analysis (3)
- Statistical estimation (1)
- Traffic analysis (1)

- Descriptive (4), Case study (1)
- Statistical review/Descriptive statistics (3)
- Causal network (1), Cost analysis (1)
- ETA, Basic regression (1)
- Analytical modeling (1)
- Paper review (1), QRA (1)
- Probabilistic/Accident rate calculation (1)

- Descriptive (35), Case study (2)
- Econometric model (17)
  - Tobit regression (10)
  - Ordered probit regression (2)
  - Linear regression (2)
  - Logit regression (1)
  - Multiple logistic regression (1)
  - Probit (1)
- Statistical review/Descriptive statistics (14)
- Analytical modeling (10)
- Simulation (7)
- Probabilistic/Accident rate calculation (7)
- FSA (4), CBA (3), CEA (3)
- Paper review (3), Fuzzy (3)   • Genetic algorithm (1)
- Survey/Questionnaire (2)   • Mechanical analysis (1)
- AHP (1), FCA (1)   • Multivariate test (1)
- Bayesian method (1)   • Neural network (1)
- BDS statistic (1)   • QRA (1), SMAS (1)
- Classification (1)   • SEM (1)
- Discriminant analysis (1)   • Stepwise approach (1)
- Effectiveness measure (1)   • Traffic analysis (1)

- **Combined methodology (19)**
  - ANN model, Taguchi method, Dempster-Shafer approach (2)
  - Cluster analysis, Neural networks (1)
  - EDN, FSA (1)
  - FSA, ETA, CBA (1)
  - FSA, Probabilistic/Accident rate calculation (1)
  - FTA, ETA, Modeling (1)
  - Modeling, Cognitive Simulation (1)
  - Multi-objective approach (1)
  - Ordinary least-squares regression, Poisson regression (1)
  - Poisson regression analysis, Negative binomial regression (1)
  - Probit, Negative binomial regressions (1)
  - QMAS, quantitative SYRAS (1)
  - Simulation, CPA (1)
  - Simulation, Modeling (1)
  - Simulation, Theoretical analysis (1)
  - Statistical review/Descriptive statistics, FSA (1)
  - Statistical review/Descriptive statistics, Risk analysis (1)
  - Statistical review/Descriptive statistics, Simulation (1)
- Not specific (4)

- Descriptive (43), Case study (7)
- Statistical review/Descriptive statistics (33)
- Econometric model (25)
  - Binary logistic regression (6)
  - Tobit regression (5)
  - Hierarchical regression (2)
  - Logit regression (2)
  - Ordered probit regression (2)
  - Binomial logistic regression (1)
  - Duration regression (1)
  - Leaner regression (2)
  - Multiple logistic regression (1)
  - Negative binomial regression (1)
  - Probit regression (1)
  - Stepwise regression (1)
- Fuzzy method (15)
  - Fuzzy (5), FAHP (3)
  - FBNs (1), Fuzzy approach (1)
  - Fuzzy FMEA (1), FFTA (1)
  - Fuzzy TOPSIS (1), DFLM (1)
  - Fuzzy-precise BN (1)
- BN (14)
- Analytical Modeling (13)
- Probabilistic/Accident rate calculation (10)
- Survey/Questionnaire (10)
- Simulation (9)
- Review (7), Paper review (5)
- FTA (5), FSA (4), Algorithm (3)
- DEA (2), AHP (2), SWOT (2)
- Grey correlation analysis (2)
- Decision tree method (2)

- A comparative analysis (1)
- AHP multicriteria approach (1)
- ARMAX model (1)
- ARPA simulator (1)
- Bayes' theorem (1)
- Bayesian simulation (1)
- Bow-tie approach (1)
- CATS (1), CART (1)
- CHAID algorithm (1)
- Chi-Square test (1)
- Classification (1)
- Cluster analysis (1)
- Comparative analysis (1)
- Content analysis (1)
- Core task analysis (1)
- Cut-off values approach (1)
- DST (1)
- Monte Carlo simulation (1)
- Potential field method (1)
- Ship handling simulator (1)
- SHS with Delphi survey (1)
- Multi-factorial risk analyses (1)
- Plastic mechanism analysis (1)
- Semi-quantitative risk assessment (1)
- Semi-structured interviews. (1)
- Software tool Nextcase (1)
- Marine traffic real-time safety Index (1)
- Dubin's theory-building framework (1)
- Geographical analysis (1)
- GESAMP's hazard evaluation (1)
- Integrating HOE analysis (1)

- CBA (1), CPA (1)
- CFD models (1)
- CREAM (1), FMEA (1)
- Decision analysis (1)
- Generic framework (1)
- GF-AHP (1)
- Graphical analysis (1)
- HFACS (1)
- HFACS-CM (1)
- HFACS-MSS (1)
- JCA (1), MAFAD (1)
- MDTC model (1)
- MLE (1),
- Modified FSA (1)
- New MRRA (1)
- PCA (1), Pilot study (1)
- QERA (1), QRA (1)
- RADTRAN (1)
- R–D diagrams (1)
- Risk matrix (1)
- Safety case approach (1)
- SARF (1), SDSS (1)
- SEM (1)
- Strategy assessment (1)
- SWOT–AHP method (1)
- System simulation (1)
- System theory (1)
- TQM (1)
- Not specific (15)

- **Combined methodology (81)**

- EFA, CFA (2)
- Factor analysis, ANOVA (2)
- Modeling, Simulation (2)
- VSL, Regression, CBA, Multi-faceted discussion (2)
- AIS data analysis, Monte Carlo simulation (1)
- ANN, Experimental study (1)
- Balanced Scorecard (BSC), Fuzzy AHP, Case study (1)
- BN &
  - Bayesian multivariate regression (1), Case study (1)
  - F–N diagram, Traffic simulator, HFACS (1)
  - Probabilistic/Accident rate calculation (1)
  - Traditional BRB, G-BRB (1)
- CATS, Statistical analysis (1)
- CFA, Hierarchical regression, ANOVA analysis (1)
- CPA, Modeling (1)
- CREAM, Marine accident investigation (1)
- DCPA, TCPA, VCD, Fuzzy, simulation (1)
- Dempster–Shafer framework, Fuzzy (1)
- DTA, FTA (1), DTA, Modeling (1)
- Duration regression, Binary logistic regression (1)
- EFA, Linear regression (1)
- ETA, CFD simulations, Frequency analysis (1)
- Factor analysis, Cluster analysis, ANOVA analysis (1)
- FAD, AHP (1), FAHP, GIS (1)
- FSA concept, BN, Risk matrix (1), FSA, EFA, CBA (1)
- FTA, ETA, Fuzzy ETA (1)
- Fuzzy &
  - ANN (1), Case study (2),
  - DST, Cross forensic analysis (1)
  - Evidential reasoning (1), Simulation (2)
  - BSC, AHP (1)
- Game model, Simulation (1)
- Traffic conflict technique, CPA, Ordered probit (1)
- Logistic regression, ROC analysis (1)

- HFACS &
  - BN, ER (1), WBA (1)
  - Multiple Correspondence, Classification (1)
- Lorenz curve, Gini index (1)
- Markov modeling, MCMC simulation (1)
- Modeling/Mathematical formulation, TQM (1)
- Modified CREAM, Fuzzy logic, BN (1)
- Monte Carlo simulation, CBA (1)
- Negative binomial, Poisson regression (1)
- One-way ANOVA, Correlation analysis (1)
- Petri nets theory, Modeling (1)
- Poisson, Negative binomial regression (1)
- Polynomial, Logistic regression, Simulation (1)
- PRA, HRA (1)
- Probabilistic/Accident rate calculation &
  - FTA, ETA, BN, Simulation (1)
  - HRA, BN (1), Unified FQSD (1)
  - Simulation (2), Trajectory Analysis (2)
- Qualitative scoring system, F–N diagram (1)
- Risk modelling, CEA (1)
- Safety Barrier Analysis, Bow-tie Muster Step Analysis, Case study (1)
- SARF (1)
- Spatial analysis, Butter analysis (1)
- Statistical description, Case study (1)
- Survey/Questionnaire &
  - Binary logistic regression, EFA (1)
  - Case study (1), Factor analysis (1)
  - EFA, CFA, Discriminant analysis (1)
  - Factor analysis, Logistic regression (1)
  - Factor analysis, Ordered logistic regression (1)
  - Mean value method, Stochastic dominance (1)
  - PCA (1), ANOVA (1)
  - EM, MI, Hierarchical cluster analysis (1)

Fig. 8. Major methodology and models used in maritime accident research.

limitations: 1) under-reporting of maritime accident data, and 2) difficulty in taking into account human error or other qualitative information such as cultural factors (Roberts et al., 2013). In the past decade, many different approaches have been developed to address these problems. For example, Human Factors Analysis and Classification System (HFACS), which has been used for accident analysis in other fields, was introduced to identify latent human errors (Celik and Cebi, 2009; Chauvin, 2011). New methods that have appeared in maritime accident research also include CREAM (Akhtar and Utne, 2015), probabilistic risk assessment based simulation (Merrick et al., 2005), and many other modeling techniques

(Tam and Bucknall, 2010; Goerlandt and Kujala, 2011; van Dorp and Merrick, 2011; Faghih-Roohi et al., 2014).

Recently, the most frequently used method for risk analysis and safety assessment was a BN (Eleye-Datubo et al., 2006; Ren et al., 2008; Wang et al., 2013; Zhang et al., 2013; Wang and Zhang, 2014; Hänninen et al., 2014). It is a powerful tool for modeling repetitive patterns (Håvold, 2010), which can replace FTA as a classification method and take into account the joint effect of several events (Faber et al., 2012). Human fatigue, usually difficult to quantify, can be analyzed using BN methodology (Akhtar and Utne, 2014).

Another new trend in recent years is the use of combined methods and coupled analysis. Nwaoha et al. (2013) used a risk matrix
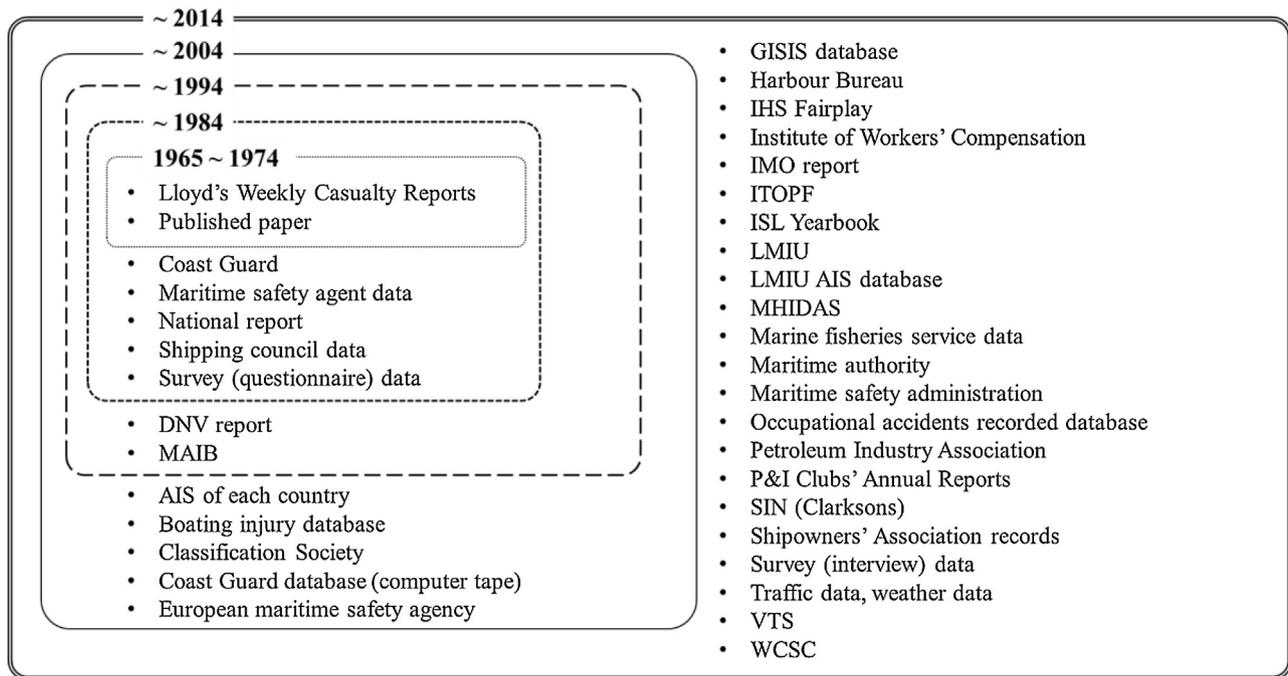
Fig. 9. Evolution of the data sources used in maritime accident research.

together with a Fuzzy ER (FER) approach. Zhang et al. (2014) combined quantitative and qualitative data using Belief Rule Base (BRB) theory. Chang et al. (2014) used both qualitative and quantitative methods to analyze safety and security risks in container shipping. Some researchers analyzed survey and questionnaire data using not only factor analysis, cluster analysis, Analysis of Variance (ANOVA), Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA), but also econometric models such as hierarchical regression and logistic regression. Ek et al. (2014) used expectation maximization (EM) and Multiple Imputation (MI) to estimate the missing value in a questionnaire. Fuzzy set analysis has also been used together with methods such as Event Tree Analysis (ETA) (Mokhtari et al., 2011), and AHP (Perera et al., 2011).

Model extension has occurred alongside the introduction of new models to this research area. Yang et al. (2013) extended the CREAM approach by incorporating Bayesian reasoning in a fuzzy environment. Akyuz and Celik (2014) combined the HFACS approach with Cognitive Mapping (CM) to focus on human error in maritime accidents. The acronym HFACS-MA qualifies HFACS as applying to maritime accidents, and has been used to analyze human and organizational factors (Chen et al., 2013); likewise, HFACS-MSS for investigating deficiencies in machinery spaces on ships (Schröder-Hinrichs et al., 2011).

3.8. Evolution of data sources

Maritime accident data play a crucial role in maritime accident research (Meek et al., 1985; Dobler, 1994). The selection of data resources requires careful consideration due to important implications for the research results. Over the past 50 years, the data sources used in the published research have also evolved, as shown in Fig. 9.

From 1965 to 1974, the main sources of maritime accident data were Lloyd's reports and published papers. Coast Guard, maritime council, and government agency data were used in accident analysis after the mid-1970s. From 1985 to 1994, Det Norske Veritas reports related to maritime accidents were published, and the UK authorities published the accident-dedicated data from Mar-

itime Accident Investigation Branch (MAIB), which is still used currently. From 1995 to 2004, computer-based databases enabled rapid access to the data and easy computation, generating a large volume of papers on accident patterns and major causes according to ship type, place, and period. During the past decade, not only variables relating to maritime accidents and vessels (age, ship type, gross tonnage, Flag of Convenience (FOC), classification societies), but also data on the marine environment, weather, and crews have been incorporated into analyses. Some very recent publications have even used data from Global Integrated Shipping Information System (GISIS) and Automatic Identification System (AIS). In this period more papers used multiple databases, due to increasing awareness of the complexity of maritime accidents and better data-processing capability. For example, Ronza et al. (2006) used climate data (average temperatures, humidity, wind roses and atmospheric stability) combined with traffic data; Qu et al. 2011 considered ships' speed data using the AIS database.

A recent trend in maritime accident research is the increasing number of studies using data from multiple sources. For example, Balmat et al. (2011) used data from Lloyd's Register, IMO, Electronic/European Quality Shipping Information System (EQUASIS), and Paris MOU; Knapp et al. (2011) combined data from Lloyd's Register Fairplay, various Port State Control (PSC) regimes, industry inspections from RightShip, Chemical Distribution Institute (CDI), Oil Company International Maritime Forum (OCIMF), flag state inspections and International Safety Management (ISM) audits from various flag states, Lloyd's Maritime Intelligence Unit (LMIU), IMO, Clarkson Shipping Intelligence Network (CSIN), and International Comprehensive Ocean-Atmosphere Data Set (ICOADS). Heij and Knapp (2014) considered various variables from diverse datasets that included CSIN, the Institute of Supply Management, Organization for Economic Cooperation and Development (OECD), Braemer Seascope (BS), International Monetary Fund (IMF), Australia MSA, IMO, Lloyd's Register Fairplay, and LMIU.

As many studies indicate, maritime accident databases are vital for finding the root causes of maritime accidents and providing preventative measures. Although many different types of databases have been developed, the lack of relevant data has been a problem

for researchers. To overcome this problem, researchers used combined data or other less data-dependent approaches. For instance, econometric models are often unsuitable for dealing with qualitative data such as human error. Risk analysis models, such as the BN model, can act in a supplementary fashion by generating data samples according to assumed priori distribution of certain variables. This is one reason why BN models have recently been introduced into maritime accident studies.

4. Summary and conclusions

In maritime community, huge effort has been directed to reduce or eliminate maritime accidents, due to their threats to the people aboard, the ships, the cargo, and the marine environment. This effort is reflected in the large collection of research papers that have been published in peer-reviewed journals. Understanding how the field has evolved can help future researchers to fill the gaps in this area, and thus better protect life and property at sea.

This study summarized the evolution of maritime accident research from broad perspectives over the past 50 years, using 572 peer-reviewed papers collected from 125 academic journals published in English. The number of papers published in the most recent decade increased rapidly compared with the previous period, due to the increasing role of maritime transportation in international trade, and recognition of the increasingly large potential damage resulting from maritime accidents. Japan, Europe and North America were the most active areas of maritime accident research in the past. Asia has now become increasingly active, due to its emerging development in maritime trade. Africa, South America and Oceania may be future growth areas.

Over the past half-century, maritime accident research has changed from being an exclusive area for naval architects to a big stage for many players from different disciplines. This reflects a shifting of the major concerns from ship structure problems to complex environmental conditions, including human error and shipping market conditions. This shift has also required the use of data from many different sources, and more advanced models and computer technologies.

The most popular dimensions in maritime accident research are risk analysis/safety assessment and accident data analysis. The focus of the former is on preventative measures, while that of the second is on learning from an accident. Analyzing accident data allows the knowledge base on the possible causes of maritime accidents to be enlarged, which can help in the development of better policies and more effective preventative measures to improve maritime safety.

Maritime transportation is the main method of conveyance for the goods and commodities of international trade, and studies on maritime accidents will continue to be a very important element in the shipping industry, requiring joint efforts from researchers, policy makers, and industry practitioners. However, the current shipping market remains at a very low "sentiment", and the current over-capacity in both the liner and the dry bulk sectors prevents the growth of "optimism". The shipping industry finds it difficult to retain high-quality seafarers to work aboard ship. As our review indicates, human factors are a major cause of shipping accidents, and the shipping market condition is an emerging factor. Analyzing the effect of the shipping market on human error, and how it affects the probability of shipping accidents, is a very promising future research area, especially in the current market conditions.

Acknowledgement

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