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The impact of shipping 4.0 on controlling shipping accidents: A systematic literature review

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ABSTRACT

Maritime shipping, with a significant role in global trade, confronts various accidents leading to loss of lives, properties, and the environment. Shipping 4.0 technologies are scaling up to address this problem by employing real-time data-driven technologies, including cyber-physical systems, advanced tracking and tracing, intelligent systems, and big data analytics. Despite growing attention, there is a general lack of clarity on the level and direction of progress in this field. Accordingly, this study aims to identify critical shipping accident risks, analyze the role of relevant shipping 4.0 technologies in controlling these risks, and consolidate the findings into a conceptual guiding framework directing future developments. Accordingly, a systematic review is performed that reveals how shipping 4.0 approaches address critical accident risks and the gaps that still exist. Overall, we found that the collision is the most frequent accident referred to, while the most frequent technology to control the accidents is the Automatic Identification System. In contrast, we see an evident lack of cloud computing, internet-of-things, and big data analytics, which play crucial roles in current industry 4.0 developments.

1. Introduction

Maritime transportation can be considered the largest carrier of global trade. On March 23, 2021, the Ever Given container ship, one of the world's largest container ships, operated by the Evergreen Marine Corporation became stuck in the Suez Canal, causing a six-day blockage. The Suez Canal Authority impounded the ship after it was freed and sought about $600 million in damages, caused by blocking the canal (Allianz, 2021). Albeit the number of ship losses has been decreased significantly in the last ten years, the number of accidents has remained still or experienced negligible changes (JTSB, 2021). According to the safety and shipping review published by the International Maritime Organization (IMO), 705 shipping accidents occurred in 2020 (IMO, 2021), resulting in damages to human life, the cargo, the environment, and the overall economic sustainability (Kulkarni et al., 2020). An indication of the abovementioned statistics is provided in Figs. 1 and 2.

Maritime transportation, therefore, bears unique planning, management, and safety challenges due to the global-scale operations, varying jurisdictions and infrastructures, high-cost structures, and other operational, geo-economic, and political uncertainties. These challenges are compounded manifold with a lack of accurate and timely information to planners (Siddiqui and Verma, 2013, 2018).

While many of these problems are initially ameliorated with the current technologies (Sullivan et al., 2020; Tirkolaee et al., 2021), transformation to a highly integrated, real-time data-driven planning and physical ship management praxes is now transpiring through industry 4.0 technologies (Almada-Lobo, 2015). The term is originally developed from a high-tech project initiated by the German government in 2011 to use smart technologies in automating the traditional manufacturing processes (Jahani et al., 2021). Here we note that the first three revolutions brought mechanization (1st), the everyday use of electrical power (2nd), and widespread digitalization (3rd). In contrast, the fourth revolution technologies are led by integrating advanced digitalization, sensor technologies, and the internet generating

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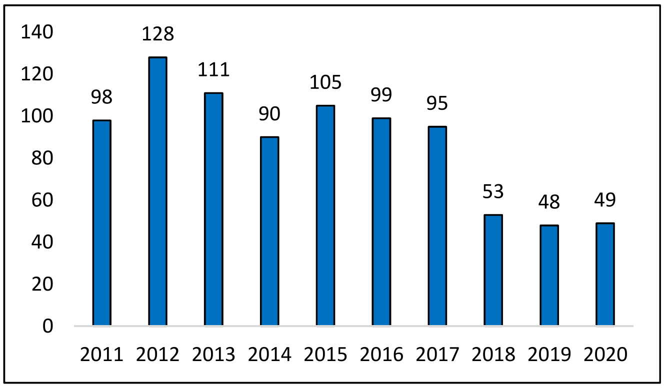

Fig. 1. The number of ship losses in the last decade (IMO, 2021).

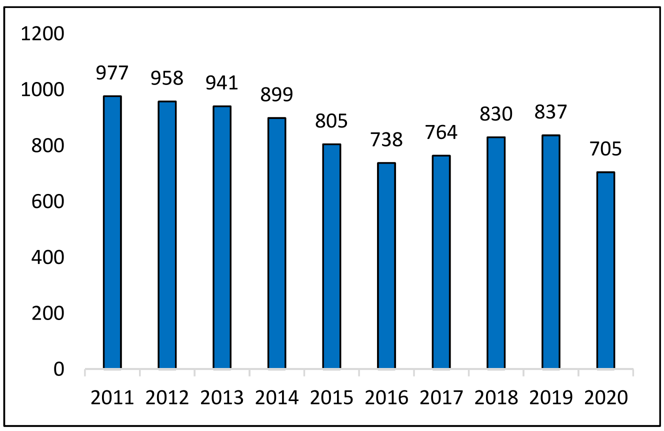

Fig. 2. The number of shipping accidents in the last decade (JTSB, 2021).

autonomous and intelligent systems (Jahani et al., 2021). These data and decision technologies can include cyber-physical systems, the internet of things, advanced tracking and tracing, cloud computing, intelligent systems, and big data analytics, all incrementally replacing high-risk manual jobs with intelligent, autonomous, and robust systems (Oztemel and Gursev, 2020).

Several technical and management improvements through these technologies have already led us to this maritime transformation as shipping 4.0, which is defined as the integrated implementation of digital processes and smart technologies in the design, development, construction, operation, and service of vessels enhancing their automation and autonomy (Aiello et al., 2020). The scope of shipping 4.0 is extensive, encompassing physical ship handling to planning and managing a global fleet at operational to strategic levels. These developments focus not only on operational productivity but on safety issues as well. This is both in terms of preventing adverse events like collisions and grounding through early detection and better ship navigation and in the mitigation of adverse events like fuel spill clean-up using advanced tracking, tracing technologies, and autonomous equipment. The academic literature is also witnessing a significantly increased focus on various aspects of this transformation, the general landscape of which has recently been captured by multiple review studies. For example, Aiello et al. (2020) analyzed the impact of industry 4.0 on shipping processes and identified the gaps in the literature. Similarly, de la Peña Zarzuelo et al. (2020) discussed the progress of industry 4.0 applications in the development of smart-ports processes. Other related studies have focused on specific aspects, such as the impact of big data on automation, monitoring, and data reporting in shipping (Brzozowska, 2016; Rødseth et al., 2016).

Despite these recent studies, there are vital shipping 4.0 areas where the progression scenario is unclear at best. Our work focuses on one such area, viz. dealing with maritime accident risks in the shipping 4.0 context. Management of maritime accident risks has always been a mainstay of the shipping industry due to its dire fallouts in the form of injuries, the loss of lives, the environment, and businesses (Lim et al., 2018; Loh et al., 2017). To ensure the smooth operation of such systems, major accidents' potential needs to be identified, and proper mitigation measures need to be developed (IMO, 2012). Examples of some of the common risks that lead to these consequences include ship collision and grounding (Goerlandt and Montewka, 2015b; Zhang et al., 2019a), fire (Kang et al., 2017; Puisa et al., 2014), flooding (Mermiris and Vassalos, 2019; Varela et al., 2014), congestion of maritime traffic (García-Domínguez, 2015; Kentis et al., 2017), and security issues (Brüggemann et al., 2016; Burns, 2013). In this context, the technological advancements anticipated within shipping 4.0 can provide opportunities for companies to facilitate the risk management process (Aiello et al., 2020; Aven, 2013). For example, advanced tracking and tracing supported via sensor technologies and augmented reality can make navigation safe, (Lehtola and Montewka, 2020; Lehtola et al., 2019), besides mitigating several other adverse consequences (Caamaño et al., 2019; Ruponen et al., 2019).

In this pretext, we see a strong need to 1) consolidate the progress in risk management research in the shipping 4.0 context; and 2) identify and explore different industry 4.0 applications in improving the management of maritime transportation risks (Aiello et al., 2020). Thus, this paper aims to capture the existing developments in the field and provide a clear guiding framework available to the researchers for their future works.

Specifically, we have focused on the following high-level research questions:

- What are the main risks faced by maritime transportation?
- What are industry 4.0 technologies currently implemented in maritime transportation?
- How do industry 4.0 technologies affect the mitigation of risks in maritime transportation?

To achieve our objectives, we have performed a systematic literature review (SLR) (Sepehri et al., 2021). This review focuses on studies published in reputable journals and refereed conference proceedings. Our elaboration consists of finding critical accident risks and the corresponding key industry 4.0 applications. Overall, our analysis shows an increasing attendance to shipping 4.0 concepts in controlling accident risks, as the relevant number of papers has increased significantly during the last two decades. We also found ship collision to be the most critical as well as the most attended risk so far. In terms of technology use, the automatic identification system is the most employed technology. This is followed by augmented reality and simulation, which is primarily used in ship design to manage various types of risks, and autonomous guidance and navigation technologies, which again focus on preventing collisions. Interestingly, we found an evident lack of cloud computing, internet-of-things, and big data analytics use, which play crucial roles in current industry 4.0 developments. Based on our analysis, we have also proposed a conceptual framework aiming to guide the future use of industry 4.0 technologies in controlling critical accident risks.

The rest of the paper uses the following structure. Section 2 explains the SLR methodology used in collecting and analyzing relevant papers in the literature. In section 3, key findings will be presented and discussed. In section 4, the development of the proposed conceptual framework is discussed, and its different elements are investigated. Finally, section 5 concludes the review by providing managerial and theoretical contributions and directions for future research.

2. SLR methodology

In this paper, a systematic literature review (SLR) is applied to collect and analyze the relevant papers, which is then used to develop a conceptual framework to guide future research employing the industry 4.0 technologies in mitigating vessel accident risks. The three main phases of our SLR framework (Fig. 3) include:

A) **Data Collection:** In this phase, an extensive search and filtering of relevant literature from the selected scientific databases using suitable keywords is performed (steps 1–4, Fig. 3). This phase is covered in detail in section 3.
B) **Literature Analysis:** A detailed analysis of the literature based on the impact of shipping 4.0 technologies on shipping risks and accidents is provided (steps 5–7, Fig. 3) in section 4, which is supported by descriptive analysis showing the publications' details in terms of years, targeted journals, subject areas, types of shipping accidents, and applied smart technologies. The extracted publications are then comprehensively reviewed resulting in identifying different categories of shipping risks and accidents and shipping 4.0 technologies.
C) **Framework Development:** The last phase of our study involves developing the conceptual framework (section 5). A methodology guides this framework development suggested in a review study on industry 4.0 by Kamble et al. (2018) that employed the seven steps methodology proposed by Tranfield et al. (2003).

3. Data collection

The data collection phase of our study is summarized in Fig. 4, which is designed based on the methodology proposed in Gil et al. (2020). In this first phase, we selected a scientific database based on its availability, coverage, relevance, and reputation. Accordingly, we chose Web-of-Science (WoS) and Scopus as our search databases. Relevant papers are found to be from well-known publishers, including Elsevier, IEEE, Springer, Taylor & Francis, Wiley, Emerald, and MDPI. The same sources are also found to be used in other industry 4.0 related studies (Nguyen et al., 2011).

We then identified the most relevant but general keywords applicable to our study, aiming for an unbiased and extensive literature search. That is, keywords related to the risks and accidents in shipping operations are derived from their categorization suggested in the European Maritime Safety Agency document (EMSA, 2017). Furthermore, keywords on industry 4.0 related to shipping are drawn from the categorization proposed in the paper by Aiello et al. (2020). Accordingly, selected keywords are divided into the following two categories.

Category 1: Industry 4.0, Maritime 4.0, Shipping 4.0, Cyber-physical systems (CPSs), Cloud systems, Big data analysis (BDA), Augmented reality and simulation, Smart shipping, Smart vessel, Artificial Intelligence (AI), Internet of Things (IoT), and Intelligent Robotics (IR).

Category 2: Hazardous material, Human error, Failure, Shipping Risk, Accident, Collision, Fire, Explosion, Hull damage, Machinery damage, War loss, Grounding, Oil spills, and Personal accidents.

Using the above keywords, we then performed the literature search in WoS and Scopus. Based on combinations of extracted keywords, a search query is defined to obtain relevant papers focusing on the application of shipping 4.0 in controlling maritime risks. The searching was last conducted on January 10, 2020 using the following query:

Query: RI = ("industry 4.0$" OR "maritime 4.0$" OR "shipping 4.0$" OR "cyber physical$" OR cloud$ OR "big data$" OR "augmented reality $" OR "simulation$" OR smart$ OR AIS$ OR ECDIS$ OR AGN$ OR GPS$ OR VDR$ OR VTS$ OR ARPA$ OR IBS$ OR IR$) AND RI = (maritime OR ship* OR vessel$) AND IR = (accident$ OR hazardous$ OR "Human error$" OR Failure$ OR Risk$ OR Accident$ OR Collision$ OR Fire$ OR Explosion$ OR "Hull damage$" OR "Machinery damage$" OR "War loss $" OR Grounding$ OR Spills$

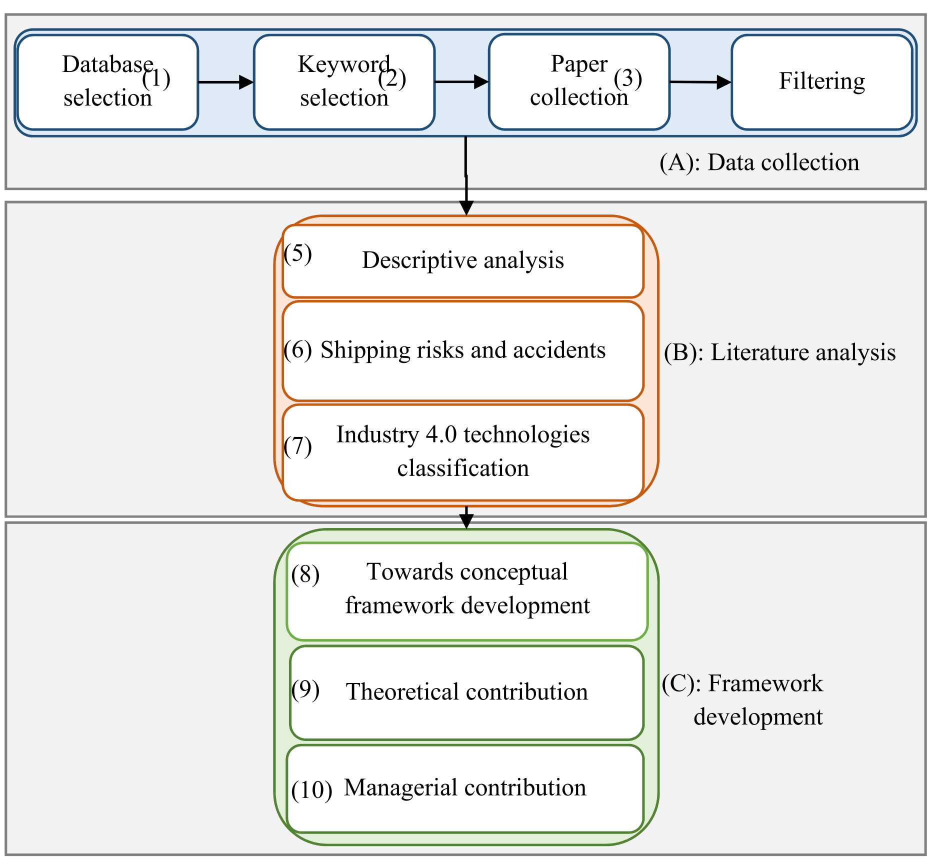

Fig. 3. Main Steps in our SLR Methodology.

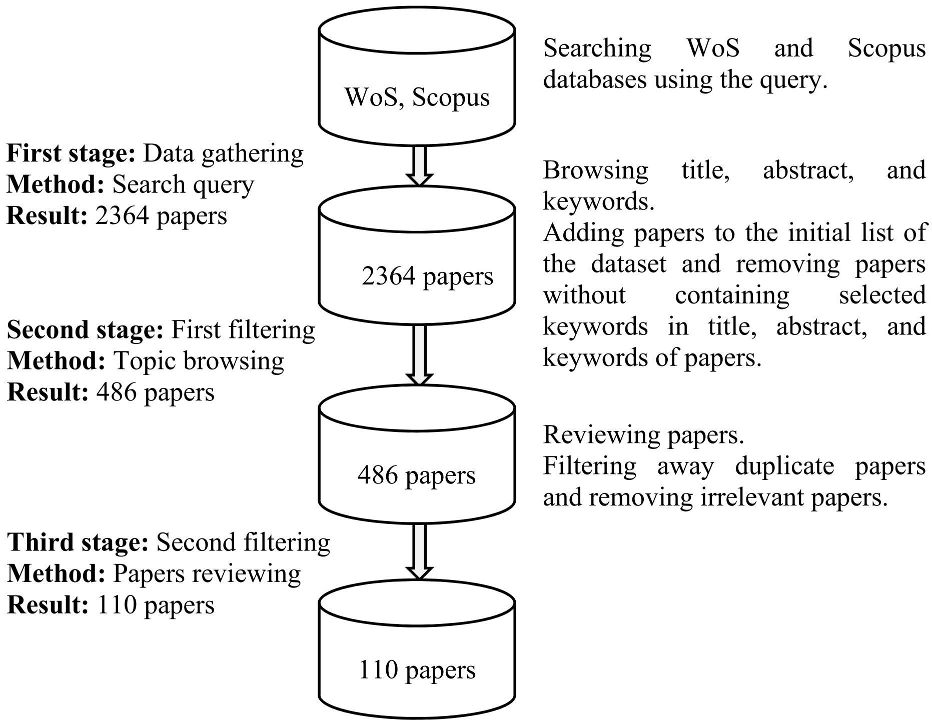

Fig. 4. The progress of data sampling.

No restriction on the years of publication was considered. However, after a preliminary analysis, it is found that the papers concentrated on industry 4.0 are published mostly post the year 2000. After filtering applied to the title, keywords, and abstract, 110 papers were shortlisted for complete analysis.

4. Literature Analysis

As proposed in Fig. 3, steps 5 to 7 in the second phase pertain to a detailed analysis of the selected literature. The analysis was conducted from **three angles**. The **first angle** focuses on the descriptive analysis of the literature. This includes publications over the years, distribution amongst publishers, paper types, journal subject areas based on the Web of Science, and the countries where the research is originated. The **second angle** aims at delineating classification schemes for maritime risk and the related industry 4.0 technologies. Finally, in the **last phase**, we present the proposed conceptual framework that would guide future research.

4.1. Descriptive analysis

This section provides a demographical analysis of the collected literature to find the year-wise trend, contributions by publishers and journals, paper and subject area focus, and contributors' origins.

The number of papers published during the last twenty years is analyzed (Fig. 5). There is not much activity in the first decade, i.e., during 2001–2010. A significant rise can be seen in the following decade showing the increasing importance of investigating the shipping 4.0 concept and its impact on controlling shipping accidents, which is also in line with a recent bibliometric study conducted by Gil et al. (2020). The increasing publication trend indicates that it has become a critical area to investigate and it can be predicted to receive more attention in the

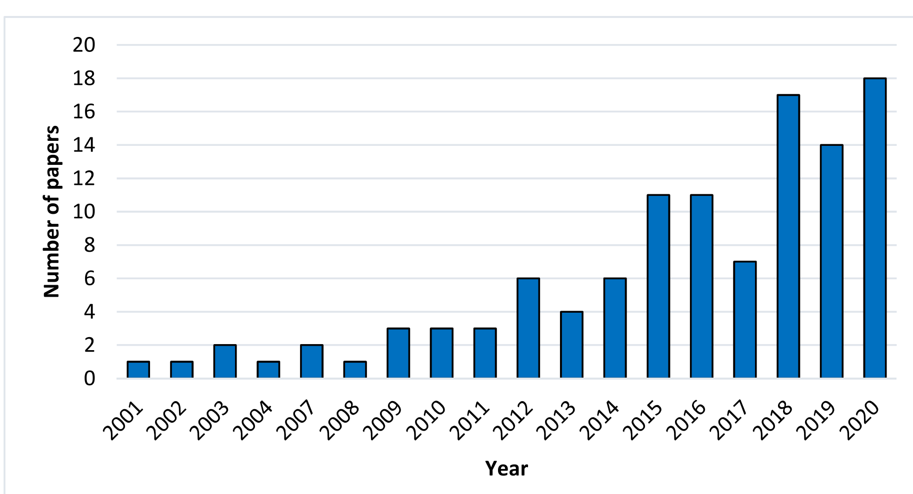

Fig. 5. Year-wise publication details.

future.

These publications are spread across various journals and referred to conference proceedings from different publishers. Analyzing the distribution of papers published by journals, we found that with 22 papers, Ocean Engineering published the most (Fig. 6), followed by Safety Science and the Journal of Navigation with 4 publications. Journal of Marine Science and Engineering, Sensors, Transportation Research Part D: Transport and Environment, Accident Analysis & Prevention, IEEE Access, are other major journals with at least two publications, while thirty-two more journals have published one paper each. Moreover, the time-wise dynamics of most relevant sources published by the journals with at least three publications are shown in Fig. 7. The data can assist scholars to identify prolific platforms hosting the related papers and find insights to elaborate their interest in the related topics. Publishing journals on the ocean and marine engineering are taking the lead having Ocean Engineering the most active journal alongside The Journal of Navigation and the Journal of Marine Science and Engineering. Similarly, journals in safety and reliability are the next popular ones, with Safety Science and Accident Analysis and Prevention taking the lead. Moreover, the journals from control engineering, computer, and data science are also identified as potential outlets to provide the related works.

Since risk and shipping 4.0 are multidisciplinary areas that can be addressed from various technical to socioeconomic perspectives, we analyzed the subject areas of the journals and conferences so that some bearing on the existing research directions can be set. To do so, we identified Web of Science subject areas of the analyzed journals and determined their occurrence frequency. The most frequent subjects are ocean studies (which accounts for around 48% of studies), followed by computer science and information systems (19%), and safety, risk, and reliability (13%) (See Fig. 8). This also can help scholars to identify the currently active areas and the emerging and potential areas of interest by the related research communities.

Finally, in terms of the first author's affiliations by country, we note that the three largest academic contributions came from the Republic of China, the Republic of Korea, and Norway (See Fig. 9). There are twenty-two other countries on the list with at least one contribution. Most of these countries have traditionally shown high maritime activity and development. The papers across different countries indicate that the interest in this topic is increasing among scholars in different geographical regions.

4.2. Shipping risks and accidents

The term **risk** can take a plethora of definitions (Aven, 2012). However, in the maritime context, we resort to its definition used by the International Maritime Organization (IMO), as provided in their Formal Safety Assessment guidelines (Goerlandt and Montewka, 2015b; IMO, 2015). Therein, the risk is seen as a combination of severity and probability of an unwanted event. Initially, it has been designed to facilitate IMO's rule-making process, i.e., to assess the risk mitigation effectiveness of new rules and regulations compared to earlier or existing regulations. However, it later spread to various areas of maritime, including:

– risk-based ship design (Krata and Jachowski, 2021; Kujala et al., 2018; Vassalos, 2009)
– risk-informed maritime spatial planning (Jolma et al., 2014; Santos et al., 2013)
– risk-based planning of ship operations (Banda et al., 2016; Goerlandt and Montewka, 2015a; Montewka et al., 2014)
– risk-informed ship routing (Krata and Szlapczynska, 2018; Lehtola et al., 2019; Siddiqui et al., 2018; Siddiqui and Verma, 2015; Szlapczynska and Szlapczynski, 2019)
– automatic detecting high-risk vessels (Antão and Soares, 2019; Balmat et al., 2009)

Under this definition, the risk of any maritime accident related to the above groups can be estimated by employing a function comprising the probability of accident occurrence and the corresponding potential consequence. The overall idea is to use these estimates to design an object or an activity while complying with the allowable regulatory risk levels (Psarros et al., 2011; Vanem, 2011). That is, aiming for the occurrence of accidents to be minimized and their consequence mitigated (IMO, 2015; Montewka et al., 2014; Puisa et al., 2021).

Clearly, the root of such an analysis lies in potential accidents, different types of which may have different probabilities of occurrences and consequences. It is thus essential to know their types and the corresponding contributing factors. The annual overview of marine casualties and incidents report published by the European Maritime Safety Agency (EMSA, 2017) reveals that in a period between years 2014–2017 the navigational accidents, such as collision, contacts, and grounding represent 44% of all accidents, loss of control takes 32% of accidents, fire represents 7%, while 2% of accidents are due to flooding. Moreover, 54% of the accidents are attributed to human action, while 28% to system/equipment failure, as shown in Table 1. While analyzing the accidents, several contributing factors (CF) were identified and categorized, showing that 65% of the factors are associated with shipboard operations, 27% relate to shore management, while 8% are taken by the external environment.

Accordingly, different shipping accidents are classified in the literature as collision, foundering, fire/explosion, grounding, and oil spills (Mrozowska, 2021). The distribution of shipping accidents according to this classification is illustrated in Fig. 10. To find the number of shipping accidents in the sample papers, first, those papers are counted which focused mainly on a single accident. Then, papers that focused on multiple accidents have been analyzed to find what their major focused accident is. For instance, a paper might mention collision and grounding, whereas the concentration of the paper was mainly on collision according to the title, abstract, and keywords. However, in cases that the concentration could not be determined, both accidents are considered. The results indicate that ship collision is the leading cause, which is followed by oil spills and ship grounding. Flooding and fire are the least attended accident in the literature. The latter can be explained by the fact that the flooding and fire are mainly covered by the literature related to passenger ships, forming a small portion of the worldwide fleet.

To control the risks of these accidents and mitigate their corresponding human, property, and other losses, shipping 4.0 technologies and methods are increasingly employed. The upcoming section discusses the most frequent shipping 4.0 applications and technologies aiming to increase maritime transportation safety.

4.3. Shipping 4.0 applications and technologies

According to Aiello et al. (2020), applying cyber-physical systems associated with offshore and onshore maritime systems leads to developing sensors, actuators, and autonomous vessels to reduce the possibility of risk occurrence. Therefore, a classification of the application of industry 4.0 in maritime transportation is proposed as elaborated in the following subsections (Aiello et al., 2020).

4.3.1. Cyber-physical systems (CPSs)

According to Rodríguez-Molina et al. (2017), cyber-physical systems in maritime transportation are technologies that interconnect physical and computational infrastructures. Other industry 4.0 applications such as big data analytics and the internet of things can be utilized within cyber-physical systems to manage the enormous amount of data for interpretation and smart vessels development (Lee et al., 2015). Accordingly, sensors, actuators, software, and communication technologies are all classified as cyber-physical systems that can be used to develop autonomous vessels, aiming to mitigate the risk of accidents besides other objectives (Brinkmann and Hahn, 2017). The most

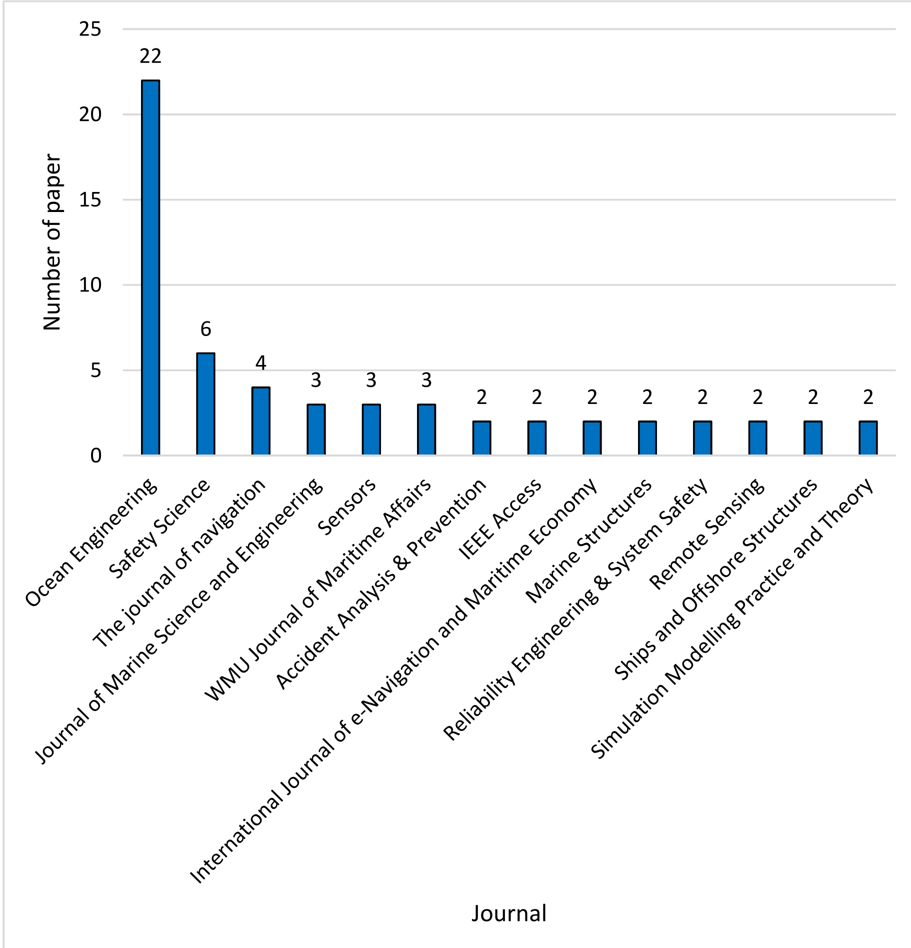

Fig. 6. Contributions from journals.

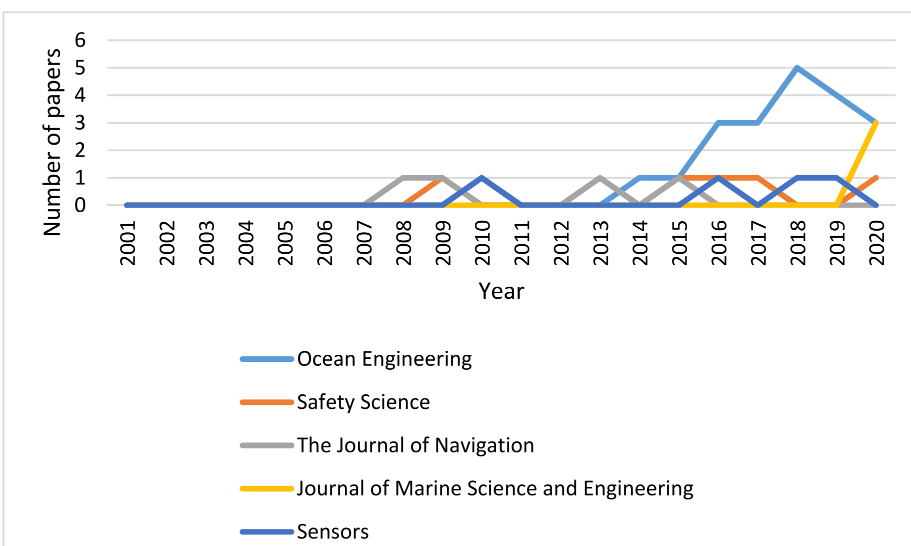

Fig. 7. The time dynamics of papers in the journals with at least three relevant publications.

relevant cyber-physical systems applicable in vessels are classified in Table 2 – as suggested in Aiello et al. (2020). One of the main concerns regarding cyber-physical systems is their potential vulnerability to cyber-attacks, especially in the case of piracy where cyber-physical devices can be attacked compromising the ship navigation control (Bae et al., 2016). In this case, cyber-security platforms are becoming increasingly significant to cover this drawback and protect vessels against these threats (Kavallieratos and Katsikas, 2020).

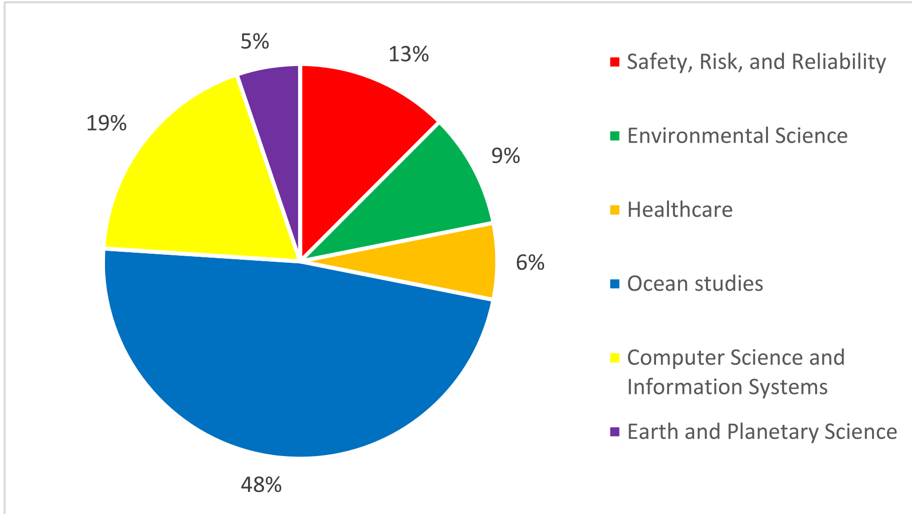

Fig. 8. Distribution of journals' subjects.

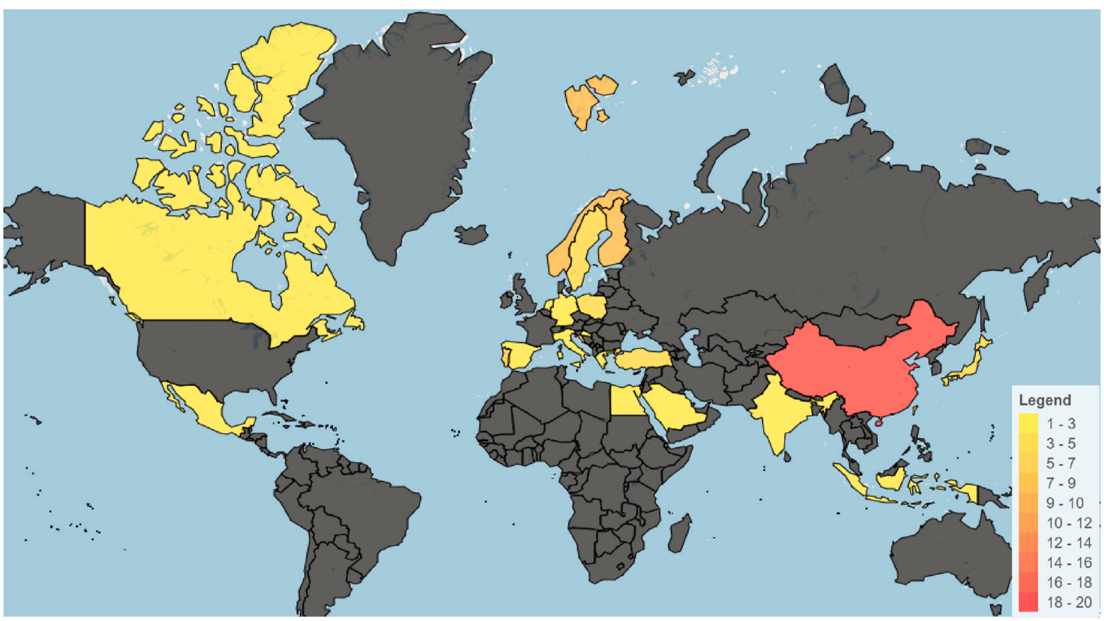

Fig. 9. Country-wise publication details.

Table 1
Relationship between accidents and contributing factors (EMSA, 2017).

Accident event types	Number of contributing factors	Contributing factors categories involved in each accident events type		
		External environment	Shipboard operation	Shore management
Hazardous material	158	1	101	56
Human action	2386	79	1749	558
Other agent or vessel	385	204	85	96
System/ equipment failure	701	6	432	263
Unknown	10	0	5	5
Total	3640	290	2372	978

4.3.2. *Augmented reality (AR) and simulation*

According to Takenaka et al. (2019), augmented reality is an abstract view of the environment that can be developed using a real-world database to make the actual environment more tangible (Carmigniani et al., 2011). This technology can utilize 3D computer graphics technology and virtual reality to detect congestions (Jaeyong et al., 2016). However, the overall goal is to improve operator performance, situational awareness, closed-loop communication, and source diversity. Nevertheless, it may increase workload while causing possible distractions (Rowen et al., 2019; Stanton et al., 2016). Despite its advantages, AR's application in day-to-day ship operations remains limited (de la Peña Zarzuelo et al., 2020). However, it is becoming widely applicable in seafarers' training and within the shipbuilding industry (Liu et al., 2020; Vargas et al., 2020). When training the personnel, augmented reality can help determine their performance when confronting a challenging situation such as an accident (Park et al., 2020). The mentioned determination can be performed by simulating vessels' behavior in a range to identify the probability of an accident.

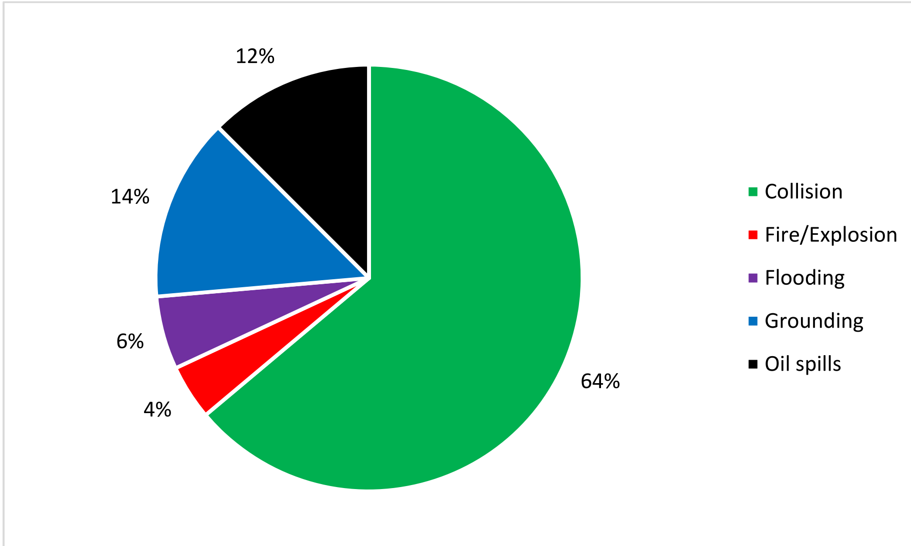

Fig. 10. Distribution of shipping accidents.

Simulation of ships' behaviors and movements in the maritime domain can be used in numerous areas, which can be divided into two broad groups: (1) area-centric; (2) ship-centric. First, considering from the perspective of maritime authorities, simulation can be used to determine locations dangerous for navigation (Goerlandt and Kujala, 2011; Hara and Nakamura, 1995; Vaněk et al., 2013; Xiao et al., 2012), in ship scheduling to avoid congestions (Li et al., 2021), to estimate the probability and consequences of maritime accidents needed in risk assessment (Park et al., 2020), or in designing the optimal shape of waterways (Gucma and Zalewski, 2020; Quy et al., 2020). Second, from a ship's perspective, it can be used to develop detailed instruction on the optimal and safe use of pathways (Kotovirta et al., 2009; Krata and Szlapczynska, 2018; Lehtola et al., 2019; Szlapczynska and Szlapczynski, 2019), in providing early warnings for sea conditions leading to dangerous ship behaviors (Acanfora et al., 2018; Acanfora et al., 2017a, b; Galeazzi et al., 2012), or in developing design limits for a ship (Azzi et al., 2011; Gil, 2021; Kujala et al., 2019; Montewka et al., 2019; Zhou et al., 2016). Adopting AR and simulation at an early stage for all the above applications allows significant improvements at a relatively low cost. However, using AR and simulation can also have their own drawbacks. Although AR and simulation can increase crew readiness toward shipping accidents, they fall short of simulating the psychological aspect of the accident. For instance, in the case of severe fire, the crew might not act as effectively as directed by the simulation model as it may be challenging to consider stressful conditions in its calculation. Also, multiple interpretations can be obtained from an AR experiment, and there are technical limitations in terms of their implementation process such as hardware issues, monitoring/sensing challenges, and data transmission and storage problems (Ratcliffe et al., 2021).

4.3.3. Big data analysis (BDA)

"*Big data analytics examines large amounts of data to uncover hidden patterns, correlations and other insights*" (SAS,). This is done to facilitate and manage various processes related to a wide range of maritime activities (Gandomi and Haider, 2015). Other areas where BDA provides value are network design, container routing, and bunker purchasing (Brouer et al., 2016). The data obtained from monitoring the routes and processes can determine the congestions in maritime routes. Therefore, the risk of accidents, the length of travel time, and the number of carbon emissions can be mitigated (Cárdenas-Benítez et al., 2016). It can also be used to divide maritime areas into clusters of varying congestion levels, which can be used to regulate the transportation of vessels and their time of travel (AbuAlhaol et al., 2018; Silveira et al., 2021; Zhou et al., 2020). Similarly, the recorded maritime traffic data, obtained from AIS, can be analyzed in indicating demanding sea areas for navigation (Goerlandt et al., 2012; Mazaheri et al., 2015a; Rong et al., 2015; Wu et al., 2017; Zhang et al., 2016, 2021); in evaluating ship flow parameters in extreme weather conditions, (Goerlandt et al., 2017; Lensu and Goerlandt, 2019; Li et al., 2017; Montewka et al., 2019; Zhang et al., 2019a); and in learning the preferences of ship navigators, which in turn can be used in the development of control algorithms of prospective autonomous vessels (Hörteborn et al., 2019; Murray and Perera, 2021; Pietrzykowski and Wielgosz, 2021; Rawson and Brito, 2021).

Implementing BDA can also have its own drawback. Its algorithms can be challenging to interpret and explain as the model "learns" and develops its algorithms based on the trained data (Williams et al., 2021). For instance, Artificial Neural Networks (ANN's) are a type of AI modality that utilizes interconnected processors to mimic a human brain's neurons. The algorithm for an ANN is not determined by the programmer; rather, the machine "learns" the relationships between variables and develops its own rules by which it makes decisions, which are usually not easily readable by humans. Along with the difficulties in the interpretation of big data, the flexibility of databases differs from one case to another. Besides, the obtained outcome from BDA might not be consistent due to the quality issues faced by the high volume, variety, and velocity of data (Abed, 2020).

4.3.4. Cloud computing (CC)

Cloud computing is a platform for storing large amounts of data while sharing flexibly amongst different stakeholders (Dillon et al., 2010). Cloud computing in the maritime domain is referred to as the maritime cloud, which is a vital part of modern e-Navigation systems (IMO, 2015). The latter is defined as "*the harmonized collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment.*"[1]

Thus, the maritime cloud is utilized two-fold. First, it facilitates exchanging relevant information and documents between relevant maritime stakeholders (e.g., company, agent, authority). Second, it improves the efficiency of ship operations, for example, by the continuous analysis of ship parameters and advising on the optimal trim of a

[1] https://www.imo.org/en/OurWork/Safety/Pages/eNavigation.aspx.

Table 2
Cyber-Physical Systems applicable in maritime transportation.

Cyber-Physical System	Description	Applications
Automatic Identification System (AIS)	A real-time vessel tracking database, reporting vessel characteristics such as location and velocity	Collision avoidance, optimizing navigation, and monitoring ship movements (Andersson and Ivehammar, 2017; Jafarzadeh and Schjølberg, 2018; Jiacai et al., 2012; Lei, 2020)
Electronic Chart Display and Information System (ECDIS)	A navigational support system to pinpoint locations and directions	Navigational safety by connecting different navigational datasets for route planning, execution, and monitoring, (Porathe et al., 2013; Tsou, 2016)
Autonomous Guidance and Navigation (AGN)	An autonomous vessel navigation system	Obstacle detection to avoid accidents using intelligent decision making (Burmeister et al., 2014; Naeem et al., 2016)
Global Positioning System (GPS)	The first navigation system that determines a vessel's location	Navigational safety through accurate and reliable data on position, navigation, and time. (Huang et al., 2020; Ozturk and Cicek, 2019)
Voyage Data Recorder (VDR)	A recording system for vessel movement data that records the data from AIS and ARPA to provide a full picture of the nearby traffic	A post-accident investigation by collecting relevant data from vessel's instruments (Cantelli-Forti, 2018)
Vessel Traffic Service (VTS)	A system to monitor traffic in coastal waters and ports	Accurate awareness of surrounding maritime traffic and relevant hydro-meter conditions (Praetorius et al., 2015; Zhang et al., 2020b)
Automatic Radar Plotting Aids (ARPA)	A supportive navigation system that detects the number of vessels within a radius	Collision avoidance by calculating proximity indicators based on input from marine radar, (Bole et al., 2013; Chin and Debnath, 2009; Ma et al., 2015)
Integrated Bridge Systems (IBS)	A series of interconnected and closely coupled screens and modules allowing centralized monitoring and access to navigation, propulsion, and vessel controls	Navigational safety by combining all relevant ship systems under one overarching system, providing space for all-in-one information display and control, improving navigator's performance (Grabowski, 2015; Perera and Soares, 2015), (Veritas, 2003)
Intelligent Robotics (IR)	A system used for cleaning and maintenance to fully autonomous vessels with no pilot, no captain, and no crew on board	Developing autonomous shipping to decrease the possibility of failures and mitigate the risk of accidents (Campbell et al., 2012; Moe et al., 2020), collecting the oil spills which is dangerous for workers exposed to chemicals, toxic fumes, and a high risk of fire or explosion (Rathour et al., 2016)

ship to reach the desired efficiency,[2] and mitigate the associated risks by delivering an optimal route, calculated based on the most recent information; informing the operator in advance about the unwanted developing scenarios (Dellios and Papanikas, 2014); and providing information about the consequences of a given accidental scenario (Pennanen et al., 2015; Ruponen, 2017; Ruponen et al., 2019). Video information can also be obtained, while the information can be stored in mobile applications or over a cloud. Furthermore, a database can be provided to identify other ships and obstacles and message the responsible people to avoid accidents (Lee and Park, 2017). Also, external information such as weather can be assimilated and stored using mobile applications (García-Domínguez, 2015).

While using cloud computing onboard ships can bring numerous advantages, technical and security issues can be considered as the main drawbacks in the implementation process. Although information and data stored on the cloud are readily accessible, there is a possibility of communication failures as well as its vulnerability to cyber-attacks and threats which needs to be thoroughly considered by shipping companies (Subramanian and Jeyaraj, 2018). Apostu et al. (2013) identified various drawbacks of using cloud computing in organizations such as technical issues, security in the cloud, prone to attack, possible downtime, cost, inflexibility, and lack of support which shipping companies should be aware of these issues before the implementation process.

4.3.5. Internet of things (IoT)

The Internet-of-Things or IoT paradigm uses different objects such as sensors and actuators to better connect different vessels in a specific area (Atzori et al., 2010). IoT can help maritime industries to increase their outputs and productivity by facilitating data analysis (Wang et al., 2015). Using IoT, different clustered areas can be defined, and congested clusters can be detected to inform the vessels to avoid those (Xia et al., 2020). Moreover, determining the vessels' behavioral characteristics using IoT can reduce the probability of congestions. It is also helpful in detecting security threats to avoid piracies and terrorism and improve situational awareness by relevant data and information exchange (Jiang et al., 2019; Martínez de Osés et al., 2015; Thombre et al., 2015, 2016).

While using IoT is undoubtedly is beneficial for shipping companies, it can also result in some issues. One of the disadvantages of using IoT in shipping industries is that the accuracy of data analysis in IoT systems varies over time (Zhang et al., 2018a). Besides, the cost of implementing IoT is very high, and the enhancement of shipping might not be as significant as its value addition. Protecting the IoT is a complex and difficult task. The number of attack vectors available to malicious attackers might become staggering, as global connectivity and accessibility are key tenets of the IoT. The threats that can affect the IoT entities are numerous, such as attacks that target diverse communication channels, physical threats, denial of service, and identity fabrication (Roman et al., 2013).

4.3.6. Shipping 4.0 in literature

While we identify various shipping 4.0 areas in the above sections, we note that all areas have not received equal attention. To depict the progress so far, we refer to Fig. 11, which shows the distribution of papers found on shipping 4.0 applications and technologies. The most attended technologies are AIS, AR, and simulation, which are covered in almost half of the reviewed papers. Other shipping 4.0 technologies that received significant attention are AGN, IR, ECDIS, CTS, ARPA, and BDA, which are discussed in at least five of the reviewed papers. The same approach as we used in counting the number of accidents, we identified and counted the focus on a single technology by the papers, while for papers that have addressed multiple technologies, we counted accordingly.

[2] https://www.wartsila.com/eniram.

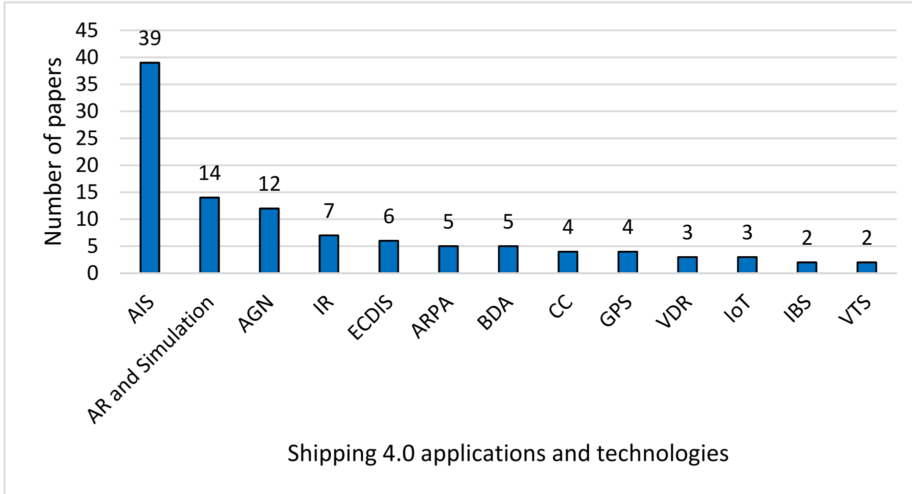

Fig. 11. Shipping 4.0 applications and technologies.

5. Towards a conceptual framework

In sections 4.2 and 4.3, we elaborated on various types of accidents faced by the maritime industry as well as industry 4.0 technologies for improving maritime operations. Based on our analysis of these two dimensions, we now present the existing research landscape that delineates the use of shipping 4.0 technologies to mitigate accident risks.

Specifically, we analyzed the literature regarding how certain technologies so far have been employed in tackling particular accident risks. The resulting landscape is laid out in Fig. 12. Overall, we found that the accident types discussed in section 4.2, i.e., collision, foundering, fire/explosion, grounding, and oil spills, have all been addressed, though to a varying extent. We also found some works considering accidents in general, so we identified this in Fig. 12 accordingly. Similarly, all shipping 4.0 technologies, including cyber-physical-based systems (Table 2), augmented reality and simulation, big data analysis, cloud computing, and the internet of things (discussed in section 4.3), are utilized – though again with a varying degree. In terms of employment of particular technology use in mitigating specific accident risks, we found that focus largely remained on the preventions of ship collisions (~45% of papers) via cyber-physical systems – especially the Automatic Identification Systems or AIS. Use of other systems with at least five works in this direction was Autonomous Guidance and Navigation or AGN, and Automatic Radar Plotting Aids or ARPA systems. This skewness towards collision accidents makes sense as it makes up to 67% of accident types (Fig. 10). Unlike collision, all other accident types have received scant attention, with merely nine papers found on spills, most of which are focused on intelligent robotics, followed by grounding, flooding, and fire/explosion accidents.

From the technology perspective, the most frequent system referred to in the scientific literature so far in the context of accident risk mitigation is AIS systems, followed by AR & Simulation and AGN systems. The systems which have received the least attention in the scientific community are Integrated Bridge Systems, GPS, and Voyage Data Recorder despite their potential and actual onboard application and Internet-of-Things. To discuss how each of shipping 4.0 technologies has specifically addressed various accidents, we analyze related literature contributions on each of these systems in the following sub-sections. We also comment on the potential applications of each of these technologies, which have remained unaddressed. Finally, we consolidate our discussion into a framework, which would guide researchers and managers on the scope and directions of existing work and the current significant gaps.

	Accidents→ ↓Technology	Accidents in general	Collision	Flooding	Fire/Explosion	Grounding	Spills	Total
Cyber Physical Systems	AIS	12	21	1		2	1	37
	ECDIS		4			2		6
	AGN	3	9					12
	GPS	2	1					3
	VDR	2	1					3
	VTS	4	2					6
	ARPA		5					5
	IBS	1	1					2
	IR		2				5	7
	AR & Simulation	6	3	2	3	3		17
	BDA	2		1			2	5
	CC	4						4
	IoT	2					1	3
	Total	38	49	4	3	7	9	110

Fig. 12. Shipping 4.0 technology to accident risk mitigation research landscape.

5.1. Automatic identification system (AIS)

Automatic Identification Systems are real-time vessel tracking and information exchange system on vessel characteristics and their motion parameters. A key aspect of the AIS system is transmitting accurate ship speed, position, and course every few seconds. This data can be used in accident avoidance via early detection of potential situations (Bye and Almklov, 2019; Qu et al., 2011).

For instance, to determine the probability of possible collisions with obstacles, AIS utilizes three factors: 1) the closest point of approach (CPA), which indicates the distance to the nearest obstacle, 2) time to the closest point of approach (TCPA), which indicates the time required to reach the nearest obstacle, and 3) encounter angle (EA) which indicates the angle at which the vessel and obstacle collide (Chen et al., 2015; Mou et al., 2010; Zaman et al., 2015; Zhang et al., 2015, 2016, 2018b). Moreover, AIS is an effective means to obtain data on steering intentions, liability discrimination (e.g., intentional human errors), and assessing the present situation (Altan and Otay, 2018; Wang et al., 2013). AIS is also helpful in the avoidance of collisions within ship clusters. Various approaches have been used, including game theory for collision within a cluster (Gao and Shi, 2020b; Liu et al., 2019). Moreover, Velocity Obstacle (VO) models that measure the velocity of a vessel and its obstacles can be utilized to identify collision candidates using the AIS trajectory database (Chen et al., 2018). Subsequently, these indices are used to increase situational awareness and facilitate collision avoidance actions in due time (Ożoga and Montewka, 2018; Tijardovic, 2009; Wawruch, 2018).

The probability of ship-ship collisions can be determined by analyzing AIS data on trajectories alongside other factors such as human performance, weather, and technical problems (Mulyadi et al., 2014; Schröder-Hinrichs et al., 2012).

AIS can also provide data useful in vessel dynamics visualization models, i.e., applicable in determining the rate of ship turn, speed acceleration, and ship encounters (Jiacai et al., 2012; Wang et al., 2020). This data can also analyze colliding ship trajectories in congested ports or waterways (Altan and Otay, 2018; Gao and Shi, 2020a; Kim and Lee, 2018; Lei, 2020; Silveira et al., 2013; Zhang and Meng, 2019). It can also improve planning estimates such as extent anchoring in managing port congestion (Andersson and Ivehammar, 2017).

To elaborate on the anticipated grounding accidents, a combination of the AIS database, vessel registry, and high-resolution maps can be employed on adjusting the location, course, and velocity of different vessels (Bakdi et al., 2020). Grounding can be classified as a navigation-related accident. An integration of accident database with AIS data can be employed to define specific variables that cause grounding accidents (Bye and Aalberg, 2018; Mazaheri et al., 2015a, 2015b, 2016).

AIS data can also help in analyzing flooding and foundering accident risks and the corresponding ship behavior. In this regard (Inazu et al., 2018), demonstrated the use of AIS data from 16 vessels during the 2011 tsunami near Tohoku, Japan. They concluded that the AIS data helps estimate the source of a tsunami and forecast its occurrence. AIS can also monitor oil waste discharge location and identify the ship responsible for it (Eide et al., 2007; Schwehr and McGillivary, 2007).

Overall, AIS integrated with big data analytics can be used in developing and testing safety criteria. These criteria can also be operationalized via AIS and other related systems such as VTS (Goerlandt et al., 2017; Similä and Lensu, 2018; Zhang et al., 2019b) and simulations (Kuuliala et al., 2017; Montewka et al., 2019; Zhang et al., 2017). It may also provide relevant knowledge to the ship crew going into a new operation area (Son et al., 2020; Zhang et al., 2020a).

5.2. Electronic chart display and information system (ECDIS)

ECDIS plays a central role in navigating a ship nowadays, combining bathymetric, navigational, and hydro-meteorological data in one space, (Jincan and Maoyan, 2015; Pillich and Buttgenbach, 2001). This is done to ensure safe and efficient navigation of a ship, making the solo watch easier and safer by reducing navigator workload, thus improving their performance (Porathe et al., 2013; Tsou, 2016).

The ECDIS system can also be integrated with other navigational systems such as AIS and ARPA for monitoring and avoiding potential grounding areas during navigation and collision-avoidance manoeuvers (Nguyen et al., 2011). However, proper settings of the device and related alarms are crucial for that purpose (Turna and Öztürk, 2020).

Additionally, ECDIS can help to find a suitable “navigational window”, where a vessel can steam through demanding waters in critical hydro-meteo conditions (Pillich et al., 2003). This is especially relevant nowadays, in the presence of the growing congested routes and ports worldwide.

5.3. Autonomous guidance and navigation (AGN)

Various techniques are proposed in the literature for autonomous guidance and navigation of ships, and the topic is on the rise (Perera et al., 2009, 2014), intending to improve maritime safety by suppressing human error, which has been recursively cited as a major cause of ship accidents (Statheros et al., 2008).

The autonomous vessel navigation employs various models accounting for a range of obstacles, with varying degrees of dynamics (Geng et al., 2019), and adopting multiple techniques and methods, such as deep learning - (Perera, 2018), collision potentiality of a location (He et al., 2017), or virtual force field (VFF) method for track-keeping in case of a collision. Overall, AGN regulates ship routing to avoid collisions and preventing damages (Lee et al., 2004; Perera et al., 2011; Thieme et al., 2018). For the scenario of congested ports and narrow waterways, AGN can use trajectory data to navigate autonomously based on optimal route selection (Burmeister et al., 2014; Naeem et al., 2016; Zaccone and Martelli, 2020).

5.4. Global navigational satellite systems

Global navigational satellite systems such as GPS, GLONASS, or Galileo offer reliable and continuous services in the following areas: positioning, navigation, and timing (Perera et al., 2014; Yim et al., 2019). Obviously, all these are crucial when it comes to informing a navigator about the motion parameters of a vessel, increasing thus situational awareness, and contributing to the reduction of the probability of accidents, such as grounding (Huang et al., 2020; Ozturk and Cicek, 2019; Thombre et al., 2020).

5.5. Voyage Data Recorder (VDR)

VDR records a vessel’s location and operational information collected from different data onboard systems. The recorder itself is placed in protective storage to stand severe shocks, pressure, and heat associated with shipping accidents (Morsi et al., 2010). The primary role of VDR in collision accidents is playing back the recorded data after the accident (Piccinelli and Gubian, 2013). The data collected by VDR tend to provide a full picture of the situation prior to the accident, delivering information about the own ship’s systems as well as surrounding traffic (Ren and Huang, 2010).

5.6. Vessel traffic service (VTS)

VTS is a system for monitoring maritime traffic over a given area that combines information from multiple sources, such as radar or network of radars, AIS, electro-optical sensors, and gateways to identify, represent and analyze interactions in a maritime environment (Ficco et al., 2018). In this regard, three distinct service levels are defined. The first level is for sharing information with all vessels (information service (INS)), the second is information about the geographical conditions (traffic organization service (TOS)), and the optionally third is assisting the ships to have a safe passage (navigational assistance service (NAS)) (Praetorius et al., 2015).

5.7. Automatic Radar Plotting Aids (ARPA)

ARPA is mainly classified as a radar-based collision-avoidance system (CAS) that employs the closest point of approach (CPA) and the time to the closest point of approach (TCPA). The system can detect other ships within a preset range, determine their proximity indicators and suggest the safe motion parameters to avoid the risk of collision with other ships and objects (Chin and Debnath, 2009; Lisowski and Mohamed-Seghir, 2019; Ma et al., 2015). Also, novel solutions based on APRA-generated information are proposed, adopting new proximity matrices, such as a range of course at risk (RCR) and a range of speed at risk (RSR) (Shi et al., 2008).

5.8. Integrated Bridge Systems (IBS)

Integrated bridge system (IBS) can be considered as a major tool within the e-Navigation concept, that comprises of "*a series of interconnected and closely grouped screens and modules allowing centralized access to navigational, propulsion, control and monitoring information*", ("Integrated Bridge Systems (IBS)" n.d.). The overall aim of IBS is to increase safe and efficient ship management by the qualified personnel, leading to improved performance of a navigator (DNV, 2019; Grabowski, 2015; Kim et al., 2020; Perera and Soares, 2015).

Adopting IBS on-board a ship allows navigators on duty to better focus on the tasks to be performed, by monitoring and following the indicators of all relevant, but distributed systems in one place. Such an approach certainly improves the performance of navigators, thus the safety of maritime transportation (Pazouki et al., 2018). It makes one-person shifts possible without putting too much mental workload on a navigator, significantly contributing to reducing the bridge crew, not deteriorating the level of safety at the same time. Additionally, IBS can ensure proper coordination between different maritime actors (Costa et al., 2018).

5.9. Intelligent robotics (IR)

Robots are utilized in maritime transportation for different uses, for example, the most frequent applications are associated with the ongoing development of autonomous shipping and collecting oil spills.

To outline the first application of robots, artificial intelligence is adopted in vessels to navigate autonomously and detect the obstacles around the vessels. In this case, data are collected from AIS and ARPA devices to propose an intelligent decision-making framework that makes optimal decisions. Hereof, the shortest and safest path is selected and the costs associated with maritime transportation are expected to be minimized (Campbell et al., 2012), through the reduction of operational costs and costs associated with the anticipated accident (Moe et al., 2020; Wróbel et al., 2017; Ziajka-Poznańska and Montewka, 2021). In this regard, autonomous shipping is defined as a platform that enables guiding the ships with various levels of autonomy.

Another application of robots is cleaning and maintenance. Hereof, cleaning robots are employed to detect oil spills that occurred in shipping accidents (Guerrero-González et al., 2016). Robots using the AIS database and AGN system can transmit the information of spills on their location, extent, direction, and speed. Adaptive navigation systems and long-term mission capabilities are significant advantages of intelligent robotics (Rathour et al., 2015, 2016). Robots can also be used as self-guiding skimmers to clean up oil spills and prevent wider spreading (Zahugi et al., 2012).

5.10. Augmented reality (AR) and simulation

Augmented Reality (AR) toolkits are on the rise recently, and their application area is expanding. First, they are used for training of seagoing crew, increasing the safety of ship and navigation. As most ship accidents are related to human errors and especially the navigators' faults, simulating navigators' decisions can help better analyze their behaviors and decrease wrong decisions (Park et al., 2020). Maritime simulators are widely used for this purpose, mimicking the relevant scenarios usually encountered on the ship's bridge and engine room. On top of the simulated scenarios, a new layer of information can be added, augmenting thus the real situation, which can help to indicate the object's location, the velocity of the surrounding ships, and prediction of the ship movement as well as the potential risk of collision (Takenaka et al., 2019). These systems can also be used as supportive navigation systems on congested routes and ports (Jaeyong et al., 2016; Köse et al., 2003).

Also, simulation methods can help design waterways and bridges to optimize the routing of vessels traditionally as well as autonomously and with limited human intervention. Ultimately leading to the mitigation of collision and grounding risks (Huang et al., 2019).

Congested ports as a result of increasing demand is another challenge that leads to vessel accidents. Simulating the arrival of vessels in each port can shorten the port's service time and decrease the delays due to anchorage and tide, i.e., without increasing the accident risks (Almaz and Altiok, 2012).

Accident simulations also provide information on damages and lead designers to concentrate on materials with high yield strength to reduce structural damages (Bae et al., 2016). Thus, quantitative methods such as Monte Carlo simulation have a significant role in ship design (Sun et al., 2017). This tool is also valuable in post-accident impact/damage analysis well (Brzozowska, 2016).

A relatively rare though impactful type of accident in shipping is fire and explosion. The leading causes of fire and explosion are human errors and structural failures. The complex internal structure of vessels and heat dissipation from the steel structure makes controlling the fire a challenge (Salem, 2016). Therefore, applying simulation methods can help in including this kind of accident in a ship's design process (Kang et al., 2017). It can also help understand uncertainties such as fire distribution, expected damages, and crew decisions in controlling the fire. Simulation of the dispersion of heat, smoke, and structural collapse using AR cameras can be utilized in the phase of crew training (Pettijohn et al., 2020).

Flooding accidents can be simulated, aiming to decrease catastrophic events (Braidotti and Mauro, 2019). A flooding accident consists of different time steps and necessary actions that can save human lives and merchandise. During flooding time steps, different scenarios can be simulated and the damages and progressive flooding according to the velocity of ships and the remained free surfaces can be studied (Ruponen, 2014). This element is crucial for the ship design process, and numerous research works have been recently going on in this field[3,4].

As grounding accidents lead to damages to the hull structure, simulation methods can be employed to analyze the hull structure's response to an accidental impact allowing identification of the most appropriate materials to sustain the damage (Kitamura, 2002). Moreover, simulating the progress of a grounding accident results in detecting the development of fractures on the hull structure (Kim et al., 2020; Lee et al., 2017).

[3] European Flare project - Flooding risk assessment and control, - www.flare-project.eu.

[4] Eurpean Floodstand prject - Integrated Flooding Control and Standard for Stability and Crises Management – www.floodstand.aalto.fi.

5.11. Cloud computing (CC)

Cloud computing plays a major infrastructural role in operationalizing modern industry 4.0 technologies by providing secure, flexible, accessible, and large-scale data storage. Currently, cloud-stored data is used with shipping decision support systems (Dellios and Papanikas, 2014). Mobile devices can also be employed with cloud systems to share and store various types of internal data such as position, type of ship, near vessel information, near obstacles detection, and external data such as items identification, weather, rain, snow, waves, and atmospheric pressure (García-Domínguez, 2015; Kanagevlu and Aung, 2015). Could compute or stored data are widely used in Vessel Traffic System (VTS) (Ficco et al., 2018).

5.12. Internet of things (IoT)

Through its integration of sensor technology and internet communication, IoTs can be used with cyber-physical systems to enhance their flexibility and responsiveness. Following are its applications found in the literature. Because of the high density of vessels in coastal countries, the IoT can separate clustered higher traffic areas from the lower ones to increase the availability of ports and routes and mitigate the risk of accidents (Xia et al., 2020). Also, employing the internet of things to simulate maritime traffic flow is a means to determine vessels' behavioral characteristics. It results in measuring the passage's capacity and decreasing navigation risks (Jiang et al., 2019). Also, the management of oil spills can be facilitated via IoT technologies (Sai et al., 2020).

5.13. Big data analysis (BDA)

Big Data Analysis is perhaps the most practical modern approach, i.e., in conjunction with CC and IoT and data collected by other cyber-physical systems. Its application is on the rise in shipping risk management applications. An example is congestion monitoring and employing a combination of Location Routing Algorithm and Cluster-Based Flooding Algorithm (LORA-CBD) used in optimal routing (Cárdenas-Benítez et al., 2016). In another work, AIS-based big data are proposed to capture spatial complexity, density, and service time to avoid congestions (AbuAlhaol et al., 2018), while trajectory-related big data is also proposed to find the optimal routes in multipath transportation (Xu et al., 2016).

Oil spills lead to socioeconomic and ecological damages to both the maritime environment and local communities. Chun et al. (2020) discussed the gap between governmental and public spheres concerning oil spills in shipping operations. Using social media big data, researchers are led to determine the significance of this issue and find solutions to minimize the damage to local communities and ecosystems. Also, specific to oil transportation, Cheng et al. (2019) employed AIS big data for the 21st Century Maritime Silk Road project to achieve an accurate mapping of oil tanker trajectories, showing the relative use of oil tanker routes maritime shipping chokepoints.

5.14. Shipping 4.0 framework on risk management

In our above discussion, we laid out the existing landscape of the shipping 4.0 vs. shipping risk Our above discussion laid out the existing landscape of the shipping 4.0 vs. shipping risk research progression. We also identified potential areas where future research can progress. This landscape is consolidated in a taxonomical framework that maps the potential of mitigating the risk of various types of major accidents via various shipping 4.0 technologies. Thus, the framework presented in Fig. 13 is laid out based on crucial accident types, i.e., collision, fire/explosion, grounding, and oil spills. We then identify the potential shipping 4.0 technologies for each accident type that can be considered for developing new solutions.

Here collision, which is also the most frequent accident, is suggested to be addressed by AR and Simulation, AIS, ECDIS, ARPA, AGN, IBS, VDR, VTS, GPS, and IR. Due to their navigational relevance, these technologies have a direct potential for accident avoidance for various types of collisions. Moreover, simulation of accidents using augmented reality can train the crew to make efficient decisions when confronting these situations. Simulation and AR can be beneficial for other types of accidents such as flooding, fire accidents, and grounding. As AIS and ECDIS are technologies for navigation data gathering and data analysis, shipping companies can use them in cases of flooding, grounding, and oil spills for location detection purposes. IR and AGN also have great potential in dealing with various risks and post-accident environments such as oil spills. One of the significant gaps found in the literature is a lack of cloud computing, internet-of-things, and big data analytics in dealing with shipping accidents. These technologies can integrate with

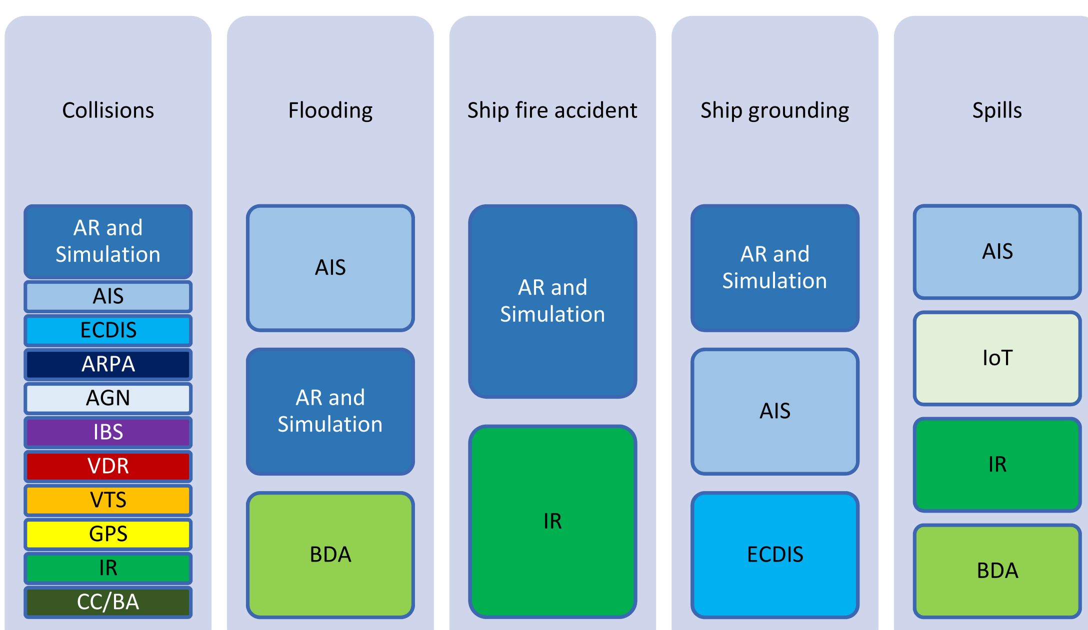

Fig. 13. Shipping 4.0 technology to accident risk management research landscape.

other technologies and can play a major role in risk mitigation.

Overall, the most frequent ship accidents in the form of collisions and grounding can be controlled by a suite of shipping 4.0 technologies and thus require greater attention by researchers. Its implications are also significant, as reflected by the latest episode of a container vessel named Ever Given's grounding episode that led to halting the Suez canal—the busiest global shipping artery (Allianz, 2021). Moreover, AR and simulation are a primary means of ship design and preparing the crew and equipment for accidents, which require further studies. Across these technologies, AIS is currently the most widely discussed technology. Integration of AIS and other technologies via cloud computing, internet-of-things, and big data analytics is another major direction requiring researchers' attention to make significant risk management progress.

Moreover, shipping 4.0 would benefit from learning from the most active players in the maritime domain, such as advanced ships operators (navy and large passenger vessels) or oil and gas industry (O&G), especially in the context of modern technology and methods applicable to maintain the safety of operations and development of a new framework based on those (Haugen et al., 2016; Montewka et al., 2018).

In fact, new building vessels are often equipped with up-to-date technologies, however, what is often missing is a framework gathering all the relevant data produced by the technology and intelligent reasoning out of it to ensure the safe operation of a ship.

One concept that could be instantly adopted in maritime transportation, which is already known and widely used in O&G is dynamic safety barrier management (DNV, 2019). Therein safety functions are defined as technical or organizational actions to avoid or prevent an adverse event or control and limit its occurrence (Bubbico et al., 2020; Pitblado et al., 2016; Sklet, 2006). One example of this approach is Accidental Risk Assessment Methodology for Industries in the Context of the Seveso (ARAMIS) which is supported in the maritime industry describes four main safety barriers: active barriers, passive barriers, human actions, and symbolic barriers (De Dianous and Fievez, 2006; Delvosalle et al., 2006; Hosseinnia Davatgar et al., 2021; Salvi and Debray, 2006).

The dynamic safety barrier (DSB) approach in the maritime transportation domain is in infancy, and application of this concept in a systemized manner is often restricted to safety-critical ship types, such as passenger (Bertheussen Karolius et al., 2021; Jasionowski, 2011; Pennanen et al., 2015; Ruponen et al., 2019) or naval vessels (Boulougouris and Papanikolaou, 2013; Reese et al., 1998). Therein, a DSB aims to ensure the appropriate level of survivability of the ship suffering from a flooding accident. While the barrier is understood as a system of watertight doors along with their estimated effect on accidental flooding suppression based on complex simulation of the flooding process.

Similarly, the DSB approach can be extended from a relatively narrow, ship-centric, perspective to a much wider maritime transportation system perspective, to help in designing and managing the proper and effective safety system over a given sea area (Banda and Goerlandt, 2018).

The DSB concept is in line with the recent call for the development of leading safety indicators for the maritime transportation systems (Grabowski et al., 2007; Wróbel et al., 2021), that would be based on solid scientific foundations and remains fully operational (Hollnagel, 2017; Kretschmann, 2020). It is evident, that the DSB approach can be seen as a prospective and proactive way to manage the risks of unwanted events thus improve the safety in the maritime transportation systems, by assembling various existing technologies mentioned earlier in this paper, thus fulfilling the goal of Shipping 4.0 paradigm.

6. Discussion

Industry 4.0 has evolved transportation systems and affected maritime transportation by developing cyber-enabled shipping via technologies such as CPSs, IoT, BDA, etc. These advanced technologies are enabling shipping industries in terms of autonomy, flexibility, and transparency, which are also allowing better management of accident risk through eradicating human error via autonomous guidance and access to detailed information in real-time. Due to its implication on human life as well as the economic impact, classifying these employed technologies, the shipping accidents and their relationship is thus the subject of this work.

The results of this paper are original and novel in comparison with the previous papers on shipping 4.0 (Aiello et al., 2020; Kavallieratos et al., 2020a, 2020b; Lambrou and Ota, 2017; Muhammad et al., 2018). Specifically, previous literature studies have concentrated on developing an architectural framework for cyber-enabled vessels (Kavallieratos et al., 2020b), analyzing the impact of shipping 4.0 technologies on enabling cybersecurity (Kavallieratos et al., 2020a), elaborating a business model for port operations (Muhammad et al., 2018), and studying the role of technologies on cyber shipping (Lambrou and Ota, 2017). This paper is the first study that broadens the focus to the prevention and mitigation of shipping accidents.

A coincidence between the technologies stands out in this elaboration. In other words, many of these technologies utilize the outcomes of each other to enhance the decision-making process. For instance, AIS, which is a tracking system, provides navigation and tracking big data. In contrast, big data analysis methods are employed to interpret the data and make the optimal decision in critical situations.

Another main contribution of this study is to shed light on the synergic and complementary impact of industry 4.0 on shipping operations. For instance, a tremendous impact is decreasing the collisions using AIS and ARPA, which provide a clear picture of the surrounding traffic (Ficco et al., 2018). In the case of oil spills, analyzing the big data of spill's location obtained from AIS can lead to determining the area of pollution and employing robots to clean the pollution up and save the marine environment (Guerrero-González et al., 2016).

6.1. Theoretical and managerial implications

From a theoretical point of view, the framework helps researchers understand the prevailing industry 4.0 technologies vs. the accident risk management landscape. As the framework identifies several technologies applicable to particular accident risks, several studies can be readily identified where competing technologies are compared in terms of their cost-efficacy, maintainability, compatibility, integration with the existing systems, and information security management. For instance, eleven technologies are found in the course of the literature review as the most frequently used in preventing ship collisions (Fig. 13). While some of these technologies are complementary, others compete with each other and thus require a detailed comparative performance analysis. The framework has also identified significant gaps in the literature, which can also guide researchers in developing vital new research directions. A more detailed discussion on future research is presented in section 6.2, after our discussion on the managerial implications below.

From the managerial perspective, the framework can direct the development and implementation decisions of new systems and practices. That is, the technologies developed and tested by researchers can be readily identified, which can then be translated and carried to the industry for actual use. Appropriate new practices can also be identified and implemented similarly. As the framework also identifies major drawbacks and shortcomings of respective technologies, their practical limitations can be well understood and considered during the actual implementations. For instance, the framework identifies cyber-security as a major drawback of several industry 4.0 technologies. Thus, their implementation can be made possible alongside appropriate information and cyber-security measures. There are some drawbacks and disadvantages about the applications of shipping 4.0 technologies which can impose some limitations on the technology implementations. Our study also identifies these issues. One of the common issues identified in implementing these smart technologies is related to cybersecurity risks due to their exposure to hacking attacks. Shipping companies need to consider precautionary actions such as developing cybersecurity platforms to prevent such incidents (Gucma and Zalewski, 2020). Employing a skilled workforce, training staff, and labor-use strategies to increase employees' competencies can enhance the cyberspace culture within the companies (Cheng et al., 2019). As discussed earlier in section 4, more comprehensive works are needed to identify the related issues and how they could be managed.

6.2. Implications for further research

Broader implications in terms of future research can be derived from this paper. Although shipping 4.0 in accident prevention and mitigation is in its early stages, using an empirical study to validate the identified relationships in this study can be a promising direction for future research. Also, our conceptual framework can lay the foundation for using emerging technologies to manage shipping accidents and risks. However, technological aspects of those technologies should be investigated to provide more insights into the implementation process. We summarize these key areas needing further investigation via Fig. 14. The color shade level helps visualize the attention received by the researcher. For instance, to the best of our knowledge, the flooding accident is studied via four papers focusing mainly on the simulation process of flooding progress, while those papers rarely identified and analyzed the factors to determine the implementation of the simulation process. Besides, there is a clear lack of focus on data acquisition, assimilation, and analysis (BDA) needed in the analysis of flooding incidents. This clearly identifies a gap in the current literature, where researchers need to focus on this glaring shortcoming.

Another interesting research direction identified is the application of VTS, VDR, IBS, and IoT in the scientific domain of maritime accidents risk management. Specifically, identifying and developing devices to facilitate the IoT integrated mobile applications for navigation, tracking, and alarming is a major possible future direction. Existing solutions contributing to the risk management of accidents, such as GPS, VTS, IBS, and VDR, are also neglected in existing papers, which most likely may stem from the fact that those technologies are already well matured and have proved their usability for the given purpose. However, the integration of these technologies with the earlier mentioned still holds great promise.

Collision, flooding, fire, grounding, and oil spills have been identified as the most frequent accidents in papers on the subject of maritime transportation. This classification was proposed by many relevant papers in this field of study and directed us to filter the keywords (Mrozowska, 2021). Analyzing less frequent accidents and investigating their relationship with the new technologies can also be an important potential venue for future works to find how these technologies can help shipping companies in managing a wide range of accidents.

One of the major gaps found in the literature is the lack of use of cloud computing, internet-of-things, and big data analytics in dealing with shipping accidents. This is a major promising direction in terms of future research. These technologies can integrate with other technologies such as AIS and can play a major role in mitigating shipping risks and accidents. An indication of research gaps is summarized in the visual summary of Fig. 14, where the number of papers in the combination of each shipping accident and shipping 4.0 technology results in different colors.

Another gap in this elaboration is the application of VTS, VDR, IBS, and IoT in the scientific domain of maritime accidents risk management. Specifically, developing shipping devices making benefits from IoT and mobile applications for tracking, navigation, and alarming the team of risk management can be a possible extension to this development. Existing solutions contributing to the risk management of accidents, such as VTS, IBS, and VDR are also neglected in the recent scientific papers, which most likely may stem from the fact, that those types of technology have been already matured and have proved their usability for the given purpose. Therefore, their contribution to the improved navigational safety is taken for granted, similar to GPS, thus not much scientific attention is paid to it in the context of accidental risk management.

Cybersecurity, which is another factor in maritime transportation risk management, is not studied in this work. The main reason for this circumstance is that this paper has a focus on accidents. In this regard, developing a new conceptual framework concentrating on risks associated with shipping such as human errors, security risks, piracy, shore, and offshore threats, etc. Collision, flooding, fire, grounding, and oil spills have been the most frequently attended accidents in papers on the subject of maritime transportation. This classification was proposed by many relevant papers in this field of study and directed us to filter the keywords (Mrozowska, 2021).

6.3. Limitations

This paper has its limitations. Two specific databases (WoS and Scopus) are adopted to select and filter the papers, which means the

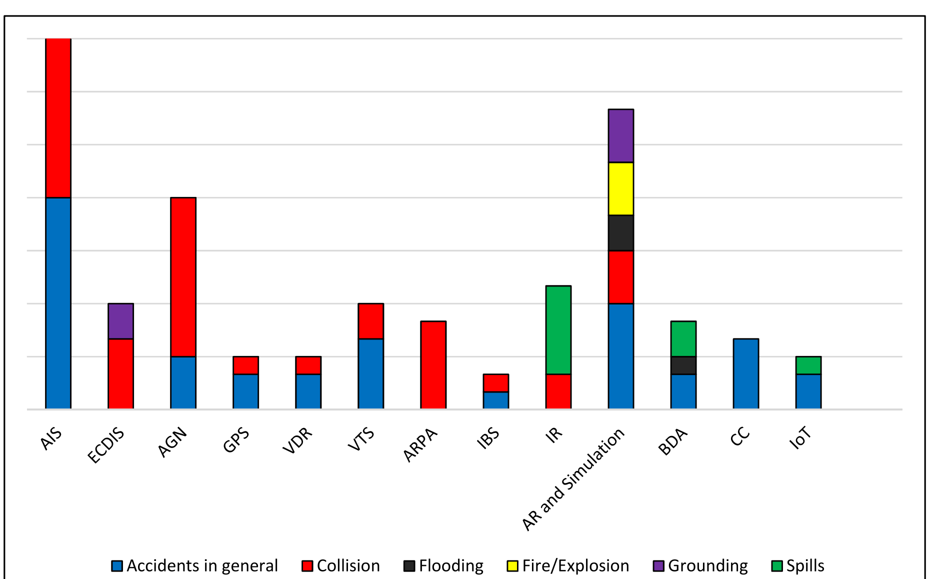

Fig. 14. Summary of research gaps.

papers that are not indexed in these two databases are missed. Therefore, employing various databases can minimize the paper's bias (Núñez-Merino et al., 2020). However, this might be a minor limitation for this elaboration.

The selection process of keywords which is limited to the titles, keywords, and abstracts of the selected papers, is another limitation of this study. Other classifications for shipping accidents might be missed, leading to a higher number of keywords for other types of accidents. From our knowledge, the selected keywords reflect the challenges that shipping industries confront in practice; because of appropriate coverage of shipping accidents and industry 4.0 technologies. Hereof, risk management is not considered, and the main concentration is on preventing accidents and making the best effort to diminish their effects.

Besides, this work has a focus on scientific papers, but the fact of omitting mandatory regulations, patents, and industry documents is the limitation of this study which can be developed in future works.

7. Conclusions

This study aimed to address three following high-level questions 1) what are the critical accident risks faced by the maritime industry, 2) what are various industry 4.0 technology implemented by the industry so far, and 3) how these technologies are being employed to prevent and mitigate accident risks. Accordingly, the study offers a systematic literature review discussing the impact of shipping 4.0 on controlling shipping accidents as prevailing in the scientific literature. The study used a three-phase approach to collect papers from journals and conference proceedings in its first phase. The next phase, responding to the first two questions, entails identifying shipping risks and accidents, and the relevant shipping 4.0 technologies applicable in predicting, preventing, and mitigating the effects of these accidents. Whereas in the final phase, which addresses the third question, a framework was proposed that a mapping showing the relationship of respective technologies in mitigating different accident types. The framework also serves as a conceptual guiding mechanism directing future research and developments.

The study illustrates an overall increasing trend of utilizing shipping 4.0 technologies in accident risk mitigation during the past twenty years. Among the active journals, Ocean Engineering has published the highest number of papers, while Safety Science, The Journal of Navigation and Transportation Research Part D: Transport and Environment are other major active journals. While an interdisciplinary approach is observed due to the nature of the field, a perspective tilt on ocean studies, computer science, and safety, risk, and reliability was observed. In terms of accidents, collision, which is also the most frequent accident type (67%), has received the most attention. Similarly, the most employed technology turned out to be AIS, while AR and simulation and AGN are the following most used systems. In terms of gaps, a major shortcoming is observed in the use of vital industry 4.0 technologies of cloud computing, internet-of-things, and big data analytics. This is besides IBS, GPS, which have not been widely addressed in the recent literature, despite their factual contribution in preventing maritime accidents. Future studies may also need to emphasize the impact of shipping 4.0 technologies on maritime supply chain risk and disruptions and their socio-economic and environmental aspects.

In terms of practical implications, our study can help risk managers find a better overview of digitalization and smart shipping in the maritime industry. By increasing reliance on real-time and relevant data, managers can effectively predict the risks and use corrective actions to avoid future incidents and disruptions.

CRediT authorship contribution statement

Arash Sepehri: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Hadi Rezaei Vandchali:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Atiq W. Siddiqui:** Methodology, Writing – original draft, Writing – review & editing. **Jakub Montewka:** Methodology, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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