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Review

A bibliometric analysis and systematic review of shipboard Decision Support Systems for accident prevention

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ABSTRACT

Maritime transport faces new safety-related challenges resulting from constantly increasing traffic density, along with increasing dimensions of ships. Consequently, the number of new concepts related to *Decision Support Systems* (DSSs) supporting safe shipborne operations in the presence of reduced ship manning is rapidly growing, both in academia and industry. However, there is a lack of a systematic description of the state-of-the-art in this field. Moreover, there is no comprehensive overview of the level of technology readiness of proposed concepts. Therefore, this paper presents an analysis aiming at (1) increasing the understanding of the structure and contents of the academic field concerned with this topic; (2) determining and mapping scientific networks in this domain; (3) analyzing and visualizing *Technology Readiness Level* (TRL) of analyzed systems. Bibliometric methods are utilized to depict the domain of onboard DSSs for operations focused on safety ensurance and accident prevention. The scientific literature is reviewed in a systematic way using a comparative analysis of existing tools. The results indicate that there are relatively many developments in selected DSS categories, such as collision avoidance and ship routing. However, even in these categories some issues and gaps still remain, so further improvements are needed. The analysis indicates a relatively low level of technology readiness of tools and concepts presented in academic literature. This signifies a need to move beyond the conceptual stages toward demonstration and validation in realistic, operating environments.

1. Introduction

Maritime Transportation Systems (MTSs) are facing rapid changes. It is happening mainly due to crew shortage, increasing sizes of ships being operated, and progressive automatization of modern merchant vessels. Continuous expansion of the global fleet and intensification of carrying goods by the sea trigger economical profits on the market (UNCTAD, 2018), prompting further development of the shipping. Consequently, such a process can lead to a greater number of maritime accidents caused by heavy traffic (Chen et al., 2019; Mou et al., 2019; Ożoga and Montewka, 2018). These factors contribute to intensified scientific production in systems designed to support navigators, as well as ship operators in decision-making related to accident prevention.

There is no strict definition of the *Decision Support System* (DSS), due to the development of the concept over the years (Power and Sharda, 2009). Its general aim is to support the decision-making process through improving human and system performance (Cummings and Bruni, 2009), e.g. by reducing mental workload. This is achieved not always through a process of automation but also merely by the facilitation of the decision-making (Bolman et al., 2018; Power and Sharda, 2009). Therefore, many various approaches can be used in such systems, which are not limited to computer-based only. These methods can utilize paperwork, engage graphical representation of data, as well as handling and processing experts' knowledge (Bolman et al., 2018).

One of the driving forces of the implementation and constant development of onboard DSSs in maritime transportation is the idea of

Abbreviations: AHP, Analytic Hierarchy Process; AIS, Automatic Identification System; ARPA, Automatic Radar Plotting Aid; BSR, Baltic Sea Region; COLREG, International Regulations for Preventing Collisions at Sea; DSS, Decision Support System; FSA, Formal Safety Assessment; GDP, Gross Domestic Product; H2020, Horizon 2020; HDI, Human Development Index; HELCOM, The Baltic Marine Environment Protection Commission; IMO, International Maritime Organization; JoN, Journal of Navigation; MASS, Maritime Autonomous Surface Ships; MCP, multiple-country publication; MTS, Maritime Transportation System; NUC, Not Under Command; OE, Ocean Engineering; OOW, Officer of the Watch; RQ, Research question; SOLAS, International Convention for the Safety of Life at Sea; STS, Ship-to-Ship; TRL, Technology Readiness Level; VTS, Vessel Traffic Service; WoS, Web of Science

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e-Navigation, introduced by the *International Maritime Organization* (IMO, 2008). The concept is focused mainly on the improvement of the operational safety of vessels by introducing new technologies and tools to assist the navigation process (Baldauf et al., 2014; Perera and Guedes Soares, 2015; Weintrit, 2016, 2013). The development of such solutions appears to have positive effects on transportation safety, given a decreasing number of collisions and groundings of vessels operated under the SOLAS convention (*The International Convention for the Safety of Life at Sea*), (Baldauf and Hong, 2016). Moreover, it is of a particular relevance for the development of *Maritime Aunomous Surface Ships* (MASS), some of which are expected to evolve from traditional vessels by utilization of DSSs, (IMO, 2019).

Despite increasingly growing interest in safety-related DSSs for the MTS, there is a lack of a systematic overview of solutions proposed in the scientific literature. Some articles present the state-of-the-art in maritime transportation problems, which are related to safety assessment and ensurance. Among exemplary review articles, there are a few focused on risk analysis (Chen et al., 2019; Goerlandt and Montewka, 2015; Lim et al., 2018), waterway traffic (Li et al., 2012; Zhou et al., 2019), maritime accidents (Baalisampang et al., 2018; Luo and Shin, 2019), as well as models utilized in collision-avoidance (Statheros et al., 2008; Szlapczynski and Szlapczynska, 2017; Tam et al., 2009). On the other hand, the reviews of Decision Support Systems in the field of waterborne transportation are mostly related to sustainability and management problems, (Bjerkan and Seter, 2019; Bolman et al., 2018; Mansouri et al., 2015), especially to marine spatial planning, (Janßen et al., 2019; Pınarbaşı et al., 2017). Nonetheless, there is no systematic literature review of decision-support systems in the prevention of various types of maritime accidents focused on the applicability of presented tools and their *Technology Readiness Level* (TRL).

Therefore, in this paper, we aim to systematize the knowledge about DSSs existing in maritime transportation using bibliometrics and systematic literature review. The research is primarily focused on onboard solutions designed for accident prevention in MTS. However, investigated solutions are directly related to the system safety of a ship, not the occupational health and safety of crew or passengers onboard. Furthermore, the study focuses on a thematic coverage of DSSs in the maritime domain by classifying papers to at least one of the following categories: *collision-avoidance*, *engine, hull loads & damage, ice navigation, routing, ship maneuvering, stability & cargo handling, weather conditions,* and *miscellaneous*. Additionally, detailed information about the most relevant tools (regarding a computed ranking score), such as end-users, potential area of application, main gaps and limitations were obtained along with bibliometric parameters of the paper being number of citations, authors' affiliations, etc. The following research questions (RQs) are addressed to organize the study: (1) Which research networks are the most active in the maritime DSS-related field? (2) What is an overall level of technology readiness of proposed solutions? (3) What further developments of DSSs designed for ensurance the maritime safety are needed? (4) What are the major topics of maritime DSSs for accident prevention?

The paper is structured as follows: In Section 2 the methods used in the study are described. Section 3 and Section 4 present the results showing respectively the bibliographic and comparative analyses. A discussion is provided in Section 5, while Section 6 summarizes and concludes the paper.

2. Methods

The review of shipboard DSSs designed for accident prevention in MTS is performed using two different approaches. The procedure and general methods used during the research are depicted in Fig. 1.

Firstly, a systematic and reproducible approach is applied to gather and filter the data sample.

Subsequently, bibliometrics is applied to investigate the collected data sample. The utilization of this method results in a global overview of DSS-related tools and concepts. In this type of analysis, quantitative data regarding scientific production, such as the number of documents, authors' contributions, and occurrences of keywords are determined. The obtained information allows for identifying various collaboration networks in order to indicate authors, countries, as well as institutions significantly involved in the analyzed domain.

Finally, a literature review is conducted. The documents aggregated during the process of data gathering are classified into nine categories. When assigning a particular paper, the purpose of each DSS, i.e. the type of operational decision it aims to support is taken into account. The data are additionally broken down and analyzed in various aspects, such as TRL, type of authors' affiliation, and the year of publishing. These factors are utilized for computing a ranking score of each document from the sample. Results are subsequently used to determine top-papers, which are selected for further thorough analysis. The comparative analysis of three the most relevant papers in each category allows the identification of existing gaps and finally, enables setting a course for further developments of maritime DSSs for safety ensurance.

2.1. Bibliometrics and research mapping

Bibliometrics is a branch of science focused on analyzing bibliographic information in a quantitative way, (Broadus, 1987; Choudhri et al., 2015; Modak et al., 2019). Total scientific production, number of citations, authors' affiliations or keywords are exemplary indicators utilized in this method. Results of such analysis can be visualized in various forms, such as maps, graphs or networks to depict large datasets in a meaningful way. Such *research mapping* is becoming an increasingly popular method for gaining insight into a field of scientific activity through the representation of bibliometric parameters. Therefore, a combination of both methods allows for determining various aspects of scientific production using conceptual (factorial analysis, thematic maps, co-occurrences networks), intellectual (references and co-citations), and social (authors and countries collaboration maps) structure of the papers sample (Aria and Cuccurullo, 2017; Cobo et al., 2011).

Bibliometrics and the research mapping were applied in several studies in both safety and transportation domains. For instance, the process safety in accidents causing domino effect was analyzed in Li et al. (2017), while studies on construction safety were reviewed by Jin et al. (2019), and the concept of safety culture in cross-disciplinary research in fields of organizational, patients, and health-care safety is investigated in van Nunen et al. (2018). In the transportation domain, Sun and Rahwan (2017) analyzed the co-authorship and scientific collaboration networks related to transportation research, whereas Heilig and Voß (2015) utilized a similar approach to investigate existing studies in the field of public transportation. Bibliometric analysis was used also to present the overview of scientific production about major problems of the transportation sector like carbon emission (Tian et al., 2018). Nevertheless, similar studies on the scientific production in the field of safety of maritime transportation are missing.

2.2. Dataset preparation

The process of dataset preparation is divided into three main stages. Firstly, the search strategy is defined and data are gathered (stage 1). An obtained sample is preliminary (stage 2) and finally (stage 3) filtered out using two different approaches. The entire process of data sample determination is presented in Fig. 2 and described in further paragraphs of this section.

In the first stage of dataset collecting, a search query was determined to gather the initial sample of documents. *Web of Science* (WoS) was selected as a data source because it is a large, commonly accepted database of abstracts and references from high-quality and impactful scientific papers (Li and Hale, 2016; van Nunen et al., 2018). Documents were obtained from two main WoS Core Collections – the *Science Citation Index Expanded (SCI-EXPANDED)* and the *Social Sciences*

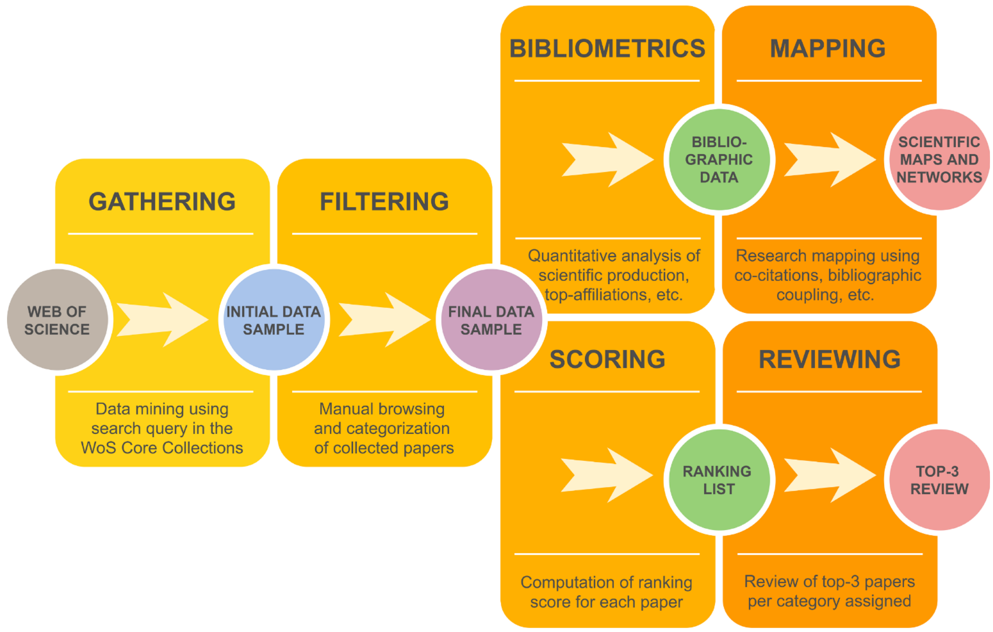

Fig. 1. The procedure and methods used in the performed study.

Citation Index (SSCI). To ensure that the search query is properly designed and conforms to the vocabulary used in the maritime domain, the wording of the loss matrix given in the *Formal Safety Assessment (FSA) Guidelines* (IMO, 2018), was applied. The query inspired by FSA allowed for filtering out results, which contain only selected types of events. The exemplary loss matrix contains the following types of accidents (IMO, 2018): collision, contact, foundering, fire/explosion, hull damage, machinery damage, war loss, grounding, other ship accidents, other oil spills, and personal accidents. Regarding the intended research scope, DSS should be an onboard solution focused on safety ensurance and should directly consider the safety of a ship, not people. Therefore, searching was conducted on 20 June 2019 and afterward was repeated in January 2020 in order to update sample with papers published in 2019 using the following query:

TS=("support system$" OR $DSS OR decision$ (making OR support*)) AND TS=(maritime OR ship* OR vessel$) AND TS=(preven* OR respons* OR acciden* OR *colli* OR safe* OR fire* OR damag* OR los$ OR contact*)

Although the scope was restricted to the papers pertaining to the *prevention* of accidents, the term *respons** was included in the query as well. After a preliminary analysis of the dataset constructed, it was found that many DSSs aim to support both accident prevention and response operations. Therefore, to avoid rejection of valuable documents, the results matching the condition with the word *response* were additionally included in the data sample. Wildcards were utilized to consider various forms of inflection and conjugation. There was no time-span limit related to the year of publication. The initial database with papers obtained after the execution of the search query contains 1553 documents.

In the second stage of data sample preparation, all papers determined from WoS were investigated by focusing on a title, abstract, and keywords (both *Author Keywords* and *KeyWords Plus*). Documents that passed the first validation were classified as relevant for further analysis. These papers were included in the new dataset and forwarded to the next step of filtering and determining the final sample (316 papers).

According to the research assumptions, a document was recognized as relevant for the analysis if a decision-support tool or concept was

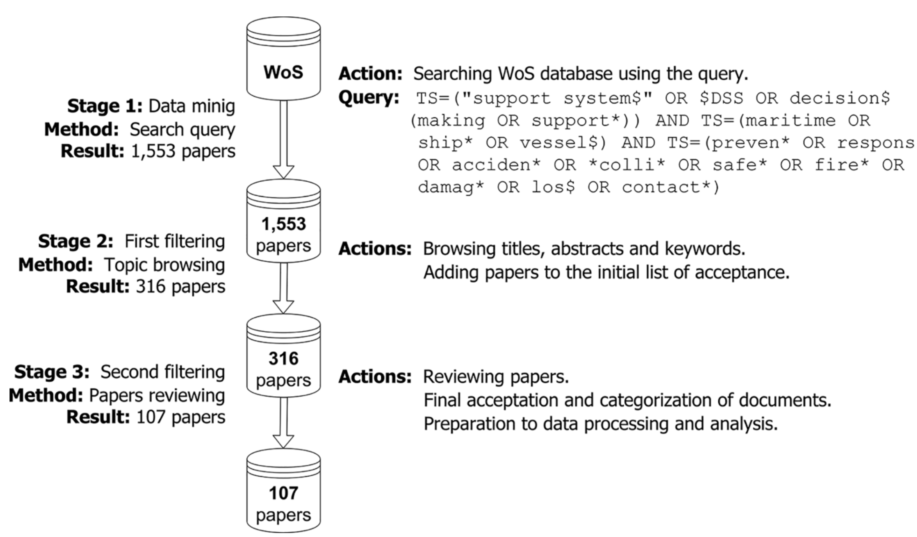

Fig. 2. The process of determining the final data sample.

Table 1
The categories of DSS distinguished in the study.

The category	The general aims of the DSS
Collision-avoidance	Prediction of a close-quarters situation; risk assessment in an encounter of vessels; calculating and proposing an evasive maneuver; real-time support in collision-avoidance
Engine	Any kind of decision support related to the main or auxiliary engine(s); provision of support for the operation, maintenance or spare parts management
Hull loads & damage	Computation of present or predicted excessive hull loads for any reason and indicating the method of their avoidance
Ice navigation	Any kind of decision support system designed for operation in ice conditions; path-planning in ice navigation; calculation of ship-ice interaction
Routing	Intentional change of ship trajectory or her passage plan based on various reasons except for the weather factor (which is extracted into the separated category)
Ships maneuvering	Advanced ship handling or piloting systems; automatic or supported execution of vessel maneuvers; improvement of ship motions in various operational conditions
Stability & cargohandling	Computation and indication of excessive values related to ship motions and her stability; consideration of the impact of loading conditions on vessel operation; generating dynamic warnings on excessive loads during the voyage or cargo handling
Weather conditions	Improvement and optimization of voyage parameters caused by hydrometeorological conditions; estimation of the impact of wind or waves on ship hull; weather routing
Miscellaneous	All other purposes not specified above

presented. Articles introducing only basic components of DSS were excluded from the study even if in the future they could be developed into DSS. Thus, papers introducing building blocks of such system were not taken into account. An example of this scope restriction could be, for instance, the issue of ship domain in collision-avoidance. In spite of many valuable papers presenting models that could be utilized as a potential component of DSS, (Szlapczynski and Szlapczynska, 2017; Zhang et al., 2012), these documents were not included in the dataset.

Thence, on the 3rd stage of dataset preparation all documents were browsed to verify if they meet the criteria and if so, these papers were assigned into a suitable thematic category. The breakdown of the categories with the general aim of each type of DSS is presented in Table 1.

A few of the reviewed papers pertained to a tool or concept, which range of application overlaps more than one kind of DSS. In such cases, documents were assigned to more than one category. At least three papers related to the similar thematic were needed to group them into a separate category. Documents, which did not meet this condition were assigned as *miscellaneous*. This additional category contains several papers unrelated to the previously determined kinds of DSS. Eventually, 107 scientific articles were included in the final data sample.

2.3. Systematic literature review

As a technique, the literature review is known and commonly used research method of finding and getting familiar with scientific contributions related to the subject of the study (Brocke et al., 2009). Review articles allow researchers to expand their bibliographic database related to a particular topic, as well as to avoid the reinvention of already explained issues and existing solutions (Baker, 2000). However, dependent on the type of literature review, which can be general, systematic or critical, an approach to its conducting differs (Fernandez, 2019). The maturity of the topic and size of related literature also impacts the utilized methodology (Torraco, 2005). The systematic review should be interpreted as a research method with elements of assessment of the sources along with a logical concept of the study, (Fernandez, 2019). Additionally, in this approach, the topic of scientific interest is tightly narrowed using precise search terms. A transparent procedure of data gathering, extraction, and results of the analysis should be provided in order to enable the reproducibility of the study (Fernandez, 2019; Robinson and Lowe, 2015). In this paper, a systematic review of the literature was selected as a method to investigate the topic of onboard DSSs for accident prevention in MTS.

Documents included in the final set were reviewed to gather additional information about the presented solutions. Other parameters of a tool or concept were determined in addition to DSS categorization. This information includes end-user (OOW – *Officer of the Watch*, VTS – *Vessel Traffic Service*, marine pilots, ship management); potential area of application; authors' affiliations (divided into *academia*, *industry*, and *others*), as well as *Technology Readiness Level*. In order to identify scientific activities performed locally in the authors' area, the contribution made by countries of the *Baltic Sea Region* (BSR) was additionally distinguished and analyzed. These countries were classified in accordance with HELCOM – *Helsinki Commission* state members (except the entire *European Union*). Thus, authors from Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, Russia, and Sweden were taken into account (HELCOM, 2014). The TRL was assigned in accordance with *European Commission* nomenclature used in the *Horizon 2020* (H2020) program (EC, 2014). The TRL scale utilized in the study and depicted in the so-called thermometer diagram is presented in Fig. 3.

To determine papers presenting the most relevant tools, a ranking list was created according to information collected about each document, as defined in Table 2. The values of parameters were normalized in the range from 0 to 1. Weights for a particular parameter were set and assigned by the authors. The final score of each paper was computed using Eq. (1), as follows:

$$s_i = \sum_{j=1}^{n=3} p_i \times w_j \quad \{i|1 \leq i \leq 107\} \qquad (1)$$

where:

s_i means the score of the paper, p_i denotes the value of its parameter, while w_j means the weight of a particular parameter. i stands for a paper number, whereas j indicates the parameter index.

Among the parameters of the papers, potential end-user and thematic areas of the application were not included as weighted factors, because they do not have a direct impact on the usability of presented solutions. Accordingly to the assumptions and objectives of the study,

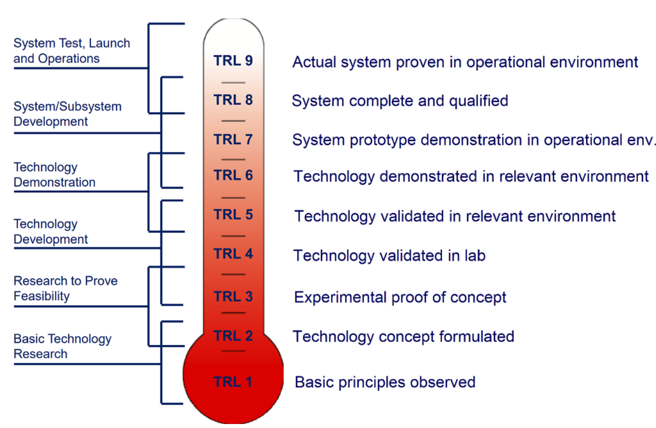

Fig. 3. The TRL scale as given originally in NASA (2016), and modified to EU H2020 (EC, 2014).

Table 2
The parameters and their weights used in computing ranking scores.

No.	Parameter(p_i)	Description	Weight(w_j)
1.	TRL value	Normalized TRL of a tool or concept presented in a particular paper. Ordinal values assigned by authors according to the EU Horizon 2020 scale where $TRL \in [1, 9]$, were transformed to ratio-scale numbers using factors presented in Conrow (2011).	0.6
2.	Type of authors' affiliations [%]	The ratio of authors from *university*, *industry*, and *others* to the total number of authors involved in the paper. The percentage of each type of affiliations was scaled using share-factor related to patents granted. The average share for the type of applicants in UE and the USA (2018) was calculated and applied.	0.3
3.	Publication year	Year of publication calculated with respect to linear function where the oldest publication (1991) denotes 0% of the weight, and the newest (2019) means 100%.	0.1

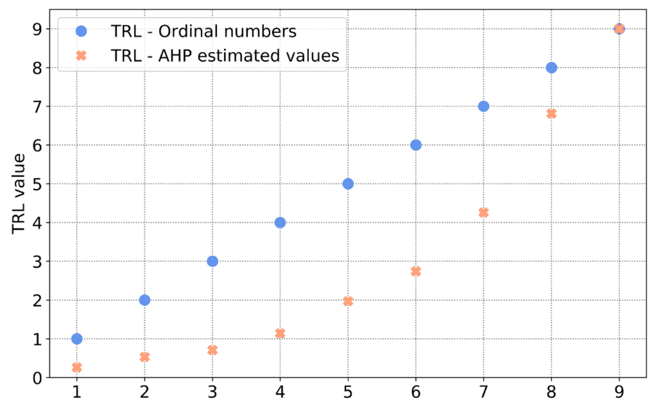

Fig. 4. The ordinal and AHP-estimated TRL values, as given in Conrow (2011).

the higher the applicability and technological readiness, the higher the score. Therefore, TRL was considered as the most important ranking factor ($w_j = 0.6$) due to the nature of DSS, which is most valuable as a fully operational tool. However, the TRL scale adopted by the EU in the Horizon 2020 program is based on ordinal values. The maturity of the system between successive levels is not equal. There is a significant change in financial outlays and time required to develop a tool from, i.e. TRL 7 to TRL 8 and this cannot be compared with the costs of improvement between TRL 2 and TRL 3. However, in a typical ordinal scale, the numbers only signify a ranking, and contain no meaningful information about the relative positions of the values in the scale. Thus, some mapping between ordinal and ratio-scale numbers is necessary to perform mathematical computations and to take into account the nonlinear nature of the technology readiness scale, (McConkie et al., 2013). To this end, the values determined using AHP (*Analytic Hierarchy Process*) method were applied to transform previously determined TRL, (Conrow, 2011). The difference between both TRL scales is depicted in Fig. 4.

While academic contributions have value in suggesting new concepts and avenues of thought, DSS should be used in practice to truly ensure maritime safety. Therefore, three types of authors' affiliations are considered during the analysis of each paper, i.e. *academia*, *industry*, and *others*. It is assumed that authors working in the industry have a greater chance to implement their contribution and turn a concept into a tool. On the other hand, a scientist employed in academia probably have fewer opportunities for implementation and they are more focused on delivering concepts, not products. Nevertheless, universities that are more entrepreneurial, as well as research and development-oriented also can produce patents, spin-offs or licenses for products (Mathieu et al., 2008). Financial support from the industry is another option to increase the chance for applicability, especially that research funded by the company is perceived not always as less accessible (Wright et al., 2014). To the last option (*others*) belong institutions, which are not clearly identified as universities or companies, such as *research and development centers*, *laboratories*, *institutes*, etc. The last statistics on patenting in the USA and EU confirm that the vast majority of applications and granted patents belong to business sector or large companies (85% USA and 71% EU), while the academia accounts for tiny percentage (5% and 9%, respectively), (European Patent Office (EPO), 2019; National Science Board, 2020). Therefore, the average value of the share in patents in both the USA and EU is taken to assign the weight of p_2 parameter for each type of affiliation: *I* (*industry*), *U* (*university*), and *O* (*others*). Finally, the ratio of affiliations from the *industry* is assumed as 100% of the weight (0.3), while other types are normalized to this level. Thus, *academia* constitutes 9% of the weight, while *others* 19%. The process of calculating the total weight (w_2) of the parameter p_2 is presented in Eq. (2).

$$w_2 = I_{\%} \cdot I_{w_{norm}} + U_{\%} \cdot U_{w_{norm}} + O_{\%} \cdot O_{w_{norm}} \quad (2)$$

where:

$I_{\%}$, $U_{\%}$, $O_{\%}$ – contribution in [%] for a particular paper of *industry*, *university*, and *others*, respectively.
$I_{w_{norm}}$ – 100% of the weight (0.300) that constitutes 78% of average patents granted.
$U_{w_{norm}}$ – 9% of the weight (0.027) that constitutes 7% of average patents granted.
$O_{w_{norm}}$ – 19% of the weight (0.190) that constitutes 15% of average patents granted.

The last parameter is the year of publication of the paper presenting a given tool or concept. It was assumed that in terms of technology level almost three decades (1991–2019) is a significant time span that should be included in the scoring formula. The oldest publications (1991) consist of 0% of the weight of the parameter, while the newest (2019) 100%. Intermediate values were calculated using a linear function. The overall weight of the parameter was relatively low (0.1), due to the belief that even old paper can still present valuable and useful DSS that can be used also today or was a base for other, newer systems.

All of the weighted parameters were normalized with regard to the maximum observed value to maintain the order of magnitude and facilitate interpretation. The ranking list was firstly prepared for the entire dataset and afterward for each DSS category separately.

3. Results of the bibliometric analysis

In this section, the authors attempt to find an answer to the posed research question (RQ1). This point concerns the determination of the most active scientific collaboration networks in the analyzed field. To this end, a bibliographic analysis was performed for two aspects, namely to provide information about social (authors, countries, institutions), and intellectual (scientific production, citations) structures. Data processing in this part of the study was carried out using the freeware *VOSviewer* (van Eck et al., 2010; van Eck and Waltman, 2017, 2014, 2010), and *bibliometrix* (Aria and Cuccurullo, 2017), an open-source package to *R* programming language.

Regarding the procedure of dataset preparation described in Section 2.2, 107 papers were classified as relevant and subsequently were processed using science mapping tools. The documents stemmed from 44 different sources and were published in the course of almost 30 years (the oldest paper was published in 1991, while the newest in 2019). A

Table 3
The summary of the bibliometric data sample.

Description	Results
Documents	107
Sources (journals, books, etc.)	44
KeyWords Plus	197
Author's Keywords	334
Period	1991–2019
Average citations per documents	15.78
Authors	248
Author appearances	317
Authors of single-authored documents	14
Authors of multi-authored documents	234
Single-authored documents	18
Multi-authored documents	89
Documents per author	0.43
Authors per document	2.32
Co-authors per document	2.96
Collaboration Index	2.63

total of 248 authors were involved in the scientific production on onboard DSSs designed for accident prevention. Among the papers, 18 were created by a single author whereas the overall *Collaboration Index* of the sample equals 2.63. This indicator denotes the average number of co-authors noted solely in multi-authored publications (Elango and Rajendran, 2012; Koseoglu, 2016). The summary generated using *bibliometrix* (Aria and Cuccurullo, 2017), includes basic statistics about the analyzed dataset is presented in Table 3.

3.1. Social structure – authors, countries, and institutions

The most productive authors in the analyzed dataset are Carlos Guedes Soares and Rafał Szłapczyński (both 8 papers affiliated with *University of Lisbon* and *Gdansk University of Technology*, respectively), as well as Xinping Yan and Ulrik Dam Nielsen (both 5 papers, affiliated with *Wuhan University of Technology* and *Technical University of Denmark*, respectively). The contribution of these authors amounts to 25% off all documents in the sample. The authors having three or more papers are depicted in Fig. 5 with the number of fractionalized articles. Fractionalized frequency indicates an individual contribution of each author by assuming equal share among all co-authors of the affiliated papers (Aria and Cuccurullo, 2017).

Noteworthy is the involvement of a particular author through the analyzed timespan. Some scientists carried out the research in the early 1990s, however, the vast majority started the contribution at the beginning of the second decade of the 21st century. Such intensification of works around 2010 and later corresponds to an overall trend in the production of papers in the analyzed topic. It is noted that several authors suspended their work on DSS but then they resumed the research in this field after many years. An example of such an author is Prof. Martha Grabowski from *Le Moyne College*. Accordingly to the query used in the WoS database and collected dataset she had a 20-years gap between the papers related to maritime decision support systems. The authors' production over time is depicted in Fig. 6. The color-code used denotes an average number of citations aggregated for papers published in a particular year.

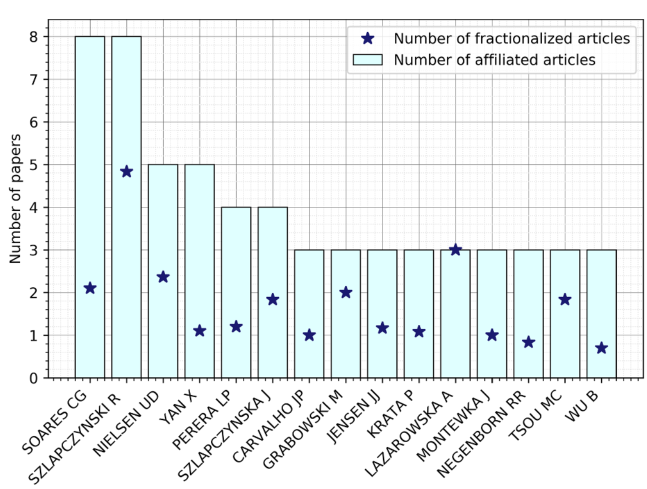

Fig. 5. The most relevant authors in the years 1991–2019.

The contribution of the most productive authors is related to the score of countries and research institutions to which they belong. However, despite the absence of authors from *Wuhan University of Technology* (China), *Gdynia Maritime University* (Poland), and *Dalian Maritime University* (China) in the first place of the top-productive authors, these institutions were classified in the top-3 of top-affiliated research centers. It stems from the fact that a notable number of authors from those universities producing DSS-related documents. In Figs. 7 and 8 the breakdown of analyzed production of top-authors by institutions and countries is shown. The universities divided into BSR and other countries along with their share in the scientific contribution are presented in Fig. 7, while in Fig. 8 the participation of a particular country is depicted with respect to the address of the corresponding author. The corresponding author's address was used because only one country can be given there, while the first author (the lead one) can affiliate more than one institution located in various regions of the world.

Because of the presence of a few Polish scientific institutions in the top relevant affiliations (*Gdynia Maritime University* – 2nd; *Gdansk University of Technology* – 3th *ex aequo*; *Maritime University of Szczecin* – 5th *ex aequo*), Poland was classified on the top of countries with the largest number of papers (18) and total citations (405) with respect to the corresponding author's country (Fig. 8). In the second place, China is classified with 13 papers and 120 citations. Surprisingly, Portugal is classified only in the 4th place with 7 documents (218 total citations), although Prof. Soares (*University of Lisbon*) is ranked on the top of the most productive authors (as per Fig. 5). This situation appears due to many co-authored documents where he is not indicated as the corresponding author.

It is also essential to analyze and compare the corresponding authors' countries in terms of international collaboration. As presented in Fig. 8, even though Poland is ranked in the first place in the ranking, it has the lowest ratio of multiple-country publications (MCP). This indicator is a proportion between the number of MCPs and the total production of the country. Among all of the presented universities which have at least one publication with authors from different countries, the Polish ratio (0.11) is the lowest. This means that while Polish authors are generally quite productive, their cooperation remains at the national level. Contrarily, the USA, China or Portugal have an index between 0.54 (PRC) and 0.67 (USA), which means that more than half of publications were a result of international collaboration. The issue of global scientific collaboration seems to be essential for networking. Efficient cooperation with international co-authors allows for gaining experience and citations, sharing knowledge, as well as increasing the visibility and availability of the research (Francisco, 2015; Rodrigues et al., 2016). Additionally, teamwork in an extended collaboration network increases the opportunity for breakthrough and innovative ideas because of the larger range of experts from various fields (Guimera, 2005).

When considering the affiliation of the corresponding author, the Baltic Sea Region is strongly represented by Poland (18), Denmark (5), Finland (3), Russia (2), Germany (3), and Sweden (1). The total number of these documents comprises 30% of the entire data sample, which results in 612 citations (36%) obtained by the authors from BSR.

Fig. 9 maps the collaboration network between countries by analyzing co-authorship. Noteworthy, in spite of the large number of publications originating from BSR, there is no significant international cooperation between those countries. The network was created using

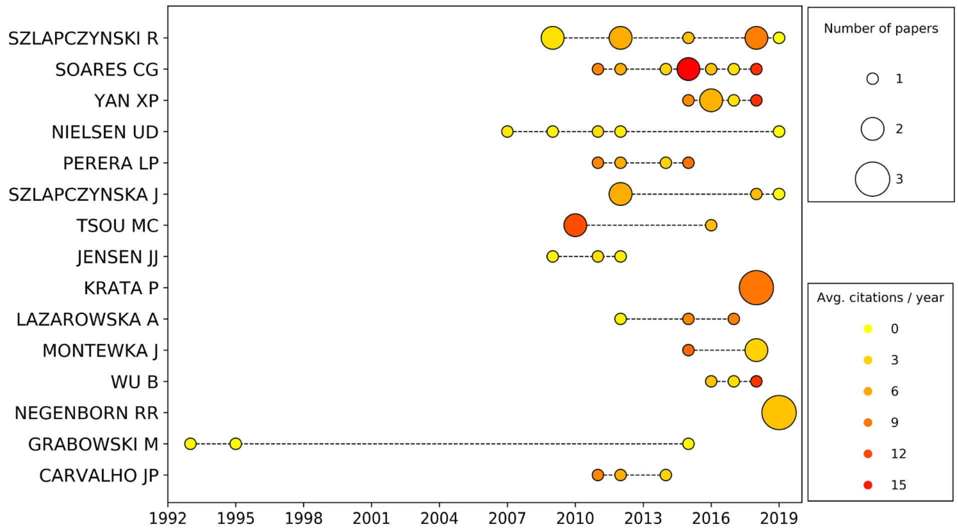

Fig. 6. Top-authors' production over time with the number of citations in a given year.

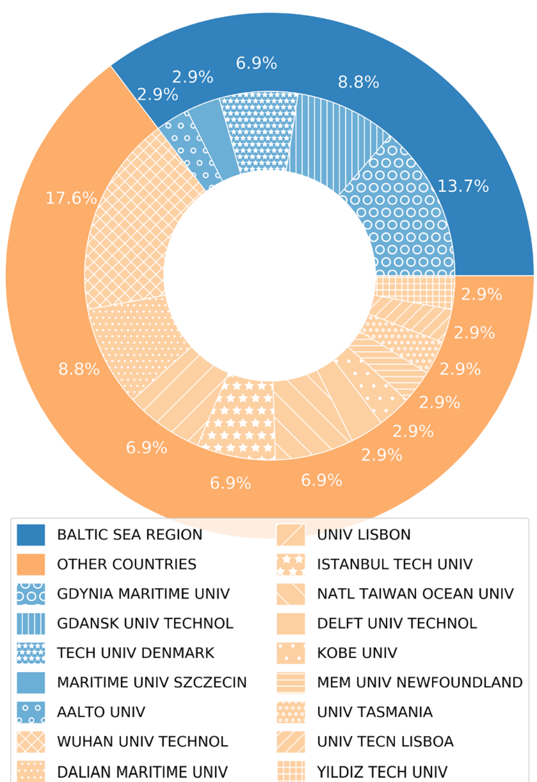

Fig. 7. Authors' affiliations and the contribution of the BSR countries.

the full-counting method with the minimum number of documents per country set to three, thus 18 countries met the threshold. Normalization was provided using association strength. The color-coded overlay presents the year of publication, whereas the weights depend on the total strength of the link. The international collaboration network indicates four main clusters. China is the most cooperative country with the highest strength of the link related to Portugal. It can be also reasoned that Chinese researchers produce nowadays most of the documents (as per color-code), and their cooperation network spreads widely also at the international level.

Despite Poland being one of the leaders in the number of documents, and its institutions ranked high, the researchers from this country cooperate mostly domestically (Fig. 9). It results in a very tiny network (clustered together with Finland, Italy, and Russia), and weakens the contribution of the entire Baltic Sea Region. Additionally, it should be noticed that only one country from BSR – Denmark – has an influential position in the network being in the cluster together with USA, England, Greece, South Korea, Norway, and Singapore.

3.2. Intellectual structure – scientific production and citations

The trend in preparation of documents among analyzed time-frames presented in Fig. 10, indicates two explicit moments of an intensified scientific production in the analyzed field. The first period is noticed in the first part of the 1990s, while the second has begun around 2010 and continues to this day.

Based on the analyzed data sample, a decrease of scientific production in the domain of onboard DSS can be observed after 1995. Nevertheless, the dynamic change of the state took place in 2009 when the difference in the number of articles in comparison to previous years increased by 700%. This upward trend started in 2009 was probably due to the focus of IMO at that time on the e-Navigation concept. Moreover, the on-going development of autonomous shipping where DSS will be utilized in vessels considered as DoA one (MASS-1), (Fan et al., 2020; IMO, 2019) should ensure maintaining this positive tendency in near future. It should be noted that conducted analysis was characterized by very strict requirements for suitable papers, as well as narrow domain focused on maritime, onboard DSSs for ensurance ship safety by accident prevention, based mainly on FSA. Therefore, scientific production in the overall field of maritime DSS or accident prevention can differ. However, the authors believe that the utilized dataset can be used to outline a general tendency in scientific production related to the scrutinized topic.

Analysis of the content from text fields, such as titles, abstracts, and keywords results in statistics of the most frequent words used by authors. In Fig. 11, mapping of the most relevant keywords (both *Author's keywords* and *KeyWords Plus*) based on the number of their mutual occurrences in analyzed documents is presented. The normalization was made using an association strength. The weights were computed with regard to the number of each keyword (full-counting), while color-code indicates different clusters.

Because of the subject of the analysis, the vast majority of determined terms were related to maritime safety issues. However, some trends concerning increasingly popular themes can be observed. The most relevant words indicate researchers' interest in automatic collision-avoidance, (e.g. *computer simulation*, *ship domain*, *criterion*, as well as less but still related terms, such as *algorithm*, *COLREGs, path planning* or *model*). This field of

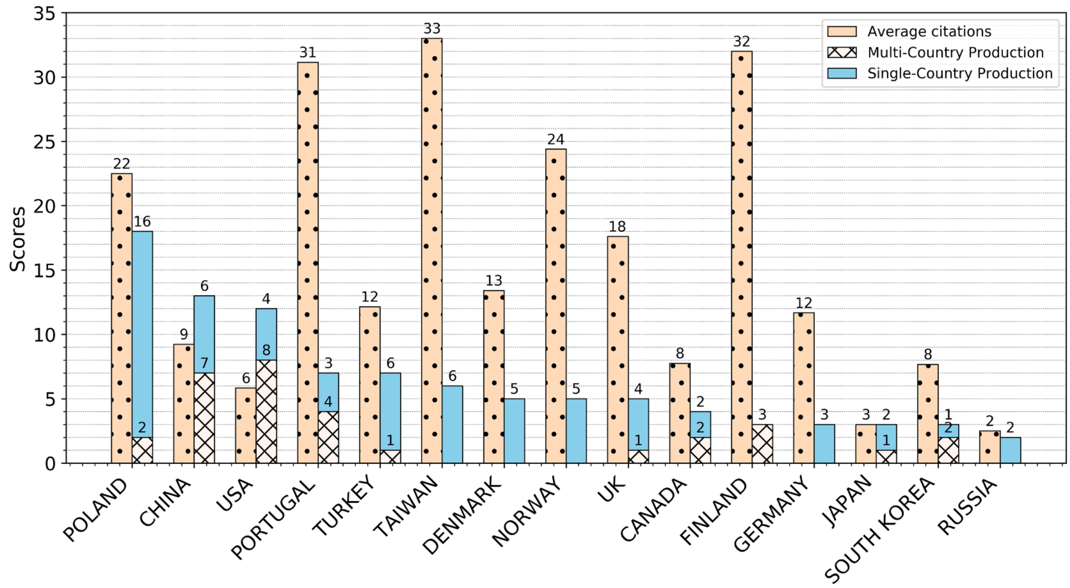

Fig. 8. Authors' contributions by the country of the corresponding author's affiliation.

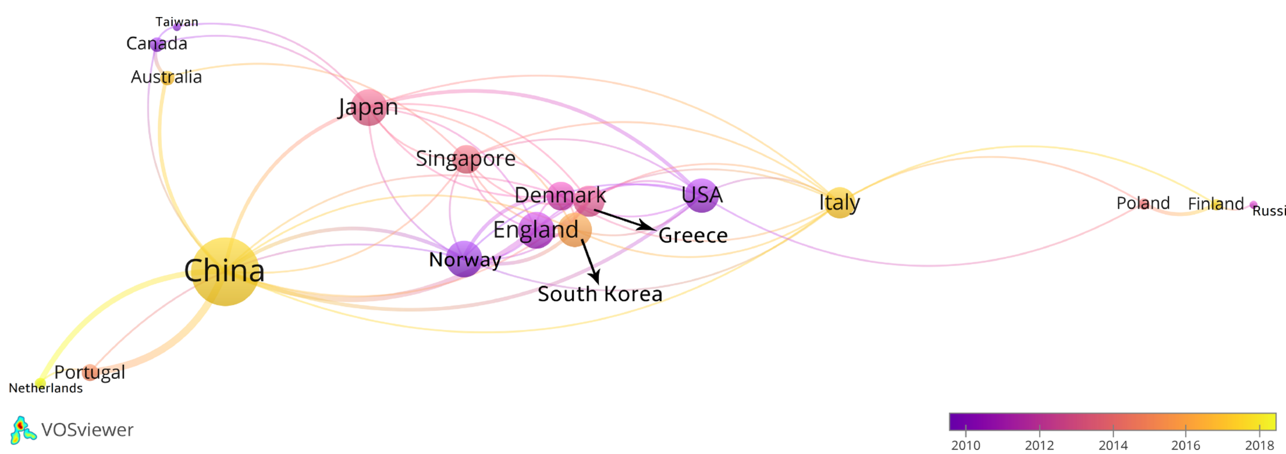

Fig. 9. The network of international collaboration using analysis of the co-authorship.

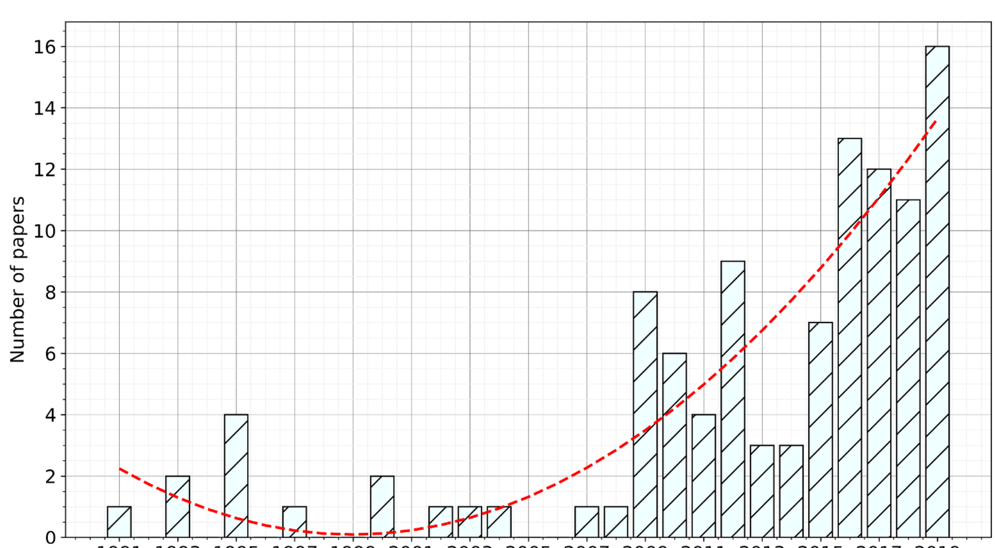

Fig. 10. The scientific production in the years 1991–2019 based on the analyzed dataset.

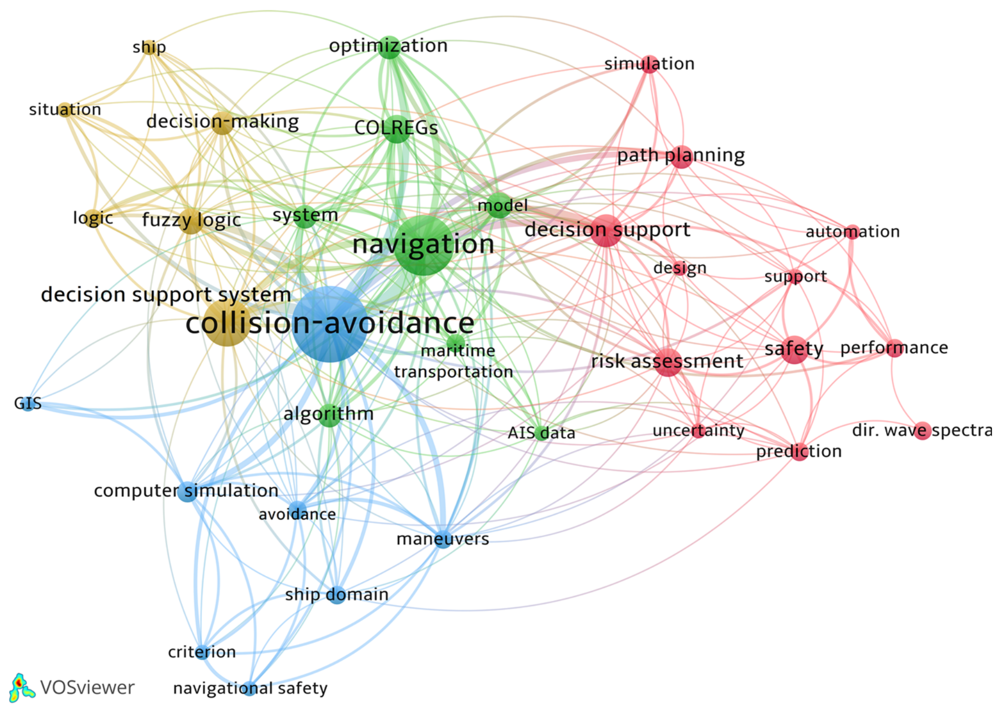

Fig. 11. The map of keyword co-occurrences based on the full-counting method.

interest can arise from the development of *e-Navigation* and autonomous systems. The terms *AIS data, prediction, uncertainty*, and *risk-assessment* can denote the utilization by scientists of real-time or historic traffic data in introducing new systems based on particular risk metrics. The presence of *logic* and *fuzzy-logic* in the ranking can indicate increasing usage of the many-valued type of logic in maritime decision-making. It can result, for instance, from the progressive introduction of artificial intelligence (AI) in the shipping industry, (Im et al., 2018; Wang et al., 2019; Xue et al., 2019; Yager, 1997; X. Zhang et al., 2019).

The analysis of citations was provided for both local and global types of references. The *local* should be interpreted as an internal citation among the processed sample, while *global* includes all citations from any documents. The top-10 cited papers from the dataset are collated and presented in Fig. 12, while the network of documents that cite each other is depicted in Fig. 13. The relatedness of a particular paper was determined by the number of its global citations. A total of 58 papers were mapped due to existing connections between them. The normalization was conducted using the fractionalization method.

The most globally cited document is *Modeling of ship trajectory in collision situations by an evolutionary algorithm* by Smierzchalski and Michalewicz (2000) with 112 citations (average 5.33 per year). Noteworthy is also the contribution of Ming-Cheng Tsou and co-authors, because of its high-impact on other papers. The documents entitled *The study of ship collision avoidance route planning by ant colony algorithm*, (Tsou and Hsueh, 2010) and *Decision Support from Genetic Algorithms for Ship Collision Avoidance Route Planning and Alerts*, (Tsou et al., 2010) are both in top-10. The mapping of citations indicates eight clusters. Four of them are associated with documents present in citations ranking: (1) (Perera et al., 2015, 2011; Smierzchalski and Michalewicz, 2000); (2) (Tam and Bucknall, 2010; Tsou et al., 2010; Tsou and Hsueh, 2010); (3) (Pietrzykowski, 2008; Wang, 2010); and (4) (Chin and Debnath, 2009; Goerlandt et al., 2015). Four other, minor clusters are linked between major parts of the network.

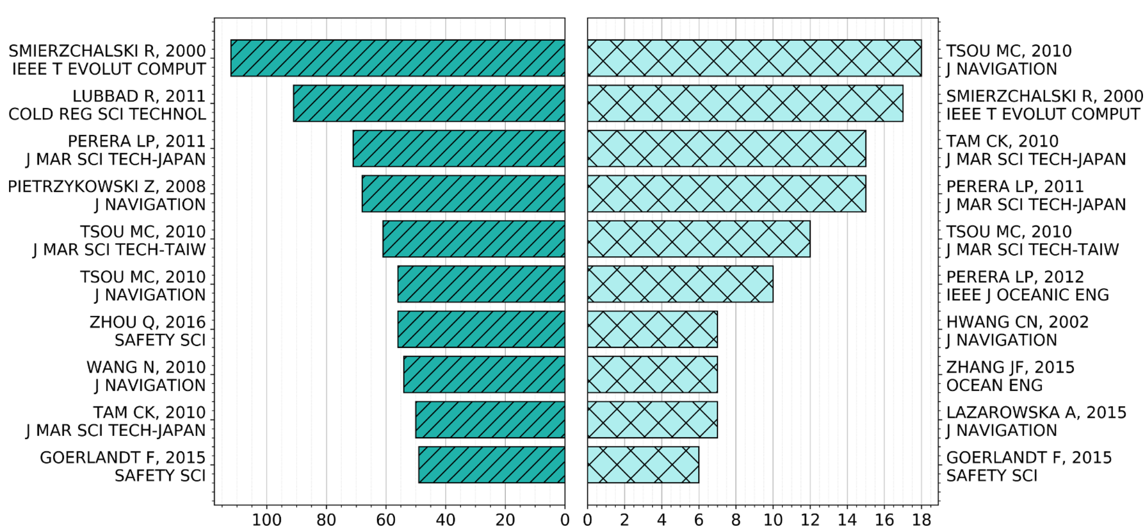

Fig. 12. Top-10 of global and local citations.

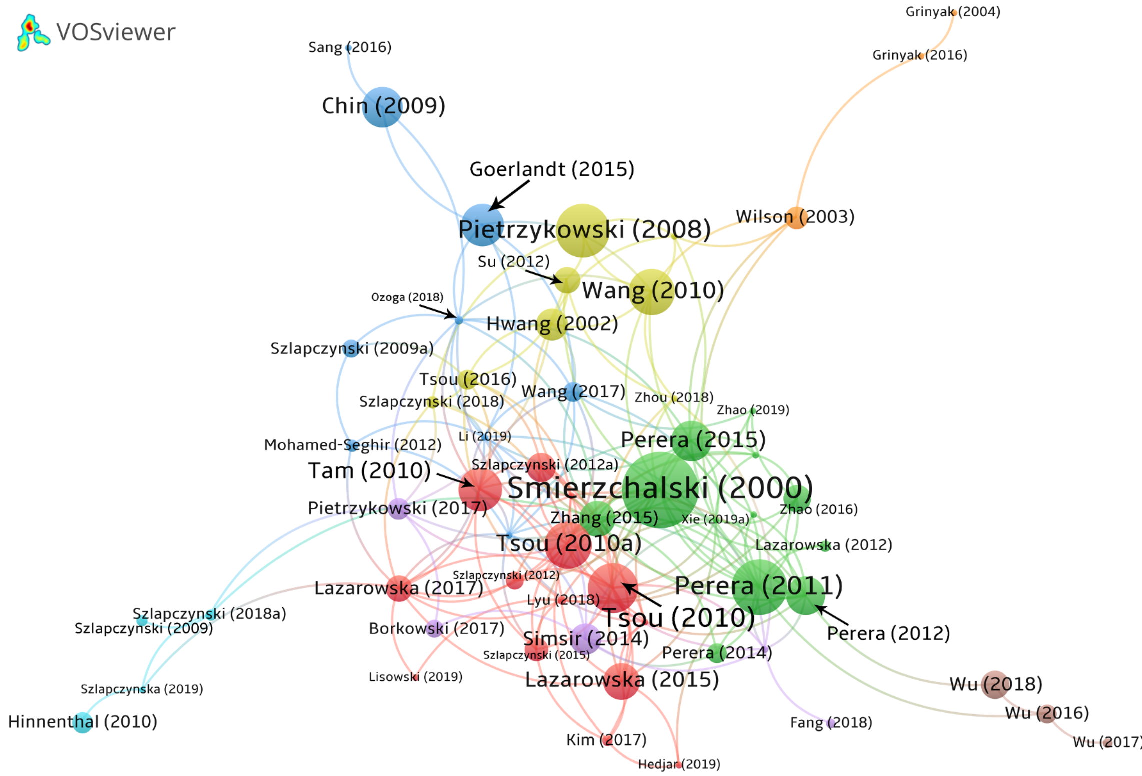

Fig. 13. The network of documents-relatedness based on citations number.

Table 4
Sources with at least four published documents.

Source	Articles
OCEAN ENGINEERING	21
JOURNAL OF NAVIGATION	15
SAFETY SCIENCE	5
MARINE TECHNOLOGY AND SNAME NEWS	4
POLISH MARITIME RESEARCH	4
RELIABILITY ENGINEERING & SYSTEM SAFETY	4

The last stage of bibliometric analysis concerned the investigation of the sources of documents included in the data sample. Those are mainly high-quality journals related to maritime transportation, safety issues or computer science. The sources with at least four published documents are presented in Table 4, while mapping is depicted in Fig. 14.

The ranking of the most relevant sources is dominated by two journals, namely *Ocean Engineering* (OE) and *Journal of Navigation* (JoN). The total number of papers published in these sources (21 and 15 documents, respectively) comprises almost 35% of all articles in the data sample. There is however a significant difference in the number of documents between the second and next places in the collation

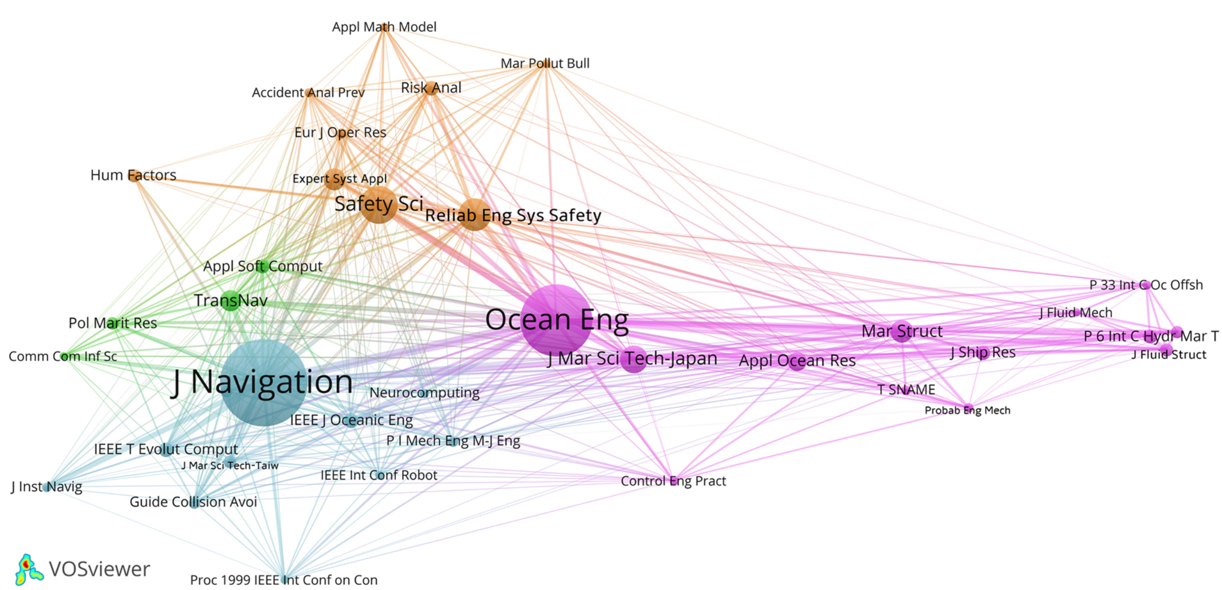

Fig. 14. The mapping of the sources with regard to the co-citations.

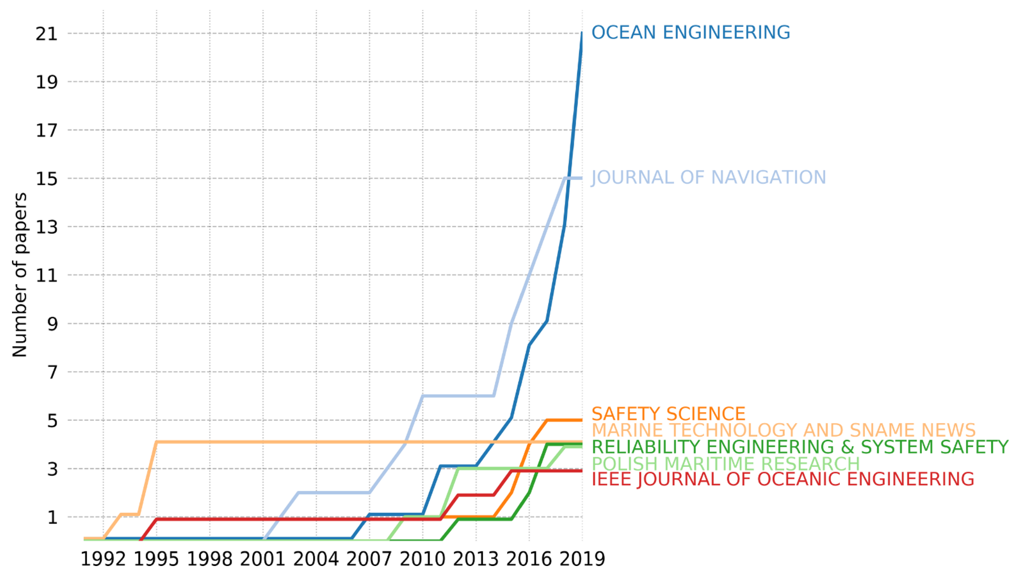

Fig. 15. The dynamics of the most relevant sources.

(Table 4). *Safety Science* being in the 3rd place has a three times lower number of published papers than JoN ranked 2nd. There are also large groups of journals with two, as well as only one paper (14 and 23, respectively). The latter group includes mainly sources related to the fields of automation and computer technology. Because of such distribution of articles published in various journals, the ranking list is explicitly flattened in its second part.

The sources were mapped with regard to their co-citations, i.e. how many times they were cited together (van Eck and Waltman, 2010). In this type of analysis, a relation between two publications depends on the number of documents that cite both of these papers, (van Eck and Waltman, 2014). Herein this kind of bibliometric network was utilized to visualize mutual relations between the sources. The minimum value of citations per source was set to 10, thus 37 of them met the threshold. The weights were set by the number of citations. Four clusters were determined using fractional counting of sources and fractionalization as a method of data normalization.

The most relevant sources determined by co-citations are *Journal of Navigation* and *Ocean Engineering*. Surprisingly, the cluster associated with JoN contains several sources focused on computing and robotics, such as *Neurocomputing*, *IEEE Transactions on Evolutionary Computation*, and *Proceedings of IEEE International Conference on Robotics and Automation*. These positions are linked with documents about regulations applicable to maritime collision-avoidance. Thus, it can be reasoned that sources where algorithms and models for path-planning and evasive maneuvers, cite many documents originated from *Journal of Navigation*. The second large cluster is associated with *Ocean Engineering* that is a journal which groups sources concerning topics of marine engineering, ship dynamics, fluid mechanics, etc. The role of OE in the network is very explicit, namely that journal is a connector between safety and navigational-related sources with positions focused more on mechanical engineering and hydrodynamics, such as *Marine Structures*, *Applied Ocean Research*, *Marine Technology and SNAME News*. The third cluster contains mainly safety-related journals which are strongly linked with *Safety Science, Reliability Engineering & System Safety*, *Risk Analysis* or *Human Factors*. The last and smallest group is placed between safety and navigational journals. This cluster includes positions related broadly to maritime transportation and marine engineering like *TransNav, The International Journal on Marine Navigation and Safety of Sea Transportation* or *Polish Maritime Research*.

The analysis of sources was not limited to the visualization of the network. The dynamics of journals was also investigated by verifying which source gained a considerable number of published papers in the analyzed period. It made possible to determine trends in publishing in recent years and to indicate the most relevant journals. The dynamics of each journal from Table 4 is depicted in Fig. 15.

The conducted analysis of the sources indicates *Ocean Engineering* as the most dynamic one from the dataset. The first paper was published in 2007 and after ten years the number of manuscripts reached the level of the previous leader – *Journal of Navigation*. Since 2007, OE maintains an upward trend and is now ranked 1st in the number of documents and the dynamics. It can be noticed that presently, the dynamics of JoN is much smaller. For the past five years, significant growth of papers in journals related more to overall safety issues can be noticed. This increase of the documents from the maritime domain published in *Safety Science* or *Reliability Engineering & System Safety* indicates the tendency to present a more safety-related approach in conducted research. The *Marine Technology and SNAME News* includes the same, relatively high number of papers (4) like 3 other journals in the ranking. However, the most dynamic growth of this source occurred at the beginning of the 1990s when it was the most relevant journal in the maritime DSS field. In spite of the 4th place on the list, the last manuscript from the sample was published there in 1995, thus the score is constant till today. It can indicate the change of journal profile or decrease in its popularity among authors. Nonetheless, the joint analysis of dynamics of the sources and scientific production over time indicate that reduction of *Marine Technology and SNAME News* coincided with the drop in overall production in the DSS field. After the return of the topic popularity, authors have started publishing in alternative sources like the JoN or OE, and this state is sustaining till today.

4. Results of the systematic review

The data sample obtained using the procedure presented in Section 2.2 has resulted in keeping only 7% of initially collected papers which were finally reviewed. The literature review carried out in a systematic way was made to investigate the technological readiness of solutions included in the data sample (RQ2). Additionally, it allows determining what kind of further works on DSS for maritime accident prevention are needed (RQ3), and on which topics the currently available solutions are focused on (RQ4).

4.1. The ranking and categorization

After the determination of the dataset, assumed formula (Eq. (1)) along with the weights for each parameter was computed and applied as given in Section 2.3. Thereafter, based on adopted criteria the ranking list was generated, see Table 5.

Table 5
The ranking list of the documents prepared accordingly to the procedure presented in Section 2.3.

#	Reference	Score
1	(Pietrzykowski et al., 2017)	0.716
2	(Lacey and Chen, 1995)	0.598
3	(Witmer and Lewis, 1995)	0.598
4	(Borkowski, 2017)	0.574
5	(Mannarini et al., 2016)	0.463
6	(Kufoalor et al., 2019)	0.419
7	(Bitner-Gregersen and Skjong, 2009)	0.412
8	(Denham et al., 1993)	0.354
9	(Grabowski and Sanborn, 1995)	0.325
10	(Sang et al., 2016)	0.314
11	(Perera et al., 2015)	0.287
12	(Santiago Caamaño et al., 2019)	0.258
13	(Iseki, 2019)	0.258
14	(Papanikolaou et al., 2014)	0.247
15	(Temarel et al., 2016)	0.240
16	(Jacobs and McComas, 1997)	0.235
17	(Hussein et al., 2016)	0.232
18	(Hui et al., 2017)	0.211
19	(Nielsen et al., 2012)	0.210
20	(Lisowski and Mohamed-Seghir, 2019)	0.203
21	(Inan and Baba, 2019)	0.203
22	(Husjord, 2016)	0.192
23	(Song et al., 2013)	0.191
24	(Acanfora et al., 2018)	0.175
25	(Sarvari et al., 2019)	0.174
26	(Hedjar and Bounkhel, 2019)	0.174
27	(Asuquo et al., 2019)	0.174
28	(Shen et al., 2019)	0.174
29	(Zhao and Roh, 2019)	0.174
30	(Zhang et al., 2019)	0.174
31	(Li et al., 2019a)	0.174
32	(Xie et al., 2019b)	0.174
33	(Li et al., 2019b)	0.174
34	(Szlapczynska and Szlapczynski, 2019)	0.174
35	(Xie et al., 2019a)	0.174
36	(Fang et al., 2018)	0.171
37	(Szlapczynski and Krata, 2018)	0.171
38	(Lyu and Yin, 2018)	0.171
39	(Ni et al., 2018)	0.171
40	(Szlapczynski et al., 2018)	0.171
41	(Zhang et al., 2015)	0.169
42	(Cebi et al., 2009)	0.167
43	(Vujicic et al., 2017)	0.167
44	(Lazarowska, 2017)	0.167
45	(Kim et al., 2017)	0.167
46	(Zhou et al., 2018)	0.167
47	(Wang et al., 2017)	0.167
48	(Wu et al., 2017)	0.167
49	(Dong et al., 2016)	0.164
50	(Zhao et al., 2016)	0.164
51	(Zhou and Thai, 2016)	0.164
52	(Grinyak and Devyatisil'nyi, 2016)	0.164
53	(Tsou, 2016)	0.164
54	(Liu et al., 2016)	0.164
55	(Goerlandt et al., 2015)	0.161
56	(Akyuz and Celik, 2018)	0.159
57	(Ożoga and Montewka, 2018)	0.159
58	(Simsir et al., 2014)	0.156
59	(Szlapczynski, 2015)	0.156
60	(Lazarowska, 2015)	0.156
61	(Perera et al., 2014)	0.156
62	(Islam et al., 2017)	0.155
63	(Christian and Kang, 2017)	0.155
64	(Thieme and Utne, 2017)	0.155
65	(Siddiqui and Verma, 2013)	0.153
66	(Brcko and Svetak, 2013)	0.153
67	(Nwaoha et al., 2017)	0.152
68	(Wu et al., 2016)	0.152
69	(Clauss et al., 2012)	0.149
70	(Szlapczynski and Szlapczynska, 2012a)	0.149
71	(Lazarowska, 2012)	0.149
72	(Su et al., 2012)	0.149
73	(Perera et al., 2012)	0.149
74	(Wang, 2012)	0.149
75	(Szlapczynski and Szlapczynska, 2012b)	0.149
76	(Mohamed-Seghir, 2012)	0.149
77	(Grabowski, 2015)	0.148
78	(Nielsen and Jensen, 2011)	0.146
79	(Vidic-Perunovic, 2011)	0.146
80	(Babel and Zimmermann, 2015)	0.144
81	(Wang, 2010)	0.142
82	(Tsou et al., 2010)	0.142
83	(Perera et al., 2011)	0.142
84	(Tam and Bucknall, 2010)	0.142
85	(Hinnenthal and Clauss, 2010)	0.142
86	(Cummings et al., 2010)	0.142
87	(Tsou and Hsueh, 2010)	0.142
88	(Man et al., 2018)	0.141
89	(Wu et al., 2018)	0.141
90	(Mennis et al., 2009)	0.139
91	(Szlapczynski, 2009)	0.139
92	(Szlapczynski and Smierzchalski, 2009)	0.139
93	(Kawaguchi et al., 2009)	0.135
94	(Akyuz, 2016)	0.134
95	(Chin and Debnath, 2009)	0.127
96	(Nielsen, 2007)	0.119
97	(Lubbad and Loset, 2011)	0.116
98	(Hwang, 2002)	0.114
99	(Yang et al., 2000)	0.109
100	(Grinyak and Devyatisil'nyi, 2004)	0.109
101	(Nielsen et al., 2009)	0.109
102	(Smierzchalski and Michalewicz, 2000)	0.106
103	(Wilson et al., 2003)	0.105
104	(Pietrzykowski, 2008)	0.105
105	(Kose et al., 1995)	0.089
106	(Grabowski and Wallace, 1993)	0.081
107	(Coenen and Smeaton, 1991)	0.074

In the top-5 articles of the ranking, two papers were categorized (see Table 1) as *collision-avoidance* DSS, two documents were assigned as multi-category (both *hull loads & damage*, as well as *routing* and *weather conditions*, respectively), and one was lumped solely to *weather conditions*.

The first place belongs to the document entitled *Decision Support in Collision Situations at Sea* created by Pietrzykowski et al. (2017). In this article made by researchers from *Maritime University in Szczecin,* NAVDEC which is a fully-operational onboard DSS (TRL 9) is presented. The tool was designed for solving close-quarters situations (Koszelew and Wołejsza, 2017). NAVDEC was tested in the real environment and certified by one of the classification societies, namely the *Polish Registry of Shipping* (Borkowski, 2017). The tool was introduced on the IMO forum in 2012 and can be utilized by navigators as an onboard solution, as well as by the shore-based institutions like VTS (*Vessel Traffic Service*), (Pietrzykowski et al., 2017).

The second place in the ranking is shared by Lacey and Chen (1995) and Witmer and Lewis (1995) who scored *ex aequo* 0.598. The papers were categorized as multi-type and belong to *hull loads and damage*. Additionally, the first was grouped to *routing*, while the latter to *weather conditions*. Both papers were published in 1995 as an effect of industrial cooperation between oil and gas (*BP Oil Co.* and *ARCO Marine Inc.*), as

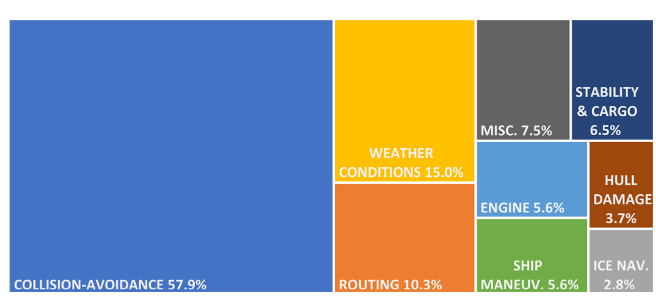

Fig. 16. The distribution of reviewed papers into categories as given in Table 1.

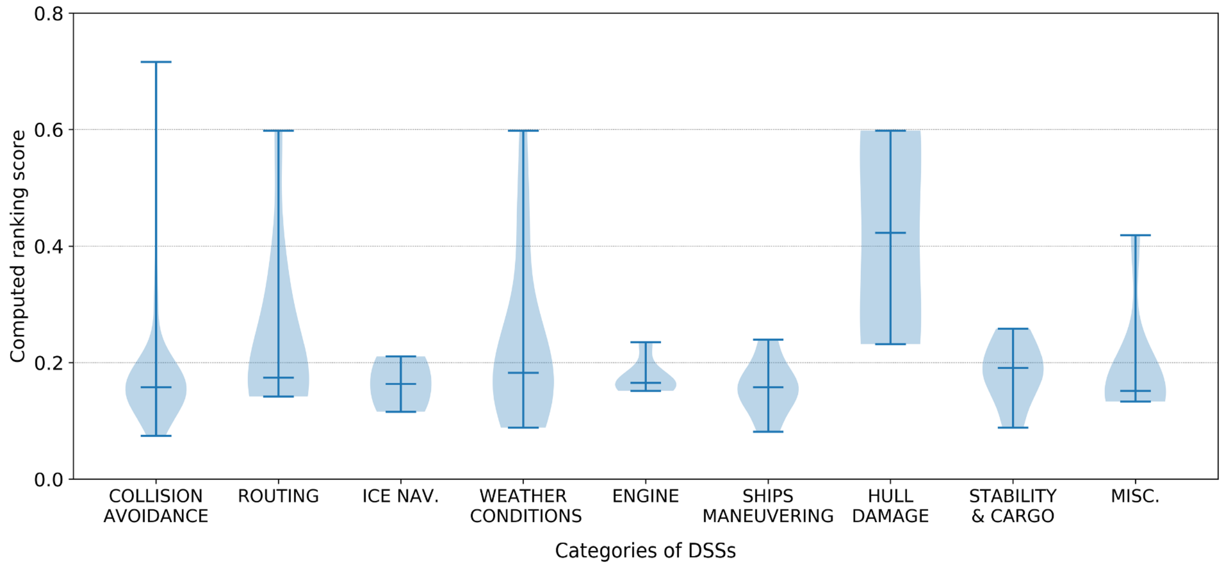

Fig. 17. The violin plot determined for the ranking score of the particular category.

well as software engineering (*Marine Services Inc*. and *Ocean Systems Inc*.) companies. The documents introduced DSSs designed for structural monitoring of operated ships. The systems were proposed as standalone devices composed of hardware (pressure sensors, accelerometers, roll/pitch sensors, positioning devices) and software (operating system, data logging, processing, and analysis). The DSSs, apart from detection of hull loads and monitoring of ship movements (e.g. to detect slamming phenomenon), allowed for improving passage plan of the vessel (also using weather forecasts). The devices were tested in real operational environments during voyages onboard tankers operated by BP and ARCO companies. The solution presented in the paper *Improved Passage Planning Using Weather Forecasting, Maneuvering Guidance, and Instrumentation Feedback* was tested onboard *ARCO California* that is *San Diego*-class tanker (deadweight 190,000 t). Whereas the DSS introduced in the paper entitled *The BP oil tanker structural monitoring system* was initially installed onboard four *Atigun Pass*-class tanker vessels. The feedback received from the crewmembers during the passages was utilized to improve the systems.

The paper entitled *The Ship Movement Trajectory Prediction Algorithm Using Navigational Data Fusion* published by Borkowski (2017) is ranked 4th. In this article, an algorithm used for a prediction of ship trajectories using data fusion, (Borkowski, 2012) from various sources is presented. The paper presents not only theoretical solution but also its implementation into the existing tool used for collision-avoidance – NAVDEC (Pietrzykowski et al., 2017). The algorithm was validated in real environmental conditions onboard one of the ferries trading in the Baltic Sea. The results of the evaluation confirmed the effectiveness of the proposed method (Borkowski, 2017).

The fifth-ranked DSS presented in the paper *VISIR: technological infrastructure of an operational service for safe and efficient navigation in the Mediterranean Sea* belongs to the *weather condition* category. The solution introduced by Mannarini et al. (2016) is the operational DSS, which utilizes weather forecasts for the purpose of route optimization. The VISIR (*discoVerIng Safe and effIcient Routes*) system was designed mainly for small vessels, such as fishing boats, pleasure craft, and sailing yachts (Mannarini et al., 2015) operating in the Mediterranean

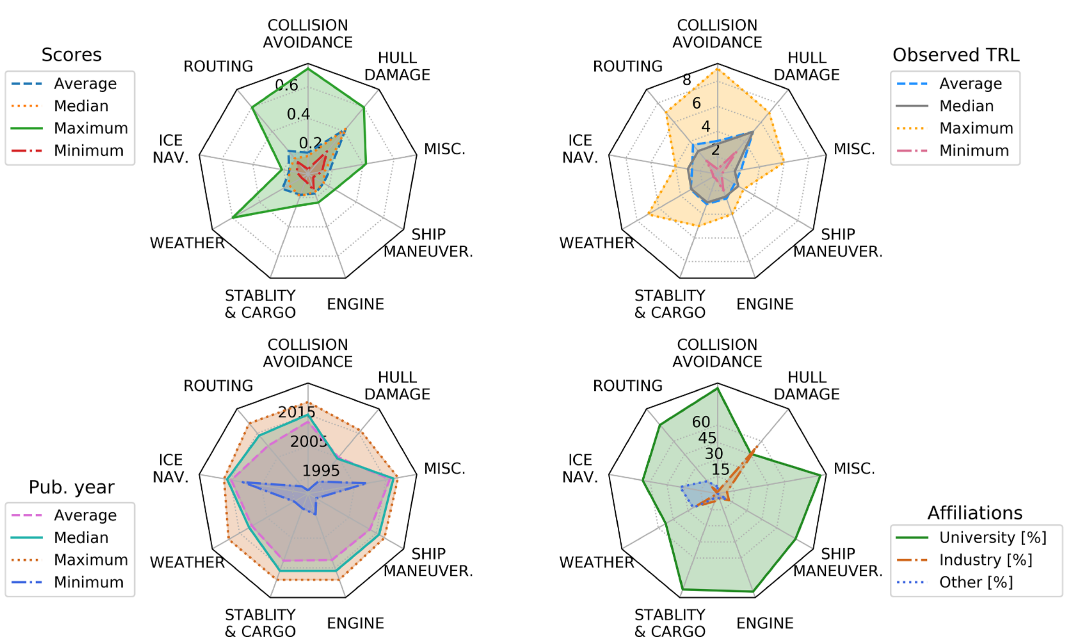

Fig. 18. Radar plots for the ranking score, TRL, affiliation, and publication year for each DSS category.

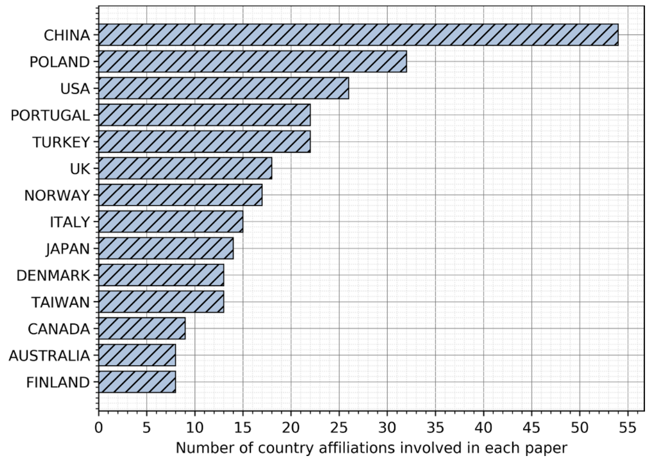

Fig. 19. Total instances of the most affiliated countries involved in the papers using the full-counting method.

Sea. The tool is available as an online service using the website and also as a mobile application. Such solutions arise from the type of end-users and the area of system operation.

The vast majority of the papers from the analyzed sample (62) were assigned to the *collision-avoidance* category. Two other sets with a significant number of documents were related to *weather conditions* (16) and pure *routing* (11). Other types of DSSs, each from six to eight documents, concerned *engine* issues, *ship maneuvering*, *stability & cargo handling,* and *miscellaneous* categories. The least prevalent groups covering each 3–4% of the dataset are *hull loads & damage* and articles related to the *ice navigation* (four and three papers, respectively). Sixteen DSSs were classified as multi-type, i.e. they belong to more than one category. The distribution of the papers into the groups (regarding assumptions presented in Table 1) is depicted as the treemap in Fig. 16.

The categories of the DSS which were most often combined with other types are *routing* and *weather conditions* with six papers each. The group of the systems concerning *weather conditions* was mainly paired with *stability & cargo handling* (three times), as well as *hull loads & damage* (two times). The distribution of the second category for *routing* is more diverse. This type was associated with *collision-avoidance* (two documents), and four other categories (one paper each): *ice-navigation*, *stability & cargo handling*, *ship maneuvering*, and *hull loads & damage*.

As presented, the vast majority of the categories are linked with weather and routing problems. This collocation arises from the assumed scope of DSSs (Table 1), and the multi-disciplinary nature of these two groups. Both are strongly related to path planning when the reason for the modification of the passage plan is necessary. Depending on the cause, a change of the trajectory can involve avoidance of collision, stability-related problems, or excessive forces affecting on ship hull. The *weather conditions* category is related to the environmental factor which is not the operational aim of DSS itself. This is a kind of hub, which links various systems focused on a particular action, while the weather is just a reason for its execution.

The analysis of the scores of the papers by the category indicates that the largest average value belongs to the *hull loads & damage* (0.419). The ranking position (see Table 5) associated with the calculated mean corresponds to 6th place. The difference in the first two categories with the highest average score (*hull damage* and *routing*) was significant and equals 0.183. The basic statistical information about computed ranking scores in a breakdown by the category is presented in Fig. 17.

In Fig. 18, the results of further analysis of reviewed papers are depicted. The detailed information of the papers was determined for each considered category. Each radar plot represents a different aspect of conducted analysis. The investigated parameters were obtained on different stages of conducted research. These are presented (Fig. 18) with the values of basic statistical measures. The computed ranking score (Table 5 in Section 4.1.), *Technology Readiness Level* (TRL) and the type of the affiliation (as described in Section 2.3.), as well as the year of publication obtained during bibliometric analysis (Section 3.2.).

To answer the RQ2, TRL of the papers from the analyzed dataset was investigated. The *Technology Readiness Level* of the solutions is an essential factor because it indicates how usable the tool is in terms of its operational and industrial applications. The general analysis of all documents within the sample indicates that an average TRL of DSS presented in scrutinized scientific articles equals 1.01 (AHP estimated values) that corresponds to TRL between 3 and 4 in the ordinal scale (Conrow, 2011). When it comes to the analysis by the category (see Fig. 18), the average value fluctuates around TRL 3 (EU H2020 scale, (EC, 2014)). Thus regarding Fig. 3, most of the DSSs are developed and presented as feasible proof of a concept without conducted validation and demonstration (EC, 2014), at least according to scientific sources. Their further development may remain unreported to a research community for commercial reasons.

Such relatively low TRL caused further in-depth analysis. All documents included in the sample were manually verified to determine (basing on their authors' affiliations) the countries involved in the production of each paper. Each affiliation of an author was considered

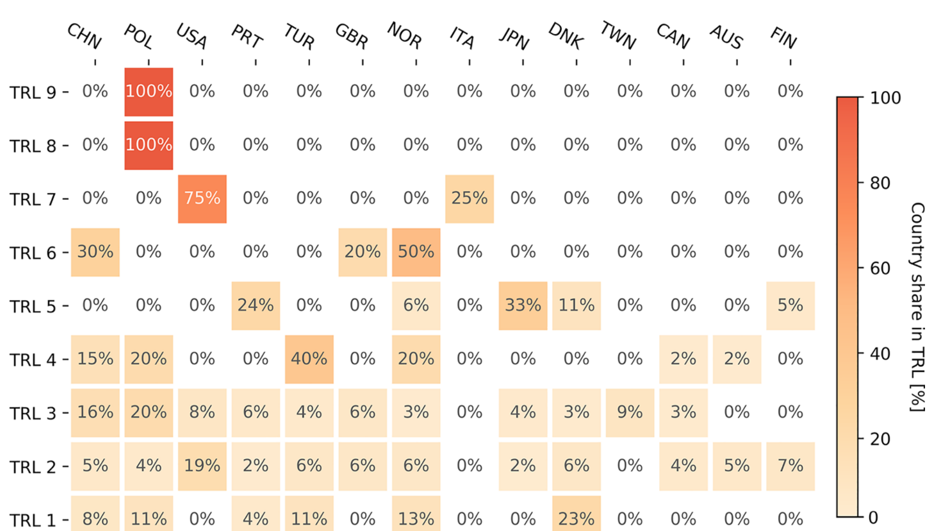

Fig. 20. The heatmap of the share in TRL of papers among selected countries.

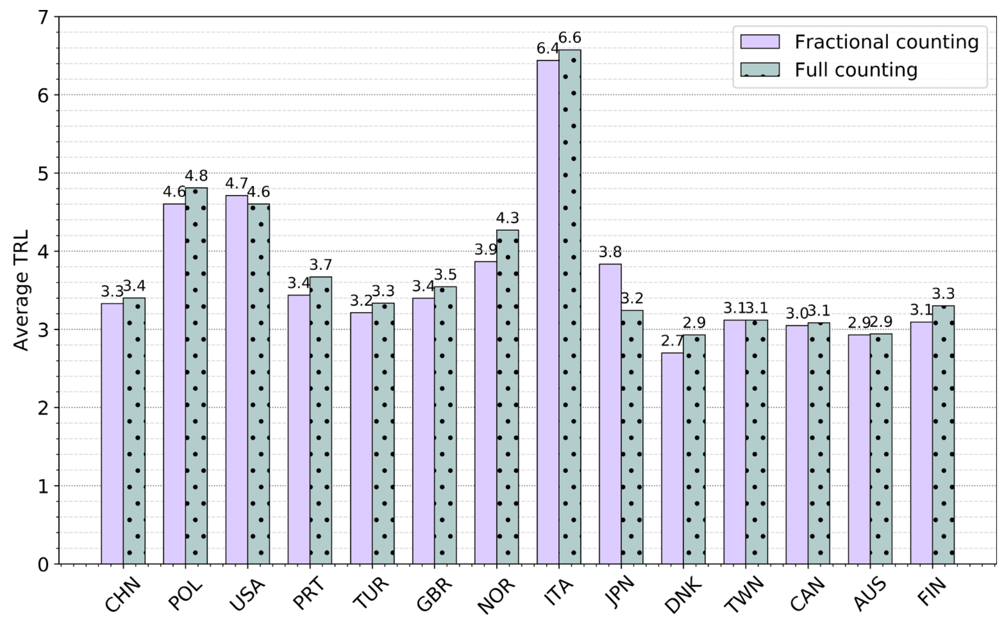

Fig. 21. The average TRL in years 1991–2019 for a particular country involved in the paper.

as a score for a country. When an author was affiliated with more than one institution from the same country, it was counted as one, as a contribution of a particular region was investigated. In Fig. 19 the countries with at least eight affiliations are depicted.

The list of the most contributing countries based on manual reviewing of authors' affiliations differs from the charts created with regard to the corresponding author (Fig. 8). This difference results mainly in the full-counting method where a large number of co-authors disturbs the distribution. An example can be, for instance, Italy (Fig. 19). Despite only one corresponding author in the previous analysis, 13 authors coming from this country published one multi-coauthored paper on high TRL 7 ranked 5th, (Mannarini et al., 2016). After the manual determination of countries involved in each paper, the fractional-counting method was utilized to verify how large is each country's share in TRL. It should also be noticed that the contribution of each author (country) has been assumed as equally-important for a particular paper and so TRL. The breakdown of the share is depicted as a heatmap in Fig. 20. Additionally, the visualization of average TRL for a given country was provided using two different methods: full and fractional counting (see Fig. 21). This was done to avoid distortion of the results for papers with a large number of co-authors. The countries were sorted in descending order with respect to the number of affiliated documents (Fig. 19). As presented, Poland has a significant share in the papers concerning the highest TRL (8 and 9). However, it should be noted that the contribution of this country comprises only one paper per each high TRL, so the percentage is biased. On the other hand, it is hard to expect many solutions on relatively high TRLs in such a small sample of data. The noteworthy is the contribution of the USA with a high TRL share (75%) on TRL 7 with three documents. Nevertheless, all these articles were published almost 25 years ago (all in 1995).

4.2. Comparative analysis of the papers

Based on the ranking computed in Section 4.1, the top-3 documents from each category were collated. The comparison of analyzed DSSs was focused on an area of their application, potential end-users, limitations and existing gaps, features, and TRL. The results of the analysis are tabulated to increase its readability (see Table 6). Italics is applied to highlight the reoccurrence of the solutions, which were classified into a few categories (multi-type). These systems indicate the multidisciplinary nature of solutions proposed by the authors of the documents.

5. Discussion

The study is conducted on a relatively high number of peer-reviewed papers in the domain of onboard DSS for safety ensurance and accident prevention in MTS. The period of increased publishing between 2009 and 2019 could suggest that scientific production meets the users' requirements. However, according to posted research questions the issues of technology readiness (RQ2), further development of the solutions (RQ3), as well as thematic coverage of the DSSs (RQ4) should be discussed.

5.1. Technology readiness level

A noteworthy observation in the conducted study is the readiness level of DSSs proposed among analyzed papers. Even if the scientific value of new concepts presented in the articles is indisputable, their practical applicability was rated remarkably low. That seems to be essential, especially since this indicator has a direct translation to the usability of a given solution. Therefore, it allows for deciding if a solution is a real tool that could support the decisive crewmembers onboard a ship or it is merely an academic concept.

Although TRL was determined for each paper subjectively by the authors (as mentioned in Section 2.3.), and the value could not have been precisely obtained, the level of technology readiness among analyzed documents can be considered in general as relatively low. The largest group among the data sample (62%) appears to represent TRL 3, which is merely a proof of the concept. Moreover, the first three levels include 85% of the analyzed dataset. Such enormous disparity indicates that much work was done in creating DSS concepts, which were finally not implemented into real operational tools. This could arise, for instance, from lack of sufficient funding to continue research and further development of a concept. Obviously, validation and demonstration phases entail larger resource comments than the conceptual stage, as indicated in Fig. 4.

Among reviewed scientific articles, only 16 were validated in any conditions, while 7.5% were somehow demonstrated in a real environment. Thus, most of the reviewed papers present only theoretical concepts and do not contain the results of their demonstration even in laboratory conditions. It should be however noted that solutions with high TRL could exist and be available on the market as fully-operational products, but they were not included in the data sample. Especially,

Table 6
The comparison of top-3 reviewed papers (by the ranking score) in each category.

DSS category	#	Reference	Score	Area of application	Potential end-users	Features	Gaps & limitations	TRL
COLLISION AVOIDANCE	1.	(Pietrzykowski et al., 2017)	0.716	Real-time collision avoidance	OOWs or VTS	Optimal heading calculation	Environmental conditions not considered. The dynamic properties of the vessel are not considered. It does not present data on the feasibility, only mentions that tests were conducted and system implemented. Uncertainties are not addressed appropriately.	9
	2.	(Borkowski, 2017)	0.574	Real-time collision avoidance	OOWs or VTS	A prediction of trajectories	Environmental conditions are not considered. It only considers the dynamic properties of its own vessel to predict her movement.	8
	3.	(*Kufoalor et al., 2019*)	*0.419*	*Real-time collision avoidance*	*OOWs, MASS*	*Cost-optimum collision-avoidance*	*It only uses a simplified model of ship kinematics. Tested for small, easy-maneuverable boat only. It does not consider weather conditions.*	*6*
ROUTING	1.	(*Lacey and Chen, 1995*)	*0.598*	*Structural conditions monitoring*	*Ship management - level of the crew and managers*	*Data analysis for better ship handling*	*Requires additional, dedicated sensors. Only feasible for big ships with significant hull loads.*	*7*
	2.	(Denham et al., 1993)	0.354	Real-time path-planning	OOWs	Data fusion from various sensors	Based on outdated technologies. Not verified in a lab or real environment.	3
	3.	(Grabowski and Sanborn, 1995)	0.325	Real-time path-planning	OOWs, pilots	Includes anti-collision warnings and decision support	System responsiveness is questionable. Real-environment tests proved system logic to be questionable. It does not describe sources of data used for calculations.	7
WEATHER CONDITIONS	1.	(*Witmer and Lewis, 1995*)	*0.598*	*Structural conditions monitoring*	*Ship management - level of the crew and managers*	*Data analysis for better ship handling*	*Requires additional, dedicated sensors to be installed. Only feasible for big ships with significant hull loads.*	*7*
	2.	(Mannarini et al., 2016)	0.463	Weather-based passage planning	Crewmembers of yachts	Principally for small boats	Only available in the Mediterranean Sea. Designed for small boats only, feasibility for bigger ships is not proven. Uncertainties are not addressed appropriately.	7
	3.	(Bitner-Gregersen and Skjong, 2009)	0.412	Weather conditions impact on ship hull	OOWs, ship management – the level of a crew	Dynamic risk calculation	Requires additional sensors and operational procedures. Not verified in a lab or real environment.	3
STABILITY & CARGO HANDLING	1.	(Santiago Caamaño et al., 2019)	0.258	Detection of stability changes	Fishing vessel crews	Roll angle measurement	Mainly applicable to big roll motions. Not verified in a real environment. Lab tests only conducted for no forward speed.	5
	2.	(Hussein et al., 2016)	0.232	Ship grounding conditions	Ship management – the level of a crew	Cargo transfer for refloating	Preparations are required on the ship design stage. No validation either in lab or real conditions	3
	3.	(Husjord, 2016)	0.192	Ship-to-Ship operations	Bridge team	Motion parameters during the STS approach	Not implemented and validated in real conditions. Must have ship hydrodynamic model pre-programmed.	4
HULL LOADS & DAMAGE	1.	(*Lacey and Chen, 1995*)	*0.598*	*Structural conditions monitoring*	*Ship management - level of the crew and managers*	*Data analysis for better ship handling*	*Requires additional, dedicated sensors. Only feasible for big ships with significant hull loads.*	*7*
	2.	(*Witmer and Lewis, 1995*)	*0.598*	*Structural conditions monitoring*	*Ship management - level of the crew and managers*	*Data analysis for better ship handling*	*Requires additional, dedicated sensors to be installed. Only feasible for big ships with significant hull loads.*	*7*
	3.	(Papanikolaou et al., 2014)	0.247	Ship stability	Ship management - level of the crew and managers	Wave load monitoring	Requires a wave direction detection module. Ship hydrodynamic data must be updated on a voyage-by-voyage basis. No validation either in lab or real conditions.	3
SHIP MANEUVERING	1.	(Temarel et al., 2016)	0.240	Prediction of wave loads	Ship managers and ship management - level of the crew	Multiple methods compared	Limited feasibility in its current stage of development. No validation either in lab or real conditions. The paper is more a theoretical review (as per assigned TRL) and does not introduce any novelty. Relatively high ranking score results from the number of authors from the industry.	1
	2.	(Wu et al., 2017)	0.167	Not Under Command ship handling	NUC OOWs	Group decision making	Usual drawbacks of group decision making, including a need to coordinate decisions and time-consuming nature of the process. No validation either in lab or real conditions.	3
	3.	(Dong et al., 2016)	0.164	Strategic passage planning	OOWs and ship managers	Passage planning including repair loss and fatigue damage	Requires ship structural data for passage planning. Sensitive to decision-maker attitude towards risk acceptance. No validation either in lab or real conditions.	3

(*continued on next page*)

Table 6 (*continued*)

DSS category	#	Reference	Score	Area of application	Potential end-users	Features	Gaps & limitations	TRL
ICE NAVIGATION	1.	(Hui et al., 2017)	0.211	Onboard ships in polar waters	Ship management -level of the crew	Passage planning in ice-covered waters	It only addresses the mechanical properties of ice to a limited extent that are not verified in a real environment. It does not consider ice thickness. Models upon which it was built are only applicable in the Arctic and not Antarctic.	4
	2.	(Liu et al., 2016)	0.164	Onboard ships in polar waters	Ship management -level of the crew	GIS solutions	Uncertainties are not addressed appropriately. Highly-dependent on the reliability of ice-cover charts. Only tested on the data provided by the Canadian government. No validation either in lab or real conditions.	3
	3.	(Lubbad and Loset, 2011)	0.116	Onboard ships in polar waters	Ship management - level of the crew	Simulation and model experiments	Limited applicability at the present stage. It does not include some of the relevant phenomena.	1
ENGINE	1.	(Jacobs and McComas, 1997)	0.235	Condition-Based Maintenance	Engine department - crewmembers	Reliability management	Only basic principles are presented. No validation either in lab or real conditions.	2
	2.	(Asuquo et al., 2019)	0.174	Maintenance strategy selection	Ship managers and engine department - crewmembers	Group decision making	Only a few experts were elicited. It only presents an application to the maintenance of auxiliary machinery. No validation either in lab or real conditions. Model uncertainties discussed to a limited extent.	3
	3.	(Cebi et al., 2009)	0.167	Machinery troubleshooting	Engine department - crewmembers	Expert-based system	Only developed to handle auxiliary machinery failures. Research uncertainties covered to only a limited extent. No validation in real conditions.	4
MISCELLANEOUS	1.	(*Kufoalor et al., 2019*)	*0.419*	*Real-time collision avoidance*	*OOWs, MASS*	*Cost-optimum collision-avoidance*	*It only uses a simplified model of ship kinematics. Tested for small, easy-maneuverable boat only. It does not consider weather conditions.*	*6*
	2.	(Sarvari et al., 2019)	0.174	Emergency preparedness	Ship designers, ship management - level of the crew	Management system for evacuation preparedness	Limited use for real-time emergency management. Only developed for ferry-boats. No validation either in lab or real conditions.	3
	3.	(Akyuz and Celik, 2018)	0.159	Oil spill prevention	Ship management - level of the crew	Expert-based	Only a few experts were elicited. Model tested on one case-study only. No validation either in lab or real conditions. Research uncertainties covered to only a limited extent.	2

Abbreviations: MASS – Maritime Autonomous Surface Ships; NUC – Not Under Command; OOW – Officer of the Watch; STS – Ship-to-Ship; VTS – Vessel Traffic Service.

because of the limitation of the document type to scientific peer-reviewed papers only. Regarding this assumption, grey literature encompassing industrial and technical reports were omitted where some systems could have been presented.

In addition, it has been observed that some relation between TRL of the DSS and factors denoting the level of development and wealth of countries may exist. Thus, investigating TRL in relation to factors, such as GDP (*Gross Domestic Product*), HDI (*Human Development Index*), etc. could be an interesting issue for follow-up research.

A solution of the low TRL issue seems to be crucial also in further automatization of maritime transport. On the 99th and the 100th sessions of the *Maritime Safety Committee*, four degrees of autonomy designated for *Maritime Autonomous Surface Ships* (MASS) were accepted, (IMO, 2019). On the first degree of ship operation, *Decision Support Systems* could be used by crewmembers, while a part of the sailing process could be automated. On a higher-level when a vessel is remotely-controlled or supervised by a shore-based operator, these systems could be useful as well (Burmeister et al., 2014; Wróbel et al., 2018). Therefore, increasing operational readiness of DSS by producing high-TRL tools could boost the introduction of autonomous shipping. Especially, due to the utilization of DSS in facilitating the effortless transfer of solutions from manned to unmanned vehicles.

Due to the posted research question (RQ1) which considers the most active scientific networks, it was found that BSR countries were involved in two solutions with the highest TRL (9 and 8). However, in other projects exceeding the level of demonstration (6 or more), no one from the BSR was engaged. It could be also valuable to verify and compare the distribution of TRL in support-systems designed strictly for accident response instead of prevention. The general number of papers, as well as the stage of implementation from a concept into a tool, could be higher due to the nature of response systems. In the post-accidental phase, the ability to make a rational decision is even more important than in accident prevention and hazard prediction. Therefore, more advanced solutions in terms of technology readiness might be noticed there.

5.2. Thematic coverage of the DSSs

In this study, the breakdown of DSSs into nine categories was applied. The grouping was based on the thematic area with respect to the purpose of system operation. In future work, the set of categories could be extended, for instance, by the aggregation of papers currently assigned to *miscellaneous* type. The number of documents in the field of collision-avoidance and routing for both weather and operational conditions was noticeable. This could suggest sufficient coverage of available tools in these categories fulfilling users' needs.

A more in-depth consideration of routing DSSs indicates that depending on the reason for trajectory optimization, the number of concepts or tools is not satisfactory, especially when considering higher TRL levels. Distinguishing causes that lead to a change of ship passage seems to be crucial for the safety of a vessel. The documents introducing routing systems for various reasons, such as evading severe weather, avoidance of excessive hull loads or reducing undue fuel consumption should be considered separately. This approach would lead to a significant decrease in the tools within the *routing* group, but a detailed breakdown could more precisely correspond to end-users' expectations.

This issue is directly related to Arctic shipping and navigation in ice-covered waters, which are popular scientific topics nowadays (Fu et al., 2018; Guinness et al., 2014; Lehtola et al., 2019; C. Zhang et al., 2019). The solutions developed for typical sea-going merchant vessels cannot be smoothly transferred into extreme ice-conditions. However, the small number of the papers included in the analyzed sample focused on this field could arise from a different terminology utilized by authors involved in this topic. The terms usually used in ice navigation include *pathfinding*, *route optimization*, *stuck* or *beset in ice* (Fu et al., 2016; Montewka et al., 2015), regarding decision support systems or their concepts. This discrepancy leads to the omission of valuable papers about decision-making in MTS due to a lack of specific terms in the search query.

5.3. Biases and limitations

The omission of valuable papers related to the topic of the analysis does not only pertain to the aforementioned ice navigation category. The utilization of different words by authors of scientific articles other than those included in the search query should be considered as a limitation of this type of study (Jonnalagadda and Petitti, 2013; Korom, 2019). One of the main challenges during the design phase of scientometric research is the adoption of the search strategy and data gathering process. The query used in the study should be formulated generally to collect a broad dataset and include all potentially valuable papers into the sample. However, it should also be detailed and comprehensive enough to reject all documents which are not related to the subject of the study. Unfortunately, such compromise and golden mean cannot be easily achieved due to the diversity and richness of the vocabulary, as well as a polysemy phenomenon. Even when wildcards are utilized for searching, and researchers try to predict potential synonyms and variations of the words, some publications could still be omitted. It happens because of data mining among thousands of combinations of the results. Such methodological problems become more prevalent when the topic of the study is narrowed and many specific conditions should be met, as in the case of this study (maritime domain, DSS for accident prevention, onboard solutions, selected types of accidents inspired by IMO FSA, etc.).

The aforementioned polysemy denoting different meanings of the same word affects the next limitation of the study related to the process of data gathering. Because of possible ambiguity of terms used in the search query the database could return papers, which are not related to the topic of the study. Moreover, these articles could pertain to other scientific field and provide the vast majority of results if concern popular topic of scientific interest. The representative example noticed in this study is the word *vessel* that besides a vehicle denotes also a kind of container. Therefore, this word combined with terms *decision-making* or *decision-support* leads to collect a number of medical documents, such as Moscatelli et al. (2015), Rovas et al. (2018), and Spencer and Mahoney (2017). Apart from the additional filtering by subsequent conditioning in the search query, manual work was still required to reject unrelated papers (see the procedure of dataset preparation in Section 2.2.). The topic-browsing stage of dataset preparation concerns reading of titles, keywords, and abstracts. It has been performed by the designated co-author to determine if a particular paper should be included in the sample. Afterward, another co-author has reviewed all documents collected during the first stage to decide about their relatedness to the topic of the analysis. Then the categorization and determination of additional parameters, such as TRL or affiliation type were conducted. At these stages of the study, manual screening was performed, and decisive actions were made by insight, experience, and interpretations of the authors. Thus, the research could be biased due to the judgments of the authors involved in the data filtering process.

The review of the papers results also in some general findings of scientific writing and structuring of papers. Because of the utilization of bibliometric analysis as one of the methods, the content of abstracts, titles and keywords played an important role. Especially, that relatedness of the documents matching to the topic was determined manually by the authors based on browsing of papers abstracts (as per Section 2.2.). Moreover, many authors do not provide information about the biases and limitations of their study and the solutions which they proposed. This could lead to re-creating and duplicating solutions instead of continuous development of already existing concepts. Finally, this oversight could result in decelerated progress or even stagnation in some categories of decision-support systems.

Because of all formerly discussed issues, obtained results may be slightly deficient. Nonetheless, the authors endeavored to attain a general picture of the state-of-the-art in DSS for safety ensurance and accident prevention in MTS. The analysis of the prepared sample of the papers depicts an overview of the scientific topic and allows for observation of general trends. However, the presented dataset should not be considered as fully-comprehensive.

5.4. Improvements and future works

In further studies, the framework of the research, as well as the utilized method could be improved. In addition to determining data sample only by the search query and topic-browsing, the set of potentially related papers could be enlarged. To maintain the transparency of the procedure, additional papers could be extracted, for instance, from references of the papers already classified to the sample. Such an approach could lead to extending data sample by relevant papers. It could partially compensate for a potential loss of valuable documents omitted by the words used in the search query. In future works, more than one database containing scientific collections could be utilized as a data source. For instance, *Scopus* could be additionally used, instead of *Web of Science* only. The combination of the results from the two databases could provide an increased range of gathered documents.

The ranking list (Table 5) prepared for the purpose of determining the most relevant DSS for accident prevention in MTS was proposed by taking into account parameters focused on applicability and technology readiness. However, even though the weight of each factor was in line with the research objectives, their values were set solely based on the authors' judgments. Such a method of priority selection caused computation of the score with regard to the relevance designed subjectively by the authors. In further studies, a unified approach could be assumed to select parameters accurately, and fairly distribute their weights.

6. Conclusions

In this paper, a review of onboard *Decision Support Systems* for accident prevention in MTS was conducted using two different methods. Bibliometrics was combined with the systematic literature review to investigate four main aspects addressed in this study.

The first aspect of the research (RQ1) concerned scientific networks in the analyzed field. Obtaining insight in the networking and collaboration indicates the contribution of the *Baltic Sea Region* as significant in the DSS field. The production of the systems in this region seems to be notable in relation to global engagement. Nevertheless, international cooperation in both worldwide and regional aspects should be improved among the BSR authors. The increase of multi-authored international articles could improve know-how sharing between the partners in the BSR. Noteworthy is that the two most advanced papers with respect to their technology readiness (TRL 9 and 8) pertain to the tools designated for collision-avoidance, which were proposed by authors from one of the Baltic Sea Region countries. Apart from the network of BSR countries, the contribution of China, especially in cooperation with Portugal is essential. The conducted analysis indicated that in the course of the last five years, the mutual scientific production of these countries was constantly increasing. The growth in the cluster associated with China causes noticeable fluctuation in global production in the topic of the study. Nowadays, the positive trend noticed in scientific production during the last decade suggests that the topic of maritime DSS for safety ensurance is not completed and will be still successively developed.

The next objectives of the analysis were the determination of the overall technological readiness of the systems (RQ2), as well as their potential further developments (RQ3). Both aspects are directly related to TRL of the solutions. The results of the study indicate that the average TRL presented in the analyzed dataset is relatively low (3). The applicability of solutions or concepts introduced in the documents should be increased to meet the requirements of dynamically changing maritime transportation. This could allow realizing its primary function i.e. providing support as a fully-operational tool by design. The approach to implemented concepts should also be more complex to consider new challenges that marine transportation faces nowadays. Improvements could take into account the changing environmental and operational conditions, for example in the collision-avoidance, to provide even better solutions. Therefore, the increase of technology readiness and further development of DSSs for accident prevention in MTS are necessary, to maintain enhancement of the safety of navigation.

The last point of the analysis was about verifying thematic coverage of scientific contributions related to the topic of the study (RQ4). To depict the overview of DSSs, 107 papers were reviewed. The positive trend and increased production of journal articles in the last years were noticed. The results indicate that coverage of solutions varies considerably in the number of documents, and depends strictly on the category of the system. The type of tools with the highest number of papers includes solutions focused on collision-avoidance. Such systems pertain to more than half of all documents. In this category, the tools with the biggest TRL (8 and 9) were included. Two other, well-covered categories (total 22%) are related to *routing* and *weather* issues, while other groups include solely several papers. However, conducted comparative analysis indicates that even if the number of papers in this field is considerable and tools at high TRL are available, certain gaps and limitations in presented documents still exist.

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