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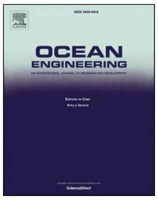

A review on the progress and research directions of ocean engineering

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ABSTRACT

This paper reviews research in ocean engineering over the last 50+ years with the aim to (I) understand the technological challenges and evolution in the field, (II) investigate whether ocean engineering studies meet present global demands, (III) explore new scientific/engineering tools that may suggest pragmatic solutions to problems, and (IV) identify research and management gaps, and the way forward. Six major research divisions are identified, namely (I) Ocean Hydrodynamics, (II) Risk Assessment and Safety, (III) Ocean Climate and Geophysics: Data and Models, (IV) Control and Automation in the Ocean, (V) Structural Engineering and Manufacturing for the Ocean, and (VI) Ocean Renewable Energy. As much as practically possible research sub-divisions of the field are also identified. It is highlighted that research topics dealing with ocean renewable energy, control and path tracking of ships, as well as computational modelling of wave-induced motions are growing. Updating and forecasting energy resources, developing computational methods for wave generation, and introducing novel methods for the optimised control of energy converters are highlighted as the potential research opportunities. Ongoing studies follow the global needs for environmentally friendly renewable energies, though engineering-based studies often tend to overlook the longer-term potential influence of climate change. Development and exploitation of computational engineering methods with focus on continuum mechanics problems remain relevant. Notwithstanding this, machine learning methods are attracting the attention of researchers. Analysis of COVID-19 transmission onboard is rarely conducted, and 3D printing-based studies still need more attention from researchers.

1. Introduction

Oceans are the birthplace of life and water waves (Luo et al., 2013; Maruyama et al., 2013). They are also the habitat of more than two million aquatic species (Mora et al., 2011). The first human settlements were largely established near the deltas, where rivers meet the ocean or the sea (Dixon, 2014; Wink, 2002). Historically, humans engineered different boats and ships to navigate through the ocean and seas (Casson, 2020; Whitewright, 2007) and discover the world since thousands of years ago (Ammerman, 2020). It is therefore not a surprise that today many important cities of the world are positioned in the vicinity of these areas or by the ocean front.

Today, while the international effects of urbanisation are increasing, more than 90% of the international trade is enabled via ocean going shipping transportation (UNCTAD, 2021). Oil and gas industries are heavily dependent on the ocean as petroleum resources form at the sea bottom over a period of million years (Levin et al., 2019). Floating or standing platforms are established to extract oil and gas reserves (McLean et al., 2020). The oceans offer relatively untapped opportunities to generate renewable, low-carbon, environmentally friendly energy from waves, tides, salinity, and temperature (Melikoglu, 2018).

Over the last 50 years the above-mentioned demands pushed engineers and ocean modellers to provide solutions for different *"Ocean Engineering"* problems. To date studies have been attempting to answer questions of relevance to ship operations, the engineering of marine structures, as well as the overall exploration and exploitation of resources. Inaugural studies were led by mathematicians interested in understanding the influence of fluid flow from water waves on ship dynamics (e.g. Bertin, 1905). More recently, globalisation and climate change pushed forward societal expectations for improved utilisation of renewable energies, the advanced prediction of ocean climate (wind, wave, ice extent, sea level rise, etc.), the exploitation of fossil fuels and

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their transfer across the supply chain, the efficient use of aquaculture and dredging.

According to the Organisation for Economic Co-operation and Development (OECD, 2016), employment in ocean-based industries will grow significantly by year 2030, reaching two-times in comparison to 2016. Significant part of this growth may primarily relate to fisheries, the extraction of oil and gas offshore, the development and implementation of modern maritime equipment, coastal tourism and port activities, shipbuilding and maintenance of innovative ships or floating offshore installations (FOI) (Brent et al., 2020). As such, to provide a sustainable economic growth and boost the long-term development prospects of emerging ocean industries, policy makers must appreciate the benefits emerging from ocean engineering research.

In line with these expectations, the United Nations (UN) proclaimed 2021–2030 as the *"Decade of Ocean Science for Sustainable Development"* (Intergovernmental Oceanographic Commission, 2020). Ocean engineering developments are expected to influence (i) the resilience of communities to ocean hazards, (ii) the expansion of the global ocean observation systems, (iii) the creation of ocean digital twins, (iv) sharing data, knowledge and technology worldwide, and (v) human perceptions of the ocean environment. These trends may in turn lead to the development of national ocean policies, new R&D strategies, novel regional and national capacity development and emergency response planning.

The social and economic role of ocean engineering scientists is to reflect upon emerging challenges and develop solutions. The UN expectations for environmental sustainability of relevance to shipping and the adverse impact of COVID-19 pandemic reflect the mounting concerns on our ability to respond to extreme events on a global scale. Recently, examples of developing specific risk mitigation measures for shipping were felt onboard cruise ships and ferries for which it is now acknowledged that the air circulation onboard should be managed by state of the art air transmission systems (Azimi et al., 2021). Alternatively, a floating asset herself may also be used for quarantine purposes complying for international safety management provisions (Codreanu et al., 2021). Extreme ocean climate events namely strong wind and waves, sea-level rise or loss of ice extents may also necessitate adaptive and mitigative measures. For example, the design of ships and offshore structures under climate change effects are discussed by Bitner-Gregersen et al., 2013.

Global organisations, regional agencies, and countries spent a huge amount of research funding to support research, development, and education in the broader field of ocean engineering. Prime examples of funding bodies with specific research interests in this field are the *"National Natural Science Foundation of China"*, the *"Ministry of Education of the People's Republic of China"*, the *"European Commission"*, and the *"Office of Naval Research (USA)"*. According to Gunes (2021), from the 1880s - 2021, nearly 49,000 published journal/conference papers that related to the ocean engineering field have been funded by these agencies. Recent bibliometric analyses, highlighting selected progress of relevance to the field of ocean engineering is presented by di Ciaccio and Troisi, 2021; Gil et al., 2020; Gunes, 2021; Sun and Hua, 2015. These studies primarily focus on the number of publications, author names, countries and institutions where the research is conducted. For example, Sun and Hua (2015) compared the annual output (number of published papers) from China against those of other countries such as the USA and UK. However, to evaluate whether ocean engineering research reflects societal demands and follows progress in technology and computer science, detailed knowledge of the structure of the field, how research topics are interlinked and developed over time, and fundamental research introduced over the years are also necessary.

This paper attempts an in-depth analysis on the research conducted in the ocean engineering field over the last 50+ years. The aim is to describe (1) the structure of the field, including its major divisions, and sub-divisions and their temporal progression, (2) the alignment of research with global technological and socioeconomic demands (e.g. clean and affordable energy Popescu, 2021), sustainability, climate change and pandemics (Barouki et al., 2021; IPCC, 2013), (3) the methods that are widely used for finding solutions to problems, (4) administrative or knowledge gaps and (5) future research directions.

The search methodology is presented in Section 2. Results from the method applied including strategic research threads and gaps are presented in Section 3. At first, the major divisions of ocean engineering are identified. Then through analysing the most occurred terms (as they appear in abstracts and the titles of papers), it is investigated whether ongoing studies reflect global demands. Throughout analysing the similarity between all published papers gaps are identified, and future research directions are suggested. After possible sub-divisions of the field are introduced, fundamental research directions based on key available references are discussed. Concluding remarks are presented in Section 4.

2. Methodology for search

The data used in this paper were identified via an elaborated *"term-based"* search carried out by using the "*Web of Science Classic Mode*". The terms used for the search are based on a very general review of the field of ocean engineering and its applications, published by leading journals namely "*Ocean Engineering*", "*Applied Ocean Research*", "*Coastal Engineering*", "*Marine Structures*", "*Frontiers in Marine Science*", "*Journal of Ship Research*", "*Ships and Offshore Structures*", "*IEEE Journal of Oceanic Engineering*", and an early search of the phrase "ocean engineering" in the "*scopus*" platform.

A combination-based Boolean approach (i.e., "*and*", "*or*") was used to limit the search to the field of ocean engineering. For some phrases that are likely to give false positives, the search was set to be limited to the title of the papers. For some others where false results were less likely to appear the search was done more broadly, and abstracts and keywords of the documents were analysed. No time limit was set for the dataset generated. The results of the search were refined after checking the output to ensure that false results are excluded. To do so, 100 documents of the data were randomly reviewed, and the ones identified as false results were selected. Then, the keywords of the data with the false results were excluded from the search query. Refining the dataset was done until no false results were identified.

3. Data analysis

Throughout the search, nearly 51,000 documents were found. These cover different ocean engineering topics, ranging from the hydrodynamics of ships to the engineering of marine structures, and to the exploration of the ocean. Studies spanned from the early 20th century to today. The ideas presented in literature have grown exponentially over recent decades. Back in the first three decades of the 20th century studies were often carried out by mathematicians (e.g. Green, 1918). Researchers were mostly concerned with the dynamics and the stability of ships and submarines (e.g. Bertin, 1905; Lorenz, 1904; Siemann, 1909; White, 1906), ship resistance (e.g. Haack, 1903a, 1903b; Havelock, 1909; Lorenz, 1907), and propulsion (e.g. Ahlborn, 1905; Berg, 1918; Helling, 1907; Hildebrandt, 1903; Kaemmerer, 1914; Lorenz, 1907; Lucke, 1921; Riehn, 1919). In the following sub-sections, the emergence of major divisions and sub-divisions of the vast field of ocean engineering are identified and discussed.

3.1. Divisions of the field

In this section the patterns of co-occurred terms cited in the titles and abstracts documented are analysed, and the major divisions of ocean engineering field are identified. The co-occurred terms formed different clusters, marked with different colours, that are similar thematically to those presented in Fig. 1.

The size of the nodes as depicted in Fig. 1a indicates the number of term occurrences within each cluster. Overall, six major clusters which

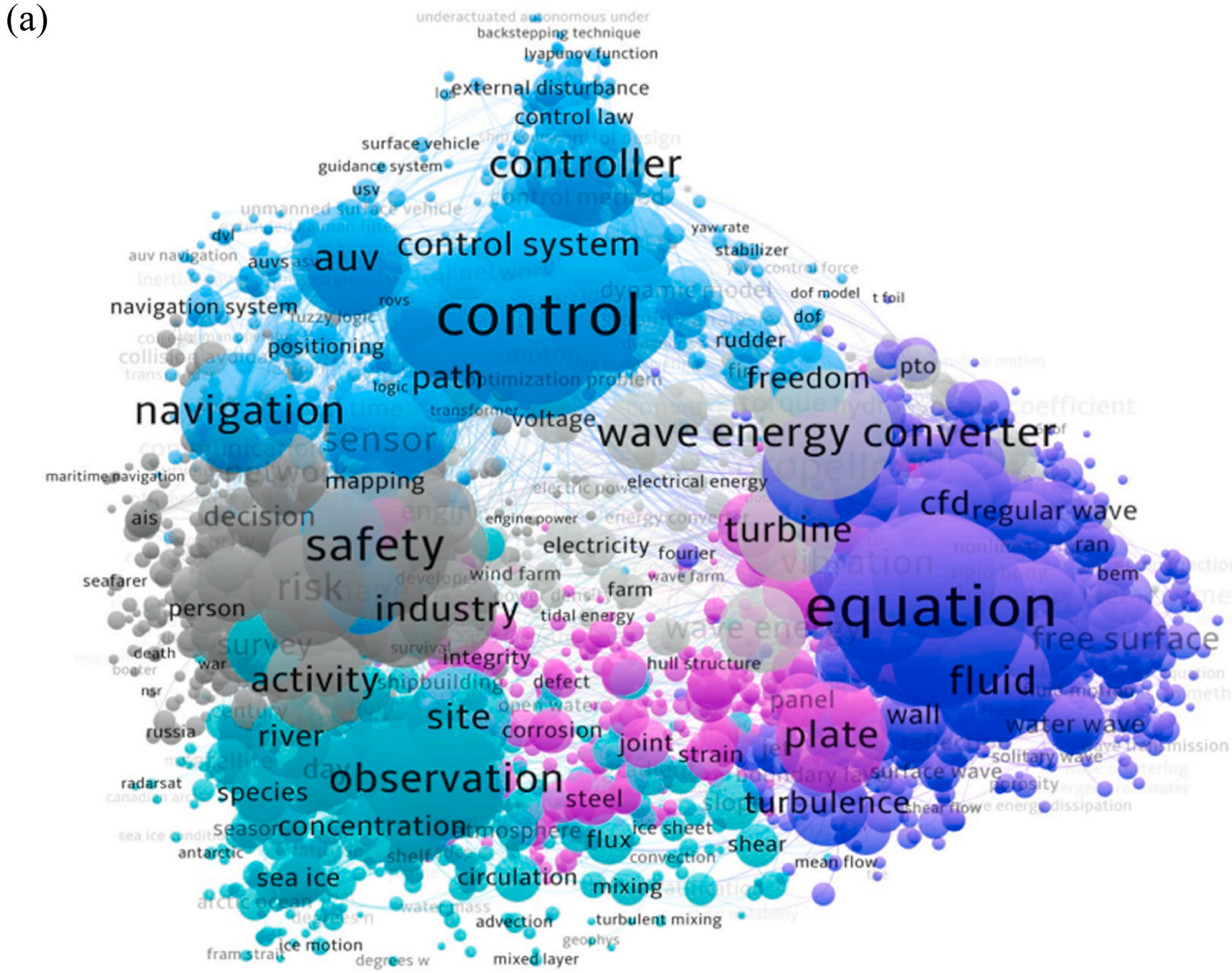

Fig. 1. Co-occurred terms in the field of ocean engineering depicting the major divisions of the field (a). Spatial maps of average publication year (b) and average citation (c). An interactive map is accessible from: https://app.vosviewer.com/?json=https://drive.google.com/uc?id=1UbV6LviTp7SPkacHHGjZ_rtwo7q3zteB.

represent the main divisions of the field of ocean engineering were identified namely (1) "*Ocean Hydrodynamics*", (2) "*Risk Assessment and Safety*", (3) "*Ocean Climate and Geophysics: Field Data and Models*", (4) "*Control and Automation in the Ocean*", (5) "*Structural Engineering and Manufacturing for the Ocean*" and (6) "*Ocean Renewable Energy*".

Cluster (1) deals with research of relevance to experimental, numerical, and theoretical modelling of fluid dynamic problems. It covers ship performance (e.g. Belibassakis et al., 2013), interaction of water waves with structures (e.g. Das et al., 2018; Huang et al., 2022a; Meng and Zou, 2013; Meylan and Sturova, 2009; Zheng et al., 2020), the hydrodynamics of propellers (e.g. Behera and Sahoo, 2015), sea loads and responses (Hirdaris et al., 2014; Meylan, 2001) including fluid-structure interactions (FSI) of ships or any other floating objects (Behera and Sahoo, 2015; Hirdaris et al., 2003; Hosseinzadeh and Tabri, 2021; Hu et al., 2022; Lin and Lu, 2013). In cluster (1), "*equation*", "*fluid*", "*cfd*", "*turbulence*", and "*regular wave*" are the most repeated terms. This suggests that CFD (Computational Fluid Dynamics) methods are a hydrodynamic modelling tool that in recent years has been favoured by many ocean engineers and researchers who increasingly work toward SBD (Simulation Based Design; see Stern et al., 2015). From a fundamental engineering science perspective, the term "*turbulence*" is mostly linked to research performed using CFD (Pena and Huang, 2021a). This term is also evident in studies dealing with the breaking of water waves (e.g. Augier et al., 2019; Babanin, 2006; Babanin and Haus, 2009; BADULIN et al., 2007; Deane et al., 2016; Ghantous and Babanin, 2014; Li et al., 2022; Nazarenko and Lukaschuk, 2016).

Cluster (2) comprises of scholarly documents addressing risk assessment in the ocean domain (e.g. Brandsater, 2002) including the exploitation of modern nuclear technology (Hirdaris et al., 2014), decision making (e.g. Shaobo et al., 2020; Wang et al., 2020; Xue et al., 2019), ship navigation (e.g. Fang et al., 2018), safety of ships and other marine structures (e.g. Bareiss and van den Berg, 2015), and ship traffic management (e.g. Zhou et al., 2019). The terms "*safety*", "*industry*", and "*activity*" characterise this cluster. This reflects that the output largely discusses industrial activities, and targets suppliers, companies, and ocean managers.

Cluster (3) highlights the geophysical aspects of the ocean that are linked to the ocean engineering space. This research division revolves around wave and wind data and modelling (e.g. Freeman et al., 2019; Hasager et al., 2011; Houser and Bluestein, 2011; Li et al., 2016; Najafzadeh et al., 2021; Thomas et al., 2005). Research in this area may be potentially used for the design of marine structures under concurrent or selected extreme events. More recently, research on sea ice motions and their effects on wave statistics grows (e.g. Najafzadeh et al., 2022; Zhao and Zhang, 2021). "*Observation*" is the most repeated term. This signifies that most research is conducted through physical observations

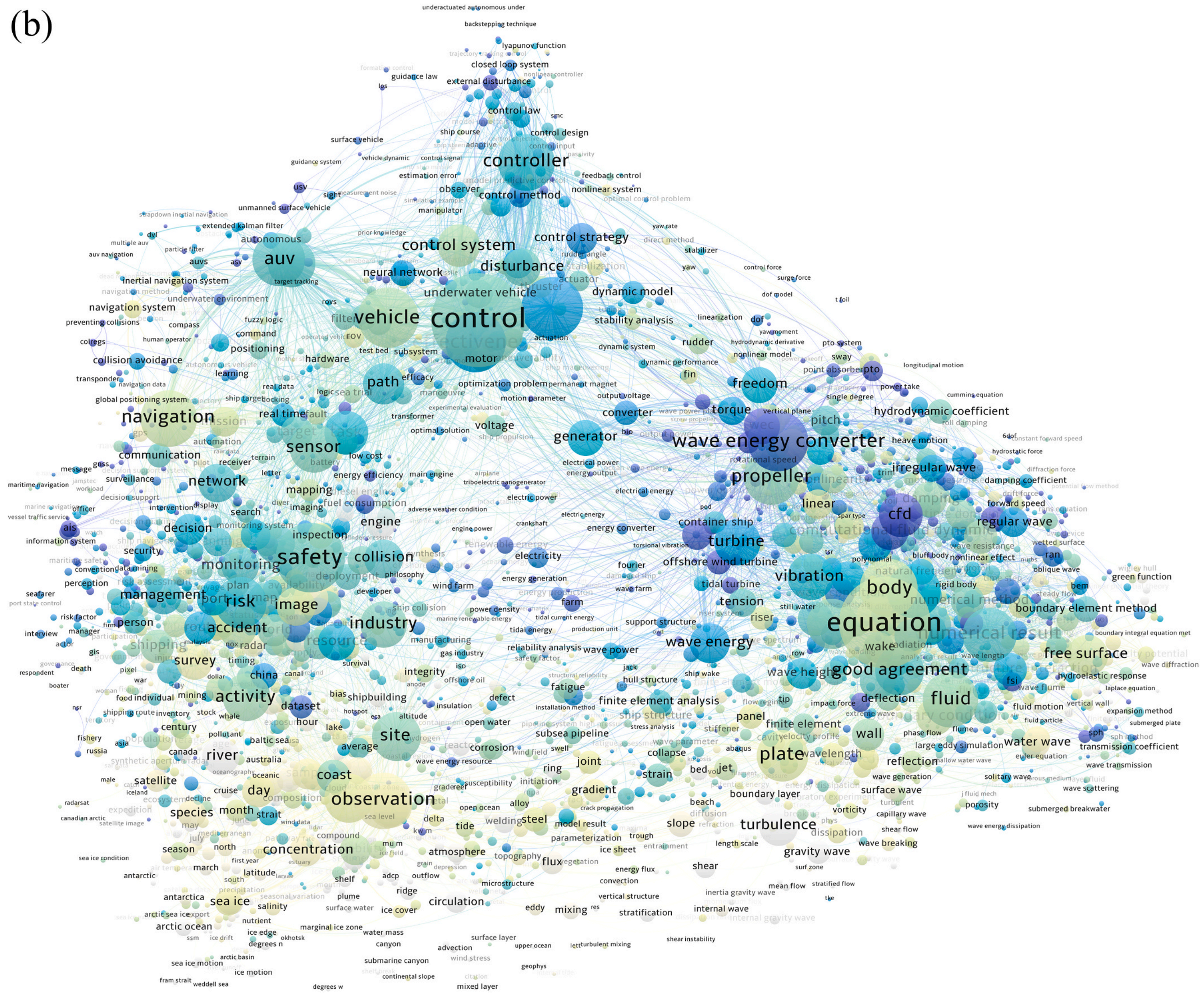

Fig. 1. (*continued*).

in a way that is usually understood by earth scientists and/or geophysicists (Sharp, 1988).

Cluster (4) covers research of relevance to the control of floating objects and vehicles in the ocean. Understanding directional control processes is useful for manoeuvring, dynamic positioning and navigational pathing of ships and FOI (e.g. Çimen and Banks, 2004; Nguyen et al., 2007; Perez and Donaire, 2009; Shih et al., 2012; Talha et al., 2017; Wang and Liu, 2021; Xia et al., 2019). Recently, studies relate more with the automation of unmanned surface or underwater vehicles (e.g. García-Valdovinos et al., 2014; Gu et al., 2019; Hou and Cheah, 2011; Liu et al., 2016; Ngatini et al, 2017; Ojha et al., 2020; Villa et al., 2016; Xiang et al., 2012; Yang and Gu, 2007), and the control of wave/wind/tidal energy converters (e.g. Deng et al., 2019; Gu et al., 2019; Wang et al., 2020). The design of controller systems, and their effects on dynamic stability of objects are studied in this cluster (e.g. Gu et al., 2019). “*Control*”, “*controller*”, “*navigation*” and “*AUV*” are the most frequently used subtopics.

Cluster (5) addresses ship structural design, ship strength including accidental loading (e.g. collisions and groundings) ship impact in waves and the overall ship building process (e.g. Akpan et al., 2002; Bhandari et al., 2015; Chen et al., 2003; Ehlers and Østby, 2012; Friis-Hansen and Simonsen, 2002; Gordo and Soares, 2009; Guedes Soares et al., 2011; Kim et al., 2022a, 2022b; Mantari and Guedes Soares, 2012; Otto et al., 2002; Petry et al., 2022; Saad-Eldeen et al., 2011a, 2011b; Soares and Teixeira, 2000; Tanaka et al., 2015; Yu and Amdahl, 2016; Zayed et al., 2018). “*Plates*”, “*Steel*”, “*Joint*” and “*Collision*” are the most repeated terms in this research division. This indicates that research is mostly focused on the mechanics of “*thin wall structures*”. However, both computational and experimental methods are utilised by researchers as much as practically possible.

Cluster (6) describes the accumulation of documents that investigate marine and offshore renewable energies. Insights into the potential sources (present day and future conditions) of renewable energy are presented in (e.g. Carballo et al., 2009; Castro-Santos et al., 2016; Fusco and Ringwood, 2010; Gonçalves et al., 2014a, 2014b; Iglesias et al., 2009; Iglesias and Carballo, 2010a, 2010b; Iglesias and Carballo, 2011, 2009; Ramos et al., 2013; Ribal et al., 2020; Rusu and Soares, 2009, 2012a; Silva et al., 2018; Veigas and Iglesias, 2013). Research in this area also focuses on methods that may be used for the extraction of ocean energy (e.g. Allen et al., 2016; Astariz and Iglesias, 2016; Babarit, 2015; Bergillos et al., 2019; Calvário et al., 2020; Chen et al., 2015; Depalo et al., 2022; Gaspar et al., 2018; Kamarlouei et al., 2022; López

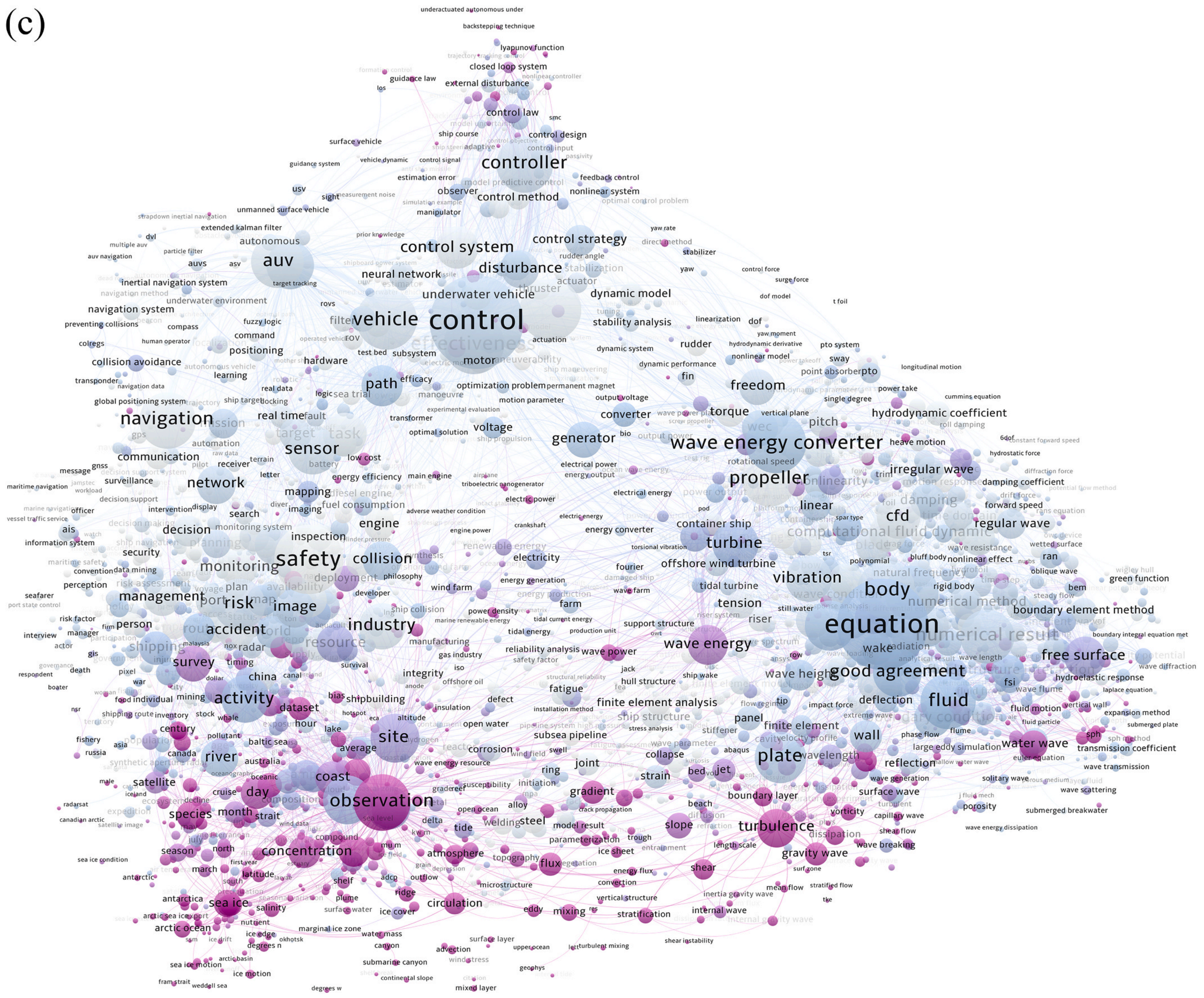

Fig. 1. (*continued*).

et al., 2019; Rezanejad et al., 2019; Rezanejad and Guedes Soares, 2021, 2018; Veigas and Iglesias, 2015; Xiao et al., 2016; Xu et al., 2020; Zheng et al., 2019) and the environmental impact of renewable energy devices (e.g. Iglesias et al., 2018; Rusu and Soares, 2013). The keywords "*wave energy converter*", "*turbine*" and "*electricity*" are the most widely used terms. This underscores that researchers primarily focus on the analysis of the performance of different ocean energy converters (OWC), the feasibility of developing these technologies and their potential environmental (operational) impact.

Fig. 1b and c presents two colour-coded maps that illustrate the average publication year of the papers and the average citation of documents respectively. The map presented in Fig. 1b is based on static data. This means that, there is no temporal progression and hence, no time history could be presented to assess the progress in each cluster. An exception to this is sub-section 3.3, for which the time history of its subdivisions (field sub-clusters) are presented.

In cluster (1) namely "*Ocean Hydrodynamics*", the terms "*cfd*", "*sph*","*bluff body*","*vof*","*fsi*" and "*large eddy simulations*" became increasingly evident in recent years (Fig. 1b). The term "*sph*" refers to "*Smoothed Particle Hydrodynamics - SPH*", a computational method used for solving free surface flows that was introduced in early 1990s (Monaghan, 1994). The term "*vof*" refers to the well-known "*Volume of Fluid – VOF*" method. This method is used to formulate air-water (or two-phase) flows. The term "*fsi*" stands for "*Fluid-Structure Interaction – FSI*" (also known as fluid-solid interaction). The terms "*Green function*", "*water wave*", "*free surface*" and "*equation*" are old terms from cluster (1). In recent years progress in the broader area of computational modelling of fluids, and more specifically FSI, led to a paradigm shift from theoretical to computational mechanics (e.g., Boundary Element for linear and weakly nonlinear hydrodynamics and CFD methods for nonlinear hydrodynamics). However, this does not mean that purely theoretical/analytical models are not important as they provide the fundamental background for research. Interestingly, papers including the terms "*water waves*", "*nonlinear effects*", "*sph*" are the most cited ones. This demonstrates the importance of advanced wave physics, and their interactions. It also suggests that SPH modelling of water waves and their effects on marine structures is a dynamic subfield of research. Overall, researchers dealing with cluster (1) have been very successful in the development of engineering science and new solutions (models), that may be used to optimize the design and/or operational performance of ships and FOIs. The development of computational models and tools (e.g. Bonnet, 2022; Cary et al., 2022; Mahfuz et al., 2021), the enhancement of engineering science of relevance to fluid dynamics, turbulence, free surface flows, and marine hydrodynamics, the development of experimental methods that can measure fluid dynamic properties (e.g., Particle image velocimetry - PIV), and their effects (loads and fluid-induced dynamic motions) are only some examples. Researchers have not considered the influence of climate change effects on the design of ocean engineering artefacts. Perhaps a fundamental reason for this has been the traditional notional distancing between marine engineering and climate sciences.

In cluster (2) namely "*Risk Assessment and Safety*", "*ais*", "*preventing collision*" and "*data mining*" are the most recent co-occurrence terms. The terms "*server*", "*image*" and "*radar*" are considered old. This implies that the researchers interested in cluster (2) are increasingly adopting machine learning methods and big data analyses techniques to address problems of significance (e.g. Sawada et al., 2021). Progress is supported by recent advances in Artificial Intelligence (AI) and the available AIS (Automatic Identification System) data. Some additional terms namely, "*fuel consumption*", "*fuel saving*", "*emissions*", "*emission reductions*", "*greenhouse gas emissions*", "*NOx emission*" and "*sustainable*" strongly emerge in recently published papers, though they are not significantly occurred in the titles of publications and the abstracts of this cluster. These observations suggest that cluster (2) is gradually advancing toward sustainability which can be achieved by achieving improved operational expenditure (less cost for fuel assumption) by ships and improved adaptation to climate change targets (reduction of CO2, NOx and greenhouses emissions). Researchers dealing with cluster (2) have been successful in risk assessment and safety of relevance to ships and ocean engineering structures (e.g. Abaei et al., 2022, 2021; BahooToroody et al., 2022; Basnet et al., 2022; Chaal et al., 2022; Zhang et al., 2023; Zhang et al., 2022), offshore technology (e.g. (Abaei et al., 2019; BahooToroody et al., 2016; Biehl and Lehmann, 2006; Gkoumas, 2010; Hallowell et al., 2018; Li et al., 2021; Meng et al., 2019; Ni et al., 2022; Toroody et al., 2016a, 2016b; Wang et al., 2022), and pipping (e.g. Arzaghi et al., 2018a, 2018b, 2017; Song et al., 2020). This is because risk and safety models can be based on concepts of statistical and big data sciences. Some of the research and innovation presented in this area has similarities with other fields of engineering (e.g., safety science). Notwithstanding this, safety models have not been yet coupled with functional safety multiphysics models of relevance to the design and operation of ships and FOIs (e.g., wave loading, resistance in waves and seakeeping analysis models). The latter could be attributed to engineering and science complexity. In this area of work coupling numerical models with risk assessment methods remains difficult.

In cluster (3) namely *"Ocean Climate and Geophysics: Field data and Models"*, the most recent co-occurrence terms are "*dataset*", "*wind data*", "*wave energy resource*", "*baltic sea*", "*decline*" (Fig. 1c). The former three terms reflect the pressing need to mitigate climate change impacts by updating the wave and wind climate datasets. Accordingly, recent studies include the keywords "*dataset*", "*wind data*", and "*wave energy resource*". Continuous reference to the "*baltic sea*" reflects the importance of this operational area for navigation under heavy marine traffic and ice infested conditions. The most cited papers mention key words such as "*observation*", "*sea ice*", "*arctic ocean*", "*Antarctica*", "*salinity*" and "*ice edges*". This trend that has not been observed in clusters (1) and (2). It highlights that research performed in cluster (3) is of multidisciplinary scientific value (e.g., climate, geography, geophysics, meteorology, etc.). Studies falling under cluster (3), have been successful in terms of introducing methods for monitoring and modelling climate data (e.g., wave climate, sea level rise, extreme events, loss of ice extent, etc). Climate models focus mostly on wave modelling using parametrised equations (e.g. Ardhuin et al., 2010; Babanin et al., 2010; Banner et al., 2000; Cavaleri et al., 2007; Stopa et al., 2016). However, climate modelling also depends on wind, bathymetry, ice extent, etc. data provided by earth - and geo - scientists. To date computational simulations of relevance to ice thinning and loss of ice extents are not that accurate primarily because of the very complicated mechanical

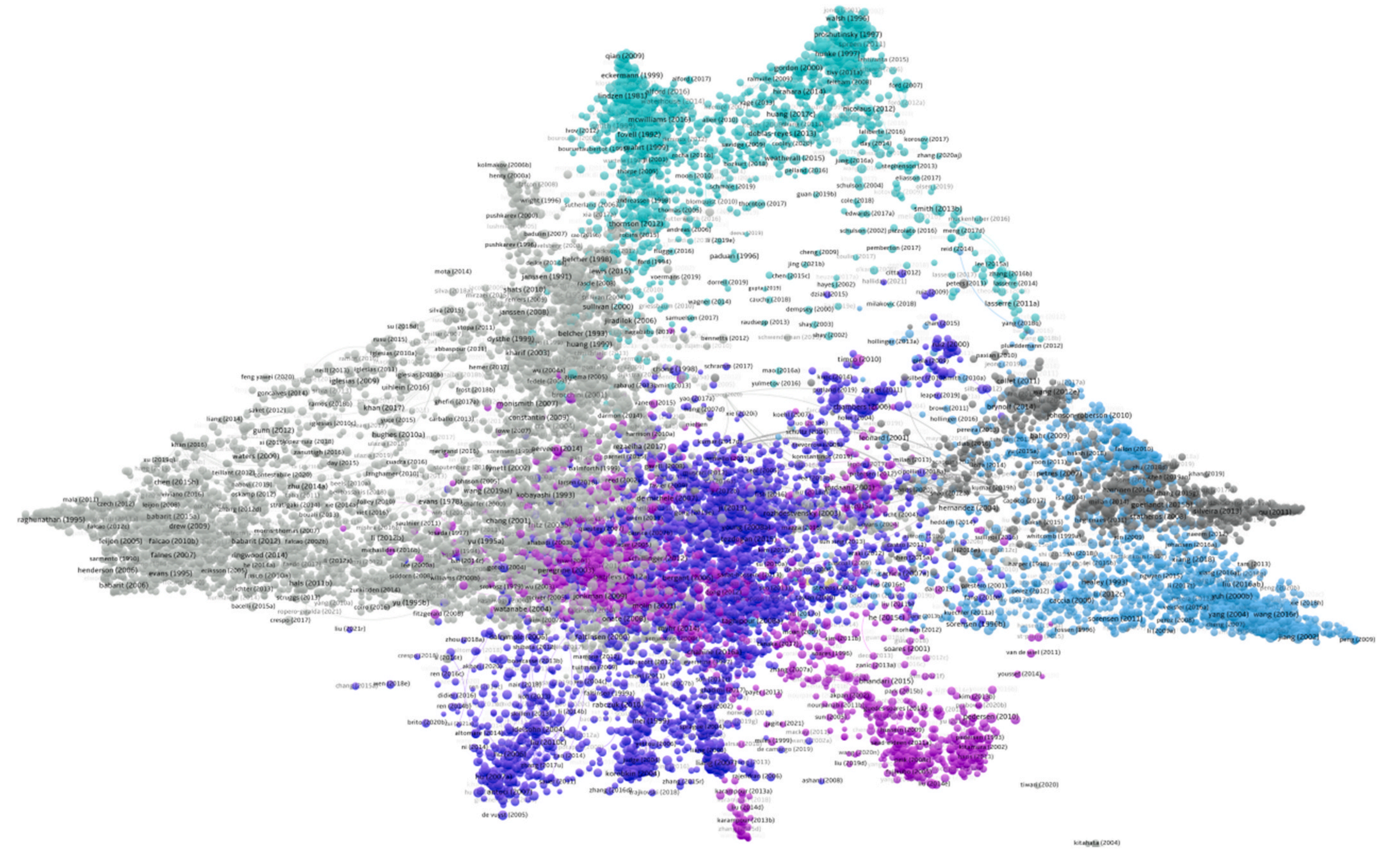

Fig. 2. A map showing all documents of the field of ocean engineering (data found through the search), generated by considering the bibliographic coupling.

properties of sea ice (Jeffries et al., 2013; Overland and Wang, 2013). Ice - water - flow interactions have been understood only within the context of linearity (Squire, 2018). With these challenges in mind, further work along the lines of research encompassed by clusters (1) and (5) may be considered advantageous. For example, experts of cluster (1) can provide more complicated models for nonlinear ice motions (e.g., Huang et al., 2019; Kostikov et al., 2022, 2021; Tavakoli et al., 2022a; Tran-Duc et al., 2020). On the other hand, researchers dealing with problems under cluster (5) may help deepen our understanding on the mechanical behaviour of ice (e.g. He et al., 2022; Lilja et al., 2021; Polojärvi, 2022; Juan Wang et al., 2020).

Most terms emerging under cluster (4) namely "*Control and Automation in the Ocean*" are found in recently published literature. Research in this area primarily supports the UN agenda for sustainable development and lower anthropogenic emissions by 2050. Terms such as "*energy efficiency*", "*unmanned surface vehicles*" and "*optimization problems*" appear in the abstracts and titles of recently published documents under this cluster. This confirms that control engineers dealing with the ocean have been concerned with (1) reducing ship fuel consumption, (2) the automation of surface vehicles and (3) the overall optimisation of the performance of marine vehicles. Problems (1) and (3) are interconnected. This is because optimization of the hull form of a marine vehicle may reduce fuel consumption and improve environmental sustainability (Dashtimanesh et al., 2022). "*Automation of surfaced vehicles*" has also been recognised as the "*Next Revolution of Maritime Transportation*" (Wall Street Journal, 2016). In this field papers that received good number of citations include the terms "*control loop*", "*control design*", "*guidance law*", and "*feedback law*". Studies carried out in cluster (4) have been successful in terms of ship automation and control (e.g. Veitch et al., 2022). This is principally because control theories matured. However, this is not the case for the specialist case of fluid control around ships and FOIs. Examples are related to cases for which air bubbles (see air lubrication systems) are generated near the ship wall to minimize resistance forces (leading to drag reduction) or slamming loads (e.g. Elhimer et al., 2017; Ma et al., 2016; Wang et al., 2022). The possible reason is that such studies are mostly carried out by researchers dealing with cluster (1), and focus on the fluid motions.

In cluster (5) namely "*Structural Engineering and Manufacturing for the Ocean*", most documents are relatively old. The most recent research used term is "*fea*" (Finite Element Analysis - FEA), a method that is mature and can be broadly used for computational modelling of structures. Other key words are "*abaqus*" (which is a very specific yet broadly accepted general FEA based code), "fracture", and "microstructure". The first two terms are related to coding and computational models used for solving solid dynamic problems and are being constantly updated. Interestingly, the terms related to meshless methods do not emerge as significant research trend. This is dissimilar to what was observed for cluster (1), in which research in meshless methods (e.g., SPH models) has been strongly evident. Papers that encompass the term *"microstructure"* emerge because of the advancement of technologies that allow for higher quality manufacturing methods (Wang et al., 2021; Zhang et al., 2022). It is recognised that state of the art manufacturing methods such as *"3D printing"* may lead to the production of lighter propulsion systems (e.g., propellers, structures and equipment as reported by Sandrine Ceurstemont, 2021). However, research intensity in this area is not evident and contradicts growing applications in other fields of engineering (Ngo et al., 2018). A reason could be the complicated structural topology of ship hulls and associated shipbuilding capital expenditure.

In cluster (6) namely "*Ocean Renewable Energy*", the co-occurrence terms "*wave energy converter*", "*offshore wind turbine*", "*tidal turbine*", "*wave farm*" and "*wind farm*" are broadly mentioned in abstracts and titles of recent papers. Research attempts to address new types of energy converters, the design of systems for efficient extraction of marine renewable energies, and the overall performance of energy production devices (e.g., converters, wind or tidal turbines). The terms "*wave energy*", "*wave power*" and "*power density*" can be found in the abstracts and titles of the papers that received the highest citations. Research papers and reports including these terms mostly discuss the concept of extraction of wave energy and examine the potential of wave and wind energy resources. Cluster (6) has been successful in terms of addressing different methods for energy extraction from the ocean along with the prediction of the future energy resources. This is mainly because the tools that can be potentially used for forecasting energy resources or for the estimation of power extraction are well developed and employed by researchers studying ocean renewable energy. Another possible reason for the success of this research cluster may be related to the fact that the performance of energy converters is often simulated using mathematical and numerical hydrodynamic models, which are well developed in cluster (1). Presently, it is hard to comment whether studies in this field have successfully considered environmental impact.

Similarity analysis for papers/reports found through the search was carried out as depicted in Fig. 2. The research documents that can be seen on the left corner of Fig. 2 cover "*Ocean Renewable Energy*" - cluster (6). The ones in the top corner of the same figure are papers that highlight "*Ocean Climate and Geophysics: Field data and Models*" - cluster (3). The two branches located at the right corner include documents that address: "*Risk Assessment and Safety*" - cluster (2) and "*Control and Automation in the Ocean*" - cluster (4). On the other hand, the documents that are in the centre and on the branches of the lower corner fall in the division of "*Ocean Hydrodynamics*" - cluster (1). The rest of documents that are in one of the branches of the lower corner relate to "*Structural Engineering and Manufacturing for the Ocean*" - cluster (5). It is noted that close topology of co-occurrence clusters implies similarity in terms of aims, findings, or the methods employed. Dashed lines (marked with a number under Fig. 2), highlight notional coincidences. The following key points should be highlighted:

- Documents presenting the performance of OWC, tidal energy turbines, and hydrodynamics of floating or fixed offshore wind turbines (e.g. Antonini et al., 2016; Benites-Munoz et al., 2020; Bourgoin et al., 2020; Delauré and Lewis, 2003; Gaurier et al., 2015; Hunter et al., 2015; Lisboa et al., 2018; Liu et al., 2011; Lloyd et al., 2021; Ma et al., 2018; Nguyen et al., 2020; Oikonomou et al., 2020; Renzi and Dias, 2012; Sun et al., 2021) are where clusters (1) - "*Ocean Hydrodynamics*" and (6) - "*Ocean Renewable Energy*" notionally coincide (see marker 1 in Fig. 2). The likely reason for this occurrence is that the study of different energy converters requires hydrodynamic modelling and analyses.
- Research papers and reports presenting wave, wind and tidal energy resources are where clusters (3) - *"Ocean Climate and Geophysics: Field data and Models"* and (6) - *"Ocean Renewable Energy"* meet (see marker 2, Fig. 2 and Khojasteh et al., 2022a, 2022b, 2018a, 2018b; Khojasteh and Kamali, 2016; Kirinus et al., 2018; Korotenko et al., 2020; Mirzaei et al., 2015; O'Hara Murray and Gallego, 2017; Robins et al., 2015; Rusu and Onea, 2017, 2013; Silva et al., 2015; Smith et al., 2017; Stopa et al., 2011; Tang et al., 2014a, 2014b; Ward et al., 2018). The reason for this co-occurrence is that some of the studies concerned with ocean energy require predictions of wave and wind climate to analyse the effects of climate change on energy resources.
- There is a big gap in the middle of the map presented in Fig. 2. This is because research papers dealing with fluid motion around objects are mostly related to environmental applications (e.g., mutual effects of human made structure/ships and the environment), and nature-related disciplines (e.g., mutual interaction of fluid flow and a viscoelastic ice layer) are positioned on the left edge of this gap (marked with number 3 in Fig. 2). These studies often focus on:

    ○ Wave-ice interactions (Bennetts and Squire, 2012; Santu Das et al., 2018; Huang and Thomas, 2019; Kohout et al., 2007, 2014, 2015; Kohout and Meylan, 2008; McGovern and Bai, 2014; Melsom, 1992; Nzokou et al., 2011; Rabault et al., 2016; Rogers et al., 2016; Squire, 2011, 2020; Voermans et al., 2021; Wu et al., 2021);

○ Ship/ferries wake waves (Bellafiore et al., 2018; Ellingsen, 2014; Fujimura et al., 2010; Lin and Kuang, 2004; Machicoane et al., 2018; Moisy and Rabaud, 2014; Noblesse et al., 2014; Parnell et al., 2015; Pethiyagoda et al., 2014; Rabaud and Moisy, 2014; Reed and Milgram, 2002; SHEN et al., 2002; Tavakoli et al., 2022b; Tings, 2021; Torsvik et al., 2015; ZHU et al., 2008; Zilman et al., 2015);

○ Effects of fouling and antifouling on the performance of ships, propellers, and turbines (Andersson et al., 2020; Niebles Atencio and Chernoray, 2019; Owen et al., 2018; Schultz, 2007, 2004; Sezen et al., 2021b; Song et al., 2020; Ünal, 2015; Yeginbayeva and Atlar, 2018), and

○ Noise emission from propulsion systems and tidal turbines (Guo et al., 2021; Ku et al., 2020; Lidtke et al., 2016; Rosli et al., 2020; Sezen et al., 2021a).

- Research documents that use mathematical models, big data analysis techniques, empirical methods, and AI to study the interaction between ships and the environment are located on the right edge of the gap (see marker 4, Fig. 2). These documents fall into two categories namely:

  ○Reduction of ship emissions (e.g., Adland et al., 2020; Coraddu et al., 2017; Gkerekos et al., 2019; Li et al., 2020; Wang et al., 2018; Yan et al., 2018) and

  ○Safer shipping in ice-covered waters (Bergström and Kujala, 2020; Browne et al., 2020; Jiang et al., 2018; Lehtola et al., 2019; Zhiyuan Li et al., 2020; Zhuang Li et al., 2020).
- Research documents on the third edge of this gap deal with Arctic routs, climate change and its effects on navigation and traffic in the Arctic as depicted by marker 5, Fig. 2 (e.g. Bennett et al., 2020; Cai et al., 2021; Chen et al., 2020; Drewniak et al., 2021; Gritsenko and Kiiski, 2016; Kotovirta et al., 2009; Ngo et al., 2018; Smith and Stephenson, 2013; Stopa et al., 2013; Stevenson et al., 2019; Wei et al., 2020).
- Research documents dealing with structural/reliability loading analysis of ships at sea (Gaspar et al., 2016; Halswell et al., 2016; Hoo Fatt and Sirivolu, 2017; Liang et al., 2002; Peng et al., 2019; Shi et al., 2016; Zayed et al., 2013; Zhu and Frangopol, 2013a), vibration (or shock response) of marine structures due to underwater explosions (Gannon, 2019; Geers and Hunter, 2002; Jin et al., 2019; Motley et al., 2011; Tran et al., 2021; Zhang and Yao, 2008), slamming and green water on decks (Chen et al., 2018; Faltinsen et al., 2004; Greco et al., 2014; Greco and Lugni, 2012; Hernández-Fontes et al., 2018, 2019, 2020; Jalalisendi et al., 2017; Korobkin, 2013; Korobkin and Iafrati, 2005; Korobkin and Khabakhpasheva, 2006; Reinhard et al., 2013; Shabani et al., 2018; Shams et al., 2015; Tassin et al., 2014; Temarel et al., 2016; Xue et al., 2021; Yan et al., 2022; Zekri et al., 2021), and the hydrodynamics of planing hulls (Bilandi et al., 2021, 2020; Dashtimanesh et al., 2020, 2019; Esfandiari et al., 2020; Ghadimi et al., 2019, 2018, 2016a, 2016b; Hou et al., 2019; Judge et al., 2020; Kim et al., 2013; Kim and Kim, 2017; Morabito, 2015; Razola et al., 2016; Roshan et al., 2021; Sun and Faltinsen, 2011, 2007; Tavakoli et al., 2020, 2018a, 2018b; Tavakoli and Dashtimanesh, 2019, 2018) are located where clusters (1) - "*Ocean Hydrodynamics*" and (4) -"*Structural Engineering and Manufacturing for the Ocean*" meet (see marker 6 in Fig. 2). These studies describe the sea or explosion loads acting on marine structures or use those loads to analyse the response of these structures. The hydrodynamics of planning hulls are studied by classic slamming theory. Therefore, research concerned with the hydrodynamics of planning hulls is positioned in way of the borders of cluster 1 ("*Ocean Hydrodynamics*") and 4 ("*Structural Engineering and Manufacturing for the Ocean*").
- Research on ship manoeuvring (e.g. Battista et al., 2020; Alejandro M. Castro et al., 2011; Shen et al., 2015; Taimuri et al., 2020; Yoon et al., 2015), the hydrodynamics of ships equipped with motion stabilization devices (e.g. Bøckmann and Steen, 2016; Ertogan et al., 2016; Huang et al., 2018; Lee et al., 2020; Ram et al., 2015), and the control of energy converters (e.g. Ding et al., 2020; Giorgi et al., 2020; Thomsen et al., 2017; Xu et al., 2021) is positioned on the border of clusters (5) -*"Control and Automation in the Ocean"* and (1) -*"Ocean Hydrodynamics"* marked with number (7) in Fig. 2. This is because some of the hydrodynamic models established to simulate dynamic motions of ships, underwater vehicles, and energy converters may be used by control engineers for different purposes (e.g., to control ship motions in waves while reducing fuel consumption).
- Research addressing collision avoidance methods/models is positioned at the intersection of cluster (2) - *"Risk Assessment and Safety"* and (5) - *"Control and Automation in the Ocean"* (e.g. Baldauf et al., 2017; Du et al., 2020; Ha et al., 2021; Huang et al., 2019; Johansen et al., 2016; Perera et al., 2015, 2011; Shah et al., 2016; Yang et al., 2019; Zaccone and Martelli, 2020). This suggests that control methods and algorithms may be applied to reduce the risk of ship collisions.

3.2. Gap analysis

The following research gaps were identified:

1) *Coupling of climate models with available models used for the design of ships and offshore structures.* The gaps in the similarity map (e.g., see cluster (3) in Fig. 2) show that the hydrodynamic-based studies (e.g., research dealing with ship performance and loads acting on marine structures), ship controls, and risk assessment of ships are of limited relevance to climate-based studies. Climate change effects can be linked to the decline of the ice extents (Stammerjohn et al., 2012; Wang and Overland, 2009), breaking of the ice shelves (Kim et al.,

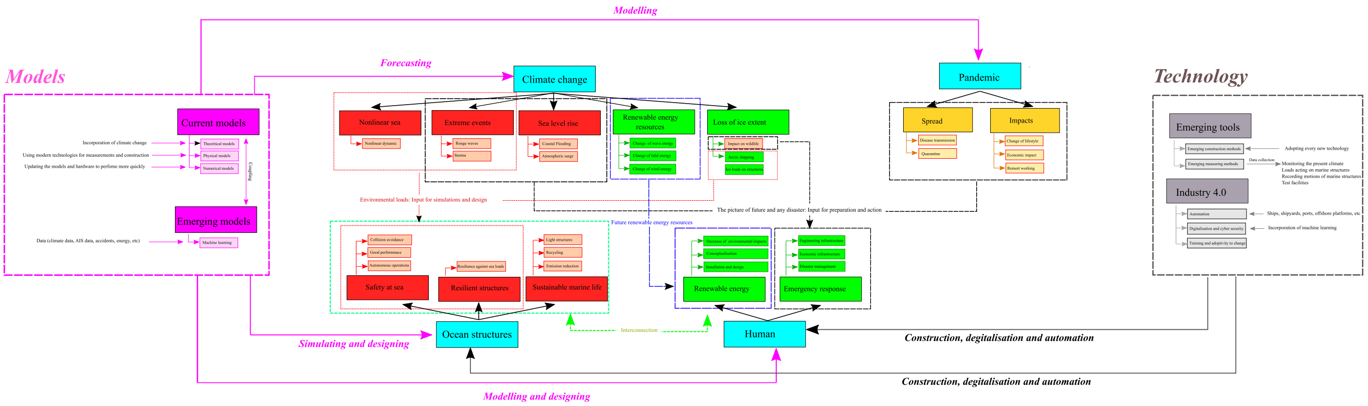

Fig. 3. Suggested plan for future research in ocean engineering. Small boxes show some examples.

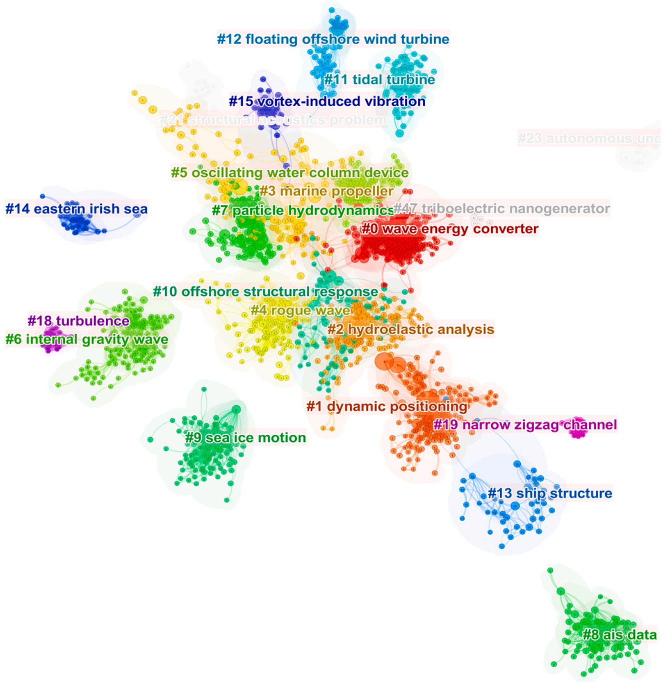

Fig. 4. A network view of document subclusters identified for ocean engineering. The figure illustrates key research sub-divisions. The title of each subcluster is chosen by the computer code and could not be changed in the map.

2015; Massom et al., 2018), and may result in sea-level rise (Frederikse et al., 2020; Hooijer and Vernimmen, 2021; Kirezci et al., 2020; Weber et al., 2021), or the emergence of more energetic wind and waves (Menéndez et al., 2008; Meucci et al., 2020a, 2020b; Stopa et al., 2013; Wang et al., 2012; Young et al., 2011, 2012; Young and Ribal, 2019). Climate change effects can cause larger waves, described by highly non-linear Gaussian Seas, leading to rouge waves (Akhmediev et al., 2009; Dudley et al., 2019; Dysthe et al., 2008a; Ma et al., 2022; Onorato et al., 2013). An example is the *"New Year Wave"* recorded on January 1st, 1995 (Clauss and Klein, 2011). In such conditions wave-induced motions on any floating object become strongly nonlinear (Miguel Onorato et al., 2013), can influence strength and significant speed loss may occur. Research that couples climate models and the existing models that are used to predict ship performance, or to design marine structures is limited (Aung and Umeda, 2020; Bitner-Gregerse et al., 2016a, 2016b; Gu et al., 2019; Jing et al., 2021; Lee et al., 2017; Mao and Rychlik, 2017; Orihara and Tsujimoto, 2018; Paravisi et al., 2019; Sasa et al., 2017; 2015; Taskar and Andersen, 2020).

2) *Wider use of machine learning in ocean engineering problems.* To date, machine learning methods boosted studies concerned with ship collision ("*Risk Assessment and Safety*" cluster), though it has not been broadly used in ocean engineering. The likely reason is that sufficient high-quality data are required to use different algorithms to train machines to predict different processes (see Jordan and Mitchell, 2015), such as ship motions in waves (Romero-Tello et al., 2022), and ship design (Çelik et al., 2021). Notwithstanding this, ship traffic data are constantly updated, and can be used to predict collision and grounding risk avoidance (e.g. Kong et al., 2016; Zhang et al., 2019). Some recent research studies adopted machine learning to predict fluid motions (Kim and Lee, 2020; Kou and Zhang, 2021; Lee and You, 2019; Pena and Huang, 2021b; Tracey et al., 2015), ship motions (Liu et al., 2020; Marlantes and Maki, 2022; Nie et al., 2020; Silva and Maki, 2022; Sun et al., 2022), marine traffic flow (Liu et al., 2022a, 2022b), wave/wind climate (Alexandre et al., 2015; Eeltink et al., 2022; Feng et al., 2017; Gopinath and Dwarakish, 2015; James et al., 2018; Ni and Ma, 2020; Peres et al., 2015; Rüttgers et al., 2019), climate change (Rolnick et al., 2023), and mechanical behaviour of thin-walled structures (Bui et al., 2014; Khatir et al., 2019; Truong et al., 2021; Wang et al., 2021). These studies suggest that machine learning methods can be applied more broadly in the field of safe and sustainable shipping (Huang et al., 2022b).

3) *The application of 3D printing in the maritime industry.* 3D printing methods are absent in between the co-occurrence terms (Fig. 1). Studies of relevance to the manufacturing of propellers and boats have been reported only recently (Bayramoğlu et al., 2019; Grammatikopoulos et al., 2021). These methods may be beneficial to (i) construct prototypes used in model testing (tank tests or open-water tests for measuring performance of propellers, (related to the "*Ocean Hydrodynamics*" cluster) and (ii) study the mechanical behaviour of materials used in marine structures and ships (related to the "*Structural Engineering and Manufacturing for the Ocean*" cluster).

4) *Aerosol transmissions onboard ships.* The emergence of COVID19 pandemic affected the economy, our lifestyle, education, energy consumption, health systems, food security (Giuntella et al., 2021; Kim, 2021; Yazir et al., 2020) and shipping (Wang et al., 2022). To date, research has been carried out with the aim to investigate the aerosol transmission in confined areas such as buildings (Chien et al., 2022; Pease et al., 2021), urban buses and trains (Ahmadzadeh and Shams, 2021). Aerosol transmissions in ships, especially cruise ships where hundreds of passengers reside onboard remains limited (Almilaji, 2021; Huang et al., 2022c).

5) *Application of meshfree methods.* Meshfree methods are useful for the solution of partial differential equations. As shown in Fig. 1, today they are widely used for solving free surface flows (e.g., wave breaking phenomena). In Fig. 2, a circle is drawn, marking papers that used the SPH method. These papers mostly deal with wave modelling and wave loads on fixed structures. Meshfree methods

Table 1
Details of subclusters of ocean engineering, including fundamental references and papers with highest coverage.

- subcluster id - size - silhouette score - mean year (ref) - year range (ref) - mean year (citing)	- title	influential references			highest coverage citing articles
		highest local citation count	strongest citation burst (strength, duration)	highest centrality	
- subcluster 0 - S = 239 - SS = 0.898 - MY (ref) = 2004 - YR (ref) = 1948–2020 - MY (citing) = 2016	*Renewable energy of Ocean: Conceptualization*	1. (Falcão, 2010) (715) 2. (Falnes, 2002) (623) 3. (Drew et al., 2009) (315) 4. (Clément et al., 2002) (308) 5. (Falnes, 2007) (304) 6. (Babarit et al., 2012) (247) 7. (Booij et al., 1999) (217) 8. (Cummins et al., 1962) (206) 9. (Cruz, 2008) (202) 10. (Evans, 1976) (199) 11. (Henderson, 2006) (190) 12. (López et al., 2013) (173) 13. (Dee et al., 2011) (151) 14. (Babarit and Clément, 2006) (151) 15. (Salter, 1974) (148) 16. (Kofoed et al., 2006) (127) 17. (Gunn and Stock-Williams, 2012) (125) 18. (BUDAR and FALNES, 1975) (124)	1. (Cruz, 2008) (20.5, 2010–2014) 2. (Iglesias et al., 2009) (16.74, 2010–2015) 3. (Waters et al., 2009) (16.32, 2010–2015) 4. (de O. Falcão, 2007) (15.58, 2009–2016) 5. (Uihlein and Magagna, 2016) (15.26, 2016–2021) 6. (Magagna and Uihlein, 2015) (14.4, 2017–2021) 7. (Ringwood et al., 2014) (13.88, 2017–2021) 8. (Rusu and Soares, 2012b) (13.7, 2013–2016) 9. (Carballo and Iglesias, 2012) (13.62, 2014–2017) 10. (Falnes, 1980) (13.37, 2013–2017) 11. (Folley and Whittaker, 2009) (13.32, 2010–2017) 12. (Gregorio Iglesias and Carballo, 2010) (13.31, 2012–2015) 13. (Li and Belmont, 2014) (13.07, 2017–2021)	1. (Cummins et al., 1962) (0.07) 2. (Falcão, 2010) (0.04) 3. (Falnes, 2002) (0.04) 4. (Hasselmann et al., 1988) (0.02) 5. (Evans, 1976) (0.02) 6. (Clément et al., 2002) (0.02) 7. (Booij et al., 1999) (0.02)	1. (Clément et al., 2002) (31) 2. (Faedo et al., 2017) (29) 3. (Day et al., 2015) (28) 4. (Ahamed et al., 2020) (26) 5. (Crespo et al., 2017) (22) 6. (Davidson and Costello, 2020) (21) 7. (Göteman et al., 2020) (18) 8. (Henriques et al., 2016b) (18) 9. (Carballo et al., 2015) (17) 10. (Gomes et al., 2016) (17) 11. (Aderinto and Li, 2019) (17) 12. (Fadaeenejad et al., 2014) (17) 13. (Falcão, 2010) (17) 14. (Carballo et al., 2015) (17) 15. (Gonçalves et al., 2014c) (16) 16. (Henriques et al., 2016a) (16) 17. (Carballo et al., 2014) (16) 18. (Henriques et al., 2016b) (16)
- subcluster 1 - S = 176 - SS = 0.971 - MY(ref) = 1997 - YR(ref) = 1898–2018 - MY(citing) = 2012	*Dynamic control and path tracking of marine vehicles*	1. (Fossen, 1994) (778) 2. (Fossen, 2011) (518) 3. (Newman, 1977) (472) 4. (Fossen, 2002) (394) 5. (Faltinsen, 1993) (380) 6. (Khalil, 2002) (220) 7. (Fossen and Strand, 1999) (136) 8. (Healey and Lienard, 1993) (124) 9. (Sørensen, 2011) (102) 10. (Krstic et al., 1995) (100) 11. (Jiang, 2002) (98)	1. (Fossen, 1994) (65.04, 1996–2012) 2. (Fossen, 2002) (54.04, 2005–2014) 3. (Krstic et al., 1995) (31.13, 1998–2010) 4. (Newman, 1977) (29.88, 1995–2012) 5. (Fossen, 2011) (26.32, 2016–2019) 6. (Healey and Lienard, 1993) (19.4, 2000–2011) 7. (Faltinsen, 1993) (18.45, 2004–2013) 8. (Khalil, 2002) (18.14, 2002–2015) 9. (Jiang, 2002) (16.53, 2009–2016) 10. (Perez, 2006) (15.76, 2008–2015) 11. (Lefeber et al., 2003) (15.44, 2009–2016) 12. (Sfakiotakis et al., 1999) (13.82, 2006–2011) 13. (Tee and Ge, 2006) (13.62, 2004–2017) 14. (Ashrafiuon et al., 2008) (13.4, 2012–2017) 15. (Do and Pan, 2005) (10.42, 2012–2016)	1. (Newman, 1977) (0.13) 2. (Fossen, 1z994) (0.08) 3. (Faltinsen, 1993) (0.05) 4. (Do, 2010) (0.03) 5. (Åström and Källström, 1976) (0.03) 6. (Fossen, 2002) (0.02) 7. (Krstic et al., 1995) (0.02)	1. (Huang et al., 2020a) (25) 2. (Do and Pan, 2009) (13) 4. (Do, 2015a) (13) 5. (Do, 2015b) (13) 6. (Herman and Adamski, 2017) (12) 7. (Li et al., 2015) (11) 8. (Fredriksen and Pettersen, 2004) (10) 9. (Do, 2015c) (10) 10. (Do and Pan, 2004) (10) 11. (Przemysław Herman and Adamski, 2017) (10)

(*continued on next page*)

Table 1 (*continued*)

- subcluster id - size - silhouette score - mean year (ref) - year range (ref) - mean year (citing)	- title	influential references			highest coverage citing articles
		highest local citation count	strongest citation burst (strength, duration)	highest centrality	
- subcluster 2 - S = 165 - SS = 0.863 - MY(ref) = 1989 - YR(ref) = 1908–2018 - MY(citing) = 2010	*Hydroelastic motion of floating objects and marine vehicles*	1. (Salvesen et al., 1970) (208) 2. (Bishop and Price, 1979) (138) 3. (Wehausen and Laitone, 1960) (129) 4. (Watanabe et al., 2004) (87) 5. (Hirdaris et al., 2014) (76) 6. (Newman, 1994) (73) 7. (Squire, 2007) (72) 8. (Fox and Squire, 1994) (54) 9. (MOLIN, 2001) (41)	1. (Salvesen et al., 1970) (26.08, 2001–2011) 2. (Wehausen and Laitone, 1960) (20.94, 1988–2008) 3. (Watanabe et al., 2004) (20.19, 2005–2010) 4. (John, 1950) (17.55, 1992–2011) 5. (Squire, 2007) (17.44, 2009–2013) 6. (Hess and Smith, 1964) (15.21, 2002–2011) 7. (Newman, 1994) (15.07, 2006–2014) 8. (Bishop and Price, 1979) (14.12, 1998′-2012) 9. (Fox and Squire, 1994) (10.72, 2006–2013) 10. (Newman, 1979) (10.66, 1991–2007) 11. (Dawson, 1977) (10.62, 1998–2005) 12. (Linton and McIver, 2001) (9.99, 2012–2016)	1. (Salvesen et al., 1970) (0.04) 2. (Wehausen and Laitone, 1960) (0.04) 3. (Fonseca and Soares, 1998) (0.02) 4. (Bishop and Price, 1979) (0.01) 5. (Watanabe et al., 2004) (0.01) 6. (Newman, 1994) (0.01) 7. (Fox and Squire, 1994) (0.01) 8. (John, 1950) (0.01) 9. (Chwang, 1983) (0.01) 10. (Chen et al., 2006) (0.01) 11. (Abramowitz and Stegun, 1965) (0.01)	1. (Xing, 2019) (18) 2. (Squire, 2008) (12) 3. (Squire, 2008)(12) 4. (Chen et al., 2006) (11) 5. (Senjanovic et al., 2008) (10) 6. (Kyoung et al., 2005) (9) 7. (Senjanovic et al., 2008) (9)
- subcluster 3 - S = 150 - SS = 0.849 - MY(ref) = 2002 - YR(ref) = 1960–2020 - MY(citing) = 2010	*CFD modelling of processes in upper oceanic boundary layer*	1. (Hirt and Nichols, 1981) (460) 2. (MENTER, 1994) (396) 3. (Jacobsen et al., 2012) (174) 4. (Celik et al., 2008) (107) 5. (Tezdogan et al., 2015) (102) 6. (Carrica et al., 2007) (90) 7. (Stern et al., 2001) (90) 8. (LONGUETHIGGINS and COKELET, 1976) (85) 9. (Weller et al., 1998) (83) 10. (Issa, 1986) (81) 11. (Ferziger and Peric, 2012) (79) 12. (Carlton, 2012) (66) 13. (Higuera et al., 2013) (63) 14. (Penalba et al., 2017) (63)	1. (Jacobsen et al., 2012) (14.96, 2017–2021) 2. (LONGUETHIGGINS and COKELET, 1976) (14.7, 2008–2014) 3. (Young, 2008) (13.17, 2010–2014) 4. (Carlton, 2012) (12.76, 2017–2021) 5. (Carrica et al., 2007) (11.93, 2007–2013) 6. (Lin and Liu, 1998) (10.02, 2006–2014)	1. (Hirt and Nichols, 1981) (0.04) 2. (Ferziger and Peric, 2012) (0.03) 3. (Celik et al., 2008) (0.02) 4. (LONGUETHIGGINS and COKELET, 1976) (0.02) 5. (Jacobsen et al., 2012) (0.01) 6. (Carrica et al., 2007) (0.01) 7. (Issa, 1986).01) 8. (Osher and Sethian, 1988) (0.01) 9. (Chorin, 1968) (0.01) 10. (Young, 2008) (0.01) 11. (Windt et al., 2018) (0.01) 12. (Chase and Carrica, 2013) (0.01) 13. (Alejandro M Castro et al., 2011) (0.01) 14. (LIN and LIU, 1998) (0.01) 15. (FELLI et al., 2011) (0.01) 16. (DONG et al., 1997) (0.01) 17. (Orlanski, 1976) (0.01) 18. (Kerwin and Lee, 1978) (0.01) 19. (Chakrabarti, 2001) (0.01)	1. (Gomes et al., 2020) (18) 2. (Huang and Huang, 2021) (16) 3. (Deng et al., 2021) (15) 4. (Chen et al., 2021) (14) 5. (Deng et al., 2019) (13) 6. (Davidson and Costello, 2020) (13) 7. (Deng et al., 2020) (12) 8. (Green et al., 2021) (10) 9. (Chow et al., 2019) (10)
- subcluster 4 - S = 137 - SS = 0.903 - MY(ref) = 1987 - YR(ref) = 1932–2014 - MY(citing) = 2007	*Freak waves and wave statistics*	1. (Lamb, 1932) (190) 2. (Zakharov, 1968) (101) 3. (Kharif and Pelinovsky, 2003) (65) 4. (Hasselmann, 1962) (64) 5. (Zakharov et al., 1992) (56) 6. (Janssen, 2003) (53) 7. (Komen et al., 1994) (44) 8. (Benjamin and Feir, 1967) (38)	1. (Hasselmann, 1962) (20.93, 1992–2010) 2. (Janssen, 2003) (20.18, 2004–2015) 3. (Zakharov et al., 1992) (18.18, 2002–2015) 4. (Kharif and Pelinovsky, 2003) (17.08, 2006–2011) 5. (Zakharov, 1968) (16.4, 2007–2011) 6. (Socquet-Juglard et al., 2005) (15.46, 2007–2011) 7. (Lamb, 1932) (15.06, 1992–2010)	1. (Lamb, 1932) (0.09) 2. (Hasselmann, 1962) (0.02) 3. (Janssen, 2003) (0.01) 4. (Komen et al., 1994) (0.01) 5. (Benjamin and Feir, 1967) (0.01) 6. (Phillips, 1977) (0.01) 7. (Mei, 1989) (0.01) 8. (Plant, 1982) (0.01) 9. (Harlow and Welch, 1965) (0.01)	1. (Toffoli et al., 2010) (14) 2. (Ruban, 2010a) (14) 3. (Ruban, 2010b) (13) 4. (Toffoli et al., 2009) (12) 5. (Jenkins, 1993) (11) 6. (Kharif et al., 2009) (10) 7. (Adcock and Taylor, 2009) (10) 8. (Zhou and Mendoza, 1993) (10)

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Table 1 (*continued*)

- subcluster id - size - silhouette score - mean year (ref) - year range (ref) - mean year (citing)	- title	influential references			highest coverage citing articles
		highest local citation count	strongest citation burst (strength, duration)	highest centrality	
			8. (Mei, 1989) (14.98, 2001–2011) 9. (Phillips, 1977) (14.8, 1994–2006) 10. (Komen et al., 1994) (12.81, 2003–2014) 11. (Benjamin and Feir, 1967) (10.94, 2000–2011) 12. (Dysthe et al., 2008b) (10.84, 2010–2016) 13. (Plant, 1982) (10.01, 1991–2002)	10. (McWilliams et al., 1997) (0.01) 11. (Belcher and Hunt, 1993) (0.01) 12. (Andrews and Mcintyre, 1978) (0.01)	9. (Chalikov, 2005) (10) 10. (Belcher et al., 1994) (10)
- subcluster 5 - S = 132 - SS = 0.948 - MY(ref) = 2000 - YR(ref) = 1965–2020 - MY(citing) = 2017	*Hydrodynamic of OWC*	1. (Falcão and Henriques, 2016) (202) 2. (Sarmento and Falcão, 1985) (128) 3. (Evans, 1982) (128) 4. (Falcão and Justino, 1999) (111) 5. (He et al., 2013) (85) 6. (Raghunathan, 1995) (83) 7. (Heath, 2012) (82) 8. (Mustapa et al., 2017) (79) 9. (Falcão and Henriques, 2014) (73) 10. (Setoguchi and Takao, 2006) (73) 11. (Ning et al., 2016) (72)	1. (Torre-Enciso et al., 2009) (15.26, 2016–2019) 2. (López et al., 2013) (14.26, 2016–2019) 3. (Ning et al., 2016) (13.07, 2017–2021) 4. (McCormick, 2007) (11.81, 2010–2017) 5. (Abramowitz and Stegun, 1965) (11.68, 1999–2012) 6. (Raghunathan, 1995) (11.15, 1999–2006) 7. (Setoguchi et al., 2001) (10.38, 2004–2007) 8. (He and Huang, 2014) (10.36, 2017–2021s)	1. (Sarmento and Falcão, 1985) (0.02) 2. (Raghunathan, 1995) (0.02) 3. (Abramowitz and Stegun, 1965) (0.02) 4. (Evans, 1982) (0.01) 5. (Falcão and Justino, 1999) (0.01) 6. (Setoguchi and Takao, 2006) (0.01) 7. (Falnes and McIver, 1985) (0.01)	1. (Falcão and Henriques, 2016) (21) 2. (Wang and Zhang, 2021a) (20) 3. (Wang et al., 2021) (19) 4. (Elhanafi et al., 2017b) (19) 5. (Zhao et al., 2021) (19) 6. (Ning et al., 2020) (18) 7. (Wang and Zhang, 2021b) (17) 8. (Chen et al., 2021) (17) 9. (Wang and Zhang, 2021a) (17) 10. (B. Guo et al., 2021)) (16) 11. (A. J.C. Crespo et al., 2017) (15) 12. (Elhanafi et al., 2017a) (15)s 13. (He et al., 2017)
- subcluster 6 - S = 130 - SS = 0.961 - MY(ref) = 1984 - YR(ref) = 1871–2003 - MY(citing) = 1998	*Wave breaking and internal gravity waves*	1. (Gill, 1982) (49) 2. (Fritts and Alexander, 2003) (43) 3. (Mellor and Yamada, 1982) (41) 4. (Jeong and Hussain, 1995) (36) 5. (Lindzen, 1981) (28) 6. (Miles, 1961) (18)	1. (Gill, 1982) (23.75, 1992–2008) 2. (Fritts and Alexander, 2003) (21.36, 2005–2013) 3. (Lindzen, 1981) (18.33, 1987–1997) 4. (Mellor and Yamada, 1982) (13.28, 2010–2014) 5. (Fritts et al., 1994) (10.43, 1996–2005) 6. (Andreassen et al., 1994) (10.43, 1996–2005)	1. (Gill, 1982) (0.05) 2. (Lindzen, 1981) (0.02) 3. (Miles, 1961)) (0.02) 4. (Duncan, 1981) (0.02)	1. (Wurtele et al., 1996) (15) 2. (Thorpe, 2005) (14) 3. (Andeasseb et al., 1998) (14) 4. (Fritts et al., 1996) (13) 5. (Frits et al., 1998) (12) 6. (Embid and Majda, 1998) (11) 7. (Majda and Embid, 1998) (10) 8. (Lin et al., 1998) (10)
- subcluster 7 - S = 124 - SS = 0.951 - MY(ref) = 2000 - YR(ref) = 1929–2019 - MY(citing) = 2015	*Smoothed Particle Hydrodynamics*	1. (Gingold and Monaghan, 1977) (220) 2. (Monaghan, 1994) (206) 3. (Wagner, 1932) (200) 4. (Lucy, 1977) (163) 5. (Zhao and Faltinsen, 1993) (162) 6. (Monaghan, 1992) (160) 7. (Faltinsen, 2006) (150) 8. (Colagrossi and Landrini, 2003) 9. (Savitsky, 1964) (118) 10. (Monaghan, 2005) (111)	1. (Faltinsen and Timokha, 2009) (15.19, 2011–2015) 2. (Monaghan, 2005) (14.88, 2010–2015) 3. (Faltinsen, 2006) (14.67, 2009–2015) 4. (Cole, 1948) (13.14, 2008–2014) 5. (Mei et al., 1999) (13.07, 2013–2017) 6. (Smagorinsky, 1963) (11.13, 2006–2012) 7. (Howison et al., 1991) (11.23, 2000–2013)	1. (Batchelor, 2000) (0.04) 2. (Zhao and Faltinsen, 1993) (0.03) 3. (Monaghan, 1992) (0.02) 4. (Cole, 1948) (0.02) 5. (Smagorinsky, 1963) (0.02) 6. (Wagner, 1932) (0.01) 7. (Colagrossi and Landrini, 2003) (0.01) 8. (Monaghan, 2005) (0.01) 9. (Oger et al., 2006) (0.01) 10. (Dalrymple and Rogers, 2006) (0.01) 11. (Faltinsen, 2000) (0.01)	1. (Liu and Zhang, 2019) (23) 2. (Cheng et al., 2019) (15) 3. (Gotoh et al., 2021) (15) 4. (Khayyer et al., 2021b) (14) 5. (He et al., 2021) (13) 6. (Rakhsha et al., 2019) (13) 7. (P N Sun et al., 2019) (14) 8. (Tagliafierro et al., 2021) (13)

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Table 1 (*continued*)

- subcluster id - size - silhouette score - mean year (ref) - year range (ref) - mean year (citing)	- title	influential references			highest coverage citing articles
		highest local citation count	strongest citation burst (strength, duration)	highest centrality	
			8. (Cummins and Rudman, 1999) (10.82, 2013–2016) 9. (Koshizuka et al., 1998) (10.64, 2014–2017) 10. (Wendland, 1995) (10.53., 2017–2021)		9. (Vandamme et al., 2011) (13) 10. (Liu and Zhang, 2019) 11. (Khayyer and Gotoh, 2011) (12) 12. (Khayyer et al., 2021b) (12)
- subcluster 8 - S = 106 - SS = 0.982 - MY(ref) = 2011 - YR(ref) = 1971–2020 - MY(citing) = 2019	*Collision Risk and Marine Traffic*	1. (Fujii and Tanaka, 1971) (116) 2. (Goodwin, 1975) (109) 3. (Mou et al., 2010) (76) 4. (Silveira et al., 2013) (67) 5. (Montewka et al., 2010) (65) 6. (Szlapczynski and Szlapczynska, 2017) (62) 7. (Qu et al., 2011) (62) 8. (Statheros et al., 2008) (60) 9. (Goerlandt and Montewka, 2015) (55)	1. (Kuwata et al., 2014) (9.94, 2016–2019) 2. (Goerlandt and Kujala, 2011) (9.29, 2012–2015) 3. (Montewka et al., 2010) (8.71, 2011–2015) 4. (Tsou et al., 2010) (5.96, 2014–2017) 5. (Davis et al., 1980) (5.15, 2016–2019)	1. (Montewka et al., 2010) (0.04) 2. (Kuwata et al., 2014) (0.03) 3. (Soares and Teixeira, 2001) (0.03) 4. (Statheros et al., 2008) (0.01) 5. (Tam et al., 2009) (0.01) 6. (Valdez Banda et al., 2015) (0.01) 7. (Huntsberger et al., 2011) (0.01)	1. (Zhang et al., 2021b) (31) 2. (Čorić et al., 2021) (23) 3. (Rong et al., 2021) (23) 4. (Huang et al., 2020b) (23) 5. (Szlapczynski and Szlapczynska, 2021) (23) 6. (Du et al., 2021) (22) 7. (Q. Yu et al., 2021) (21) 8. (Gil, 2021) (21) 9. (Wang et al., 2021) (19) 10. (Cai et al., 2021) (18) 11. (H. Yu et al., 2021) (18) 12. (Zhang et al., 2021a) (18)
- subcluster 9 - S = 105 - SS = 0.988 - MY(ref) = 1992 - YR(ref) = 1958–2009 - MY(citing) = 2002	*Sea ice motion*	1. (Karl et al., 1996) (88) 2. (Hibler, 1979) (69) 3. (Thorndike and Colony, 1982) (52) 4. (Kwok et al., 1998) (48) 5. (Rothrock et al., 1999) (35) 6. (Aagaard and Carmack, 1989) (27)	1. (Hibler, 1979) (27.8, 1989–2011) 2. (Thorndike and Colony, 1982) (24.46, 1989–2008) 3. (Kwok, 2000) (23.57, 2000–2012) 4. (Rothrock et al., 2000) (20.38, 2001–2009) 5. (Karl et al., 1996) (17.19, 1999–2014) 6. (Aagaard and Carmack, 1989) (11.23, 1996–2008) 7. (Agnew et al., 1997) (11.23, 2000–2006)	1. (Karl et al., 1996) (0.03) 2. (Hibler, 1979) (0.03) 3. (Thorndike and Colony, 1982) (0.02) 4. (Rothrock et al., 1999) (0.02)	1. (Meier et al., 2000) (12) 2. (Rothrock et al., 2000) (12) 3. (Martin and Augstein, 2000) (11) 4. (Maslanik et al., 2000) (11) 5. (Alexandrov et al., 2000) (11) 6. (Kwok, 2000) (10) 7. (Meier and Maslanik, 2003) (10) 8. (Thomas et al., 2003) (10) 9. (McLaren et al., 1989) (10) 10. (Serreze et al., 1989) (10) 11. (Venegas and Drinkwater, 2001) (10)
- subcluster 10 - S = 80 - SS = 0.933 - MY(ref) = 1984 - YR(ref) = 1944–2011 - MY(citing) = 2009	*Theoretical and Statistical Analyses of Response of Structures to waves*	1. (Morison et al., 1950) (218) 2. (Pierson Jr. and Moskowitz, 1964) (148) 3. (Sarpkaya and Isaacson, 1981a) (110) 4. (France et al., 2003) (53) 5. (Chakrabarti, 1987) (52) 6. (Fenton, 1985) (45)	1. (Sarpkaya and Isaacson, 1981a) (23.24, 1999–2011) 2. (Sarpkaya and Isaacson, 1981b) (15.83, 1991–1996) 3. (Falzarano et al., 1992) (14.19, 1999–2010) 4. (France et al., 2003) (11.02, 2006–2012)	1. (Pierson Jr. and Moskowitz, 1964) (0.07) 2. (Sarpkaya and Isaacson, 1981a) (0.05) 3. (Morison et al., 1950) (0.01) 4. (Chakrabarti, 1987) (0.01) 5. (Thompson, 1997) (0.01)	1. (Najafian, 2007a) (16) 2. (Najafian, 2007b) (15) 3. (Najafian, 2007c) (13) 4. (Najafian, 2007d) (12) 5. (Spyrou and Thompson, 2000) (10) 6. (El-Bassiouny, 2007) (7)

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Table 1 (*continued*)

- subcluster id - size - silhouette score - mean year (ref) - year range (ref) - mean year (citing)	- title	influential references			highest coverage citing articles
		highest local citation count	strongest citation burst (strength, duration)	highest centrality	
					8. (Najafian, 2007e) (7) 9. (Jiang et al., 2000) (7)
- subcluster 11 - S = 68 - SS = 0.982 - MY(ref) = 2009 - YR(ref) = 1983–2019 - MY(citing) = 2017	*Hydrodynamic of tidal turbines*	1. (Bahaj et al., 2007b) (156) 2. (Mycek et al., 2014) (75) 3. (Bahaj et al., 2007a) (61) 4. (Pelc and Fujita, 2002) (55) 5. (Pope, 2000) (50) 6. (Turner et al., 2002) (47) 7. (Batten et al., 2008) (47) 8. (Garrett and Cummins, 2007) (46) 9. (Khan et al., 2009) (45)	1. (Bahaj et al., 2007a) (12.61, 2012–2016) 2. (Khan et al., 2009) (12.61, 2012–2016) 3. (Rourke et al., 2010) (11.91, 2013–2017) 4. (Bahaj et al., 2007b) (11.24, 2012–2015)	1. (Bahaj et al., 2007b) (0.03) 2. (Pelc and Fujita, 2002) (0.01) 3. (Turner et al., 2002) (0.01) 4. (Lewis et al., 2015) (0.01)	1. (Ng et al., 2013) (17) 2. (Zhang et al., 2020) (15) 3. (Thiébot et al., 2020) (10) 4. (lo Brutto et al., 2016a) (9) 5. (Edmunds et al., 2020) (9) 6. (Nachtane et al., 2020) (9) 7. (lo Brutto et al., 2016b) (9) 8. (Michelet et al., 2020) (8) 9. (Hill et al., 2020) (8) 10. (Thiébaut et al., 2020) (8)
- subcluster 12 - S = 54 - SS = 0.978 - MY(ref) = 2007 - YR(ref) = 1981–2020 - MY(citing) = 2017	*Hydrodynamic of offshore wind turbines*	1. (Jonkman et al., 2009) (216) 2. (Roddier et al., 2010) (109) 3. (Jonkman, 2010) (71) 4. (Robertson et al., 2014) (59) 5. (IEC, 2009) (43) 6. (Coulling et al., 2013) (43) 7. (Robertson et al., 2017) (42)		1. (Schillinger et al., 2012) (0.02) 2. (Roddier et al., 2010) (0.01) 3. (Jonkman et al., 2009) (0.01)	1. (Yuri Bazilevs et al., 2012) (23) 2. (Akkerman et al., 2012) (19) 3. (Y. Bazilevs et al., 2012a) (19) 4. (Y. Bazilevs et al., 2012b) (19) 5. (Akkerman et al., 2011) (16) 6. (Schillinger et al., 2012) (9) 7. (Schillinger et al., 2012) (8)
- subcluster 13 - S = 46 - SS = 0.985 - MY(ref) = 2004 - YR(ref) = 1959–2018 - MY(citing) = 2012	*Ship structure*	1. (Paik and Thayamballi, 2003) (76) 2. (Alsos et al., 2009) (42) 3. (Hughes et al., 2010) (39) 4. (Minorsky, 1958) (36) 5. (Smith, 1977) (30) 6. (Alsos and Amdahl, 2009) (29) 7. (Caldwell, 1965) (27)	1. (Paik and Thayamballi, 2003) (17.54, 2007–2015) 2. (Alsos et al., 2009) (14.58, 2012–2015) 3. (Smith, 1977) (8.8, 2003–2016) 4. (Alsos and Amdahl, 2009) (8.37, 2013–2016) 5. (Caldwell, 1965) (7.92, 2003–2016)	1. (Minorsky, 1958) (0.06) 2. (Pedersen, 2010) (0.05) 3. (Smith, 1977) (0.02) 4. (Caldwell, 1965) (0.02) 5. (Alsos et al., 2009) (0.01) 6. (Jones, 1989) (0.01) 7. (Mouritz et al., 2001) (0.01) 8. (Gordo et al., 1996) (0.01)	1. (Decò and Frangopol, 2013) (7) 2. (Villavicencio et al., 2013) (6) 3. (Liu et al., 2015) (6) 4. (Samuelides, 2015) (6) 5. (Ehlers et al., 2011) (5) 6. (Yao, 2003) (5) 7. (D. K. Kim et al., 2013a) (5) 8. (D. K. Kim et al., 2013b) (5) 9. (Ehlers et al., 2015) (5) 10. (Zhu and Frangopol, 2013b) (5)
- subcluster 14 - S = 34 - SS = 0.991 - MY(ref) = 1988 - YR(ref) = 1959–2005 - MY(citing) = 1997	*Hydrodynamic of tidal currents*	1. (Shchepetkin and McWilliams, 2005) (37) 2. (Davies, 1991) (12) 3. (Davies and Jones, 1990) (9) 4. (Davies and Gerritsen, 1994) (8) 5. (Galperin et al., 1988) (7) 6. (Davies, 1986) (7)	1. (Shchepetkin and McWilliams, 2005) (11.2, 2010–2017) 2. (Davies, 1991) (7.69, 1993–2001) 3. (Davies and Jones, 1990) (6.03, 1993–2007) 4. (Davies and Gerritsen, 1994) (5.22, 1996–201)	1. (Davies, 1991) (0.02) 2. (Galperin et al., 1988) (0.01)	1. (Xing and Davies, 1996a) (15) 2. (Davies and Jones, 1996) (14) 3. (Davies, 1993) (13) 4. (Aldridge and Davies, 1993) (13) 5. (Xing and Davies, 1996b) (10) 6. (Xing and Davies, 1996c) (10) 7. (Davies et al., 1997a) (9) 8. (Davies et al., 1997b) (9)

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Table 1 (*continued*)

- subcluster id - size - silhouette score - mean year (ref) - year range (ref) - mean year (citing)	- title	influential references			highest coverage citing articles
		highest local citation count	strongest citation burst (strength, duration)	highest centrality	
- subcluster 15 - S = 28 - SS = 0.992 - MY(ref) = 2001 - YR(ref) = 1950–2020 - MY(citing) = 2018	*Vortex Induced Vibrations: Modelling and Application*	1. (Williamson and Govardhan, 2004) (122) 2. (Sarpkaya, 2004) (99) 3. (Bernitsas et al., 2008) (78) 4. (Blevins, 1990) (71) 5. (Launder and Spalding, 1974) (59) 6. (Khalak and Williamson, 1999) (54) 7. (Bearman, 2011) (49) 8. (Shih et al., 1995) (25)	1. (Bathe, 1996) (9.85, 2007–2013) 2. (Bearman, 2011) (8.89, 2011–2016) 3. (Gabbai and Benaroya, 2005) (6.15, 2013–2017) 4. (Williamson and Govardhan, 2004a) (5.28, 2017–2021) 5. (Williamson and Govardhan, 2008) (5.18, 2017–2021)	1. (Blevins, 1990) (0.01) 2. (Bathe, 1996) (0.01) 3. (Gabbai and Benaroya, 2005) (0.01)	1. (Zhu et al., 2018) (10) 2. (Ding et al., 2017) (8) 3. (Hongjun and Gao, 2018) (8) 4. (Wong et al., 2017) (7) 5. (Jia-song Wang et al., 2020) (7) 6. (Sun et al., 2018) (7) 7. (Ding et al., 2018) (7)

may also be used for analysing the mechanics thin-walled structures (e.g., Barbieri et al., 2019; Bui et al., 2011; Thai et al., 2016) and fluid-structure interaction problems (e.g. Antoci et al., 2007; Gotoh et al., 2021; Khayyer et al., 2021a, 2021b; Liu et al., 2013; Sun et al., 2019). Recently Meng et al. (2022) pointed out that "*meshless solvers can be coupled in a consistent manner, and potentially produce proper fluid-structure interface boundary conditions*". Yet, studies using SPH to test the performance of energy converters remain limited (Chang et al., 2015; Marrone et al., 2019; Tagliafierro et al., 2022; Wen et al., 2018).

An informative graph on future research is depicted in Fig. 3. Two global challenges namely climate change and pandemic and their possible consequences are highlighted. The LHS (left hand side) of the graph summarises current and emerging models. On the RHS (right hand side) of the graph, technology tools that can be used in ocean engineering are displayed. The lower part summarises ocean engineering problems related to marine structures and health and safety. It is expected that over the medium to long term concurrent and emerging models (e.g., finite discretization and machine learning methods), will be coupled and updated. In addition, environmentally friendly human-made artefacts will be designed and installed in an attempt to decrease our fingerprints on climate change. Technology can help with (i) data collection (climate data, ship and fluid motions, etc.); (ii) the manufacturing of objects in small or real scales; (iii) automation which can decrease human errors of marine vehicles and may lead to efficient performance of different devices (e.g., energy converters, may accelerate the construction progress, and enable cleaner recycling); (iv) digitalization and cyber security for commination in shipyards, offshore structures and onboard ships or FOIs. These trends may boost Industry 4.0 priorities for the benefit of ocean engineering (Sullivan et al., 2020).

3.3. *Sub-divisions of the field*

A co-citation analysis was carried out using the methodology introduced by Chen, 2004. This analysis classified documents that co-cite thematically similar references and present key sub-divisions in the field of ocean engineering (Fig. 4). A general view of the results for the period from 1970 to 2021 is depicted in Fig. 4. The 16 sub-divisions (co-citation clusters) identified are based on the important references that ocean engineering articles cited. The term *"subcluster"* is used to refer to *"subdivisions"*. It is noted that other bibliographical studies tend to name *"subdivisions"* as *"co-citation clusters"*.

Subclusters are ranked based on the number of influential references (also called "*size of cluster*"). Each subcluster is termed using the most repeated phrase found in the title of citing papers weighted by the total coverage of the citing articles where the term was extracted from (i.e., by giving heavier weight to articles that have cited more references of that subcluster, and are thus, are more relevant). The identified subclusters are "*Renewable energy of Ocean: Conceptualization*" (subcluster 0), "*Dynamic control and path tracking of marine vehicles*" (subcluster 1), "*Hydroelastic motion of floating objects and marine vehicles*" (subcluster 2), "*CFD modelling of processes in the upper oceanic boundary layer*" (subcluster 3), "*Freak waves and wave statistics*" (subcluster 4), "*Hydrodynamics of OWC*" (subcluster 5, here OWC stands for Ocean Wave Converters), "*Wave breaking and internal gravity waves*" (subcluster 6), "*Smoothed Particle Hydrodynamics*" (subcluster 7), "*Collision Risk and Marine Traffic*" (subcluster 8), "*Sea ice motions*" (subcluster 9), "*Theoretical and Statistical Analyses of Response of Structures to waves*" (subcluster 10), "*Hydrodynamics of tidal turbines*" (subcluster 11), "*Hydrodynamics of offshore wind turbines*" (subcluster 12), "*Ship structures*" (subcluster 13), "*Hydrodynamic of tidal currents*" (subcluster 14), "*Vortex Induced Vibrations: Modelling and Application*" (subcluster 15).

In Fig. 4, each node represents a fundamental reference that may be either a paper, a report, or a book. Each colour represents a subcluster. The size of each node represents its burst strength. This means that the document has suddenly attracted the attention of researchers publishing papers in that subcluster over a specific period (see Table 1). Nodes of different subclusters are seen to be linked to each other. This indicates that they may share many citing articles. Based on results depicted in Fig. 4, the following observations can be made:

I) "*Renewable energy of Ocean: Conceptualization*" (subcluster 0), "*Hydroelastic motion of floating objects and marine vehicles*" (subcluster 2), "*CFD modelling of processes in upper oceanic boundary layer*" (subcluster 3), "*Freak waves and wave statistics*" (subcluster 4), "*Hydrodynamics of OWC*" (subcluster 5), "*Smoothed Particle Hydrodynamics*" (subcluster 7), "*Theoretical and Statistical Analyses of Response of Structures to waves*" (subcluster 10) are linked to each other to a higher level, compared to other subclusters. These subclusters mostly deal with fluid dynamics, hydrodynamic modelling of floating objects (in calm and rough water conditions) and ocean renewable energy (but mostly the wave energy). This suggests that studies related to the hydrodynamics of floating objects, marine structures, and ships (modelling of their motions and environmental forces acting on them) are highly interconnected with the fundamental studies related to the ocean wave energy and wave statistics, all of which together form a large body of studies in the field of ocean engineering. Logically, this is due to the pressing need to model energy conversion

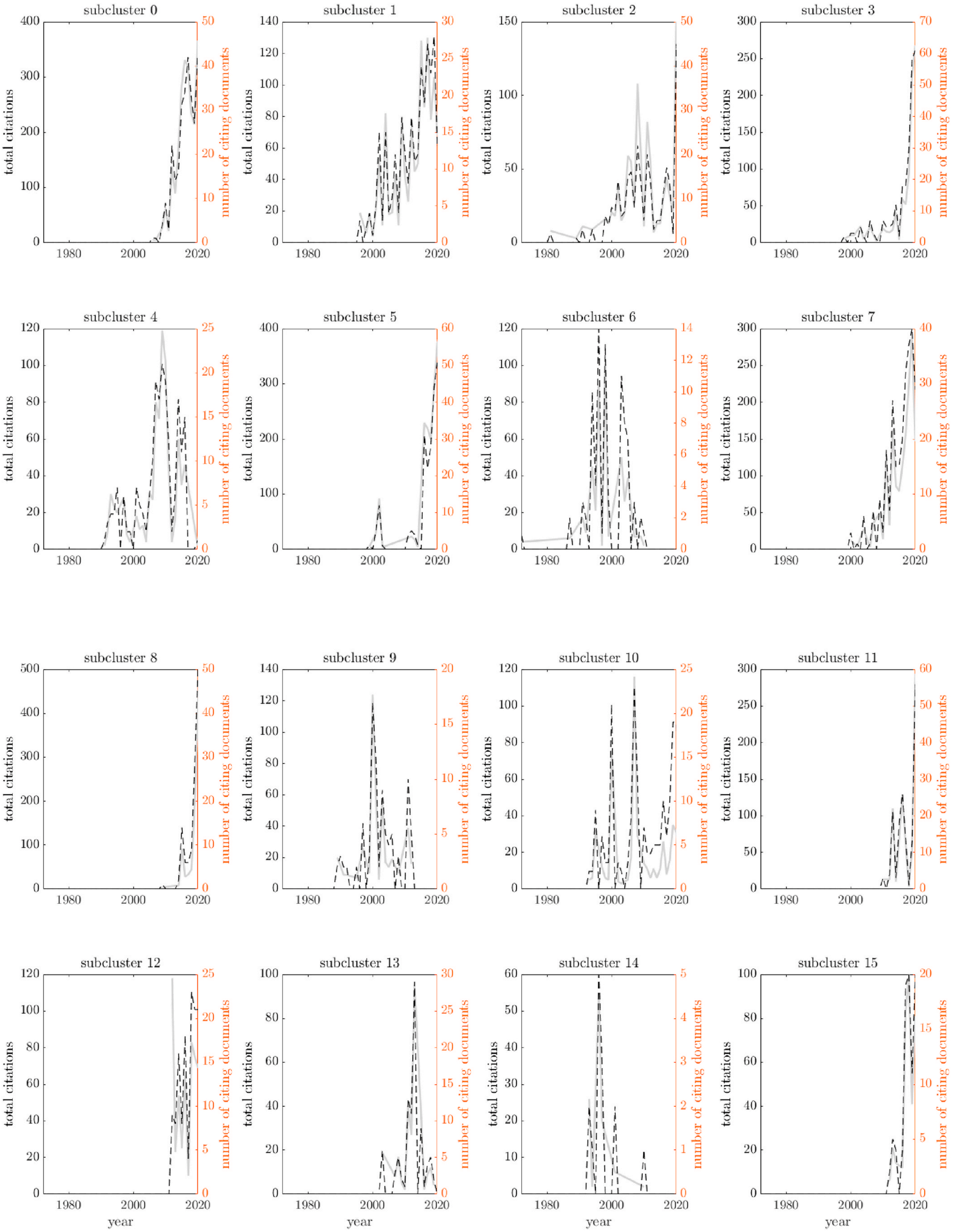

Fig. 5. Time histories of citations of fundamental references of subclusters (dashed) and number of citing documents of subclusters (solid).

(subcluster 5), forecast climate (subclusters 0 and 4), and develop solvers which can be used for theoretical solutions as well as CFD based and hydroelastic simulations (subclusters 2, 3 and 7).

II) References of relevance to the "*control and path tracking of marine vehicles*" (subcluster 1) and "*Collision Risk and Marine Traffic*" (subcluster 8) are sharing connections. That suggests that the research streams of positioning, control and path tracking of ships share fundamental background. This is mostly due to the need to control of ships and track their position for collision avoidance.

Time history plots of citations under all subclusters are shown in Fig. 5 by dashed curves. The number of citing papers under different subclusters are displayed by solid curves. This suggests how research uptaking or downturns may relate with each subcluster. Expectedly, citation and citing plots follow each other. The following interesting points can be observed from Fig. 5:

- Subclusters 0 ("*Renewable energy of Ocean: Conceptualization*"), 5 ("*Hydrodynamics of OWC*"), 11 ("*Hydrodynamics of tidal turbine*") and 12 ("*Hydrodynamics of offshore wind turbines*") emerged and started to grow in the late 2000s. This is possibly because of the energy crisis and the need to reduce the fossil fuel emissions (environmental sustainability demands), which initiated in 1990s (Esteban, 2009). They all relate to "*Ocean Renewable Energy*" cluster (6). It is also interesting to note that research in "*Vortex Induced Vibrations: Modelling and Application*" (subcluster 15) started to grow in late 2000s. A paper published by Bernitsas et al., 2008 that presented a new mechanism for the extraction of clean energy from vortex induced vibrations instigated significant interest in this field.
- Research related to subclusters 1 (*"Dynamic control and path tracking of marine vehicles"*) and 3 (*"CFD modelling of processes in upper oceanic boundary layer"*) accelerated in the late 1990s and they are still growing. The main reason can be the sudden advancement in computational fluid dynamics (Stern et al., 2015) and of the emergence of integrated navigation systems (Matikka, 2021). These advances may be considered fundamental in terms of influencing research of relevance to subclusters 1 and 3.
- Two subclusters that slowed down recently are *"Freak waves, wave statistics"* and *"ship structures"*. The former provides a general idea about ocean physics and the statistical properties of waves (e.g. Canard et al., 2022; Jiang et al., 2022; Kirezci et al., 2021a, 2021b; Onorato et al., 2006, 2004; Petrova et al., 2022). However, within the context of ocean engineering it becomes very important when it is linked to the dynamics of ship structures and offshore platforms (e.g. Miguel Onorato et al., 2013; Zhang and Guedes Soares, 2016). The decline of research in coupling computational solid and fluid dynamic solvers and the broader acceptance of studying structural responses of ships within the context of hydroelastic analysis has profound impact on the research conducted in this area. Advances may well fall into the subcluster namely *"Hydroelastic motion of floating objects and marine vehicles"* (Hirdaris and Temarel, 2009; Korobkin et al., 2011; Wang et al., 2010). Another reason for the decline may relate with the maturity of the subject and the strong emergence of materials science. For example, today many researchers work more on lightweight materials engineering topics and the use of 3D printing (Jandyal et al., 2022; Lee et al., 2017; Singh et al., 2020). Such research may not be traditionally linked to the field of ocean engineering. Yet, the number of practical applications becomes increasingly relevant.
- The subcluster of research related to *"Theoretical and Statistical Analyses of Response of Structures to Waves"* reached an early peak in the late 1980s and grew again in the mid-2010s. Research back in the 1980s was primarily based on classical hydrodynamics (e.g., see Sarpkaya and Isaacson, 1981a, 1981b) and was gradually replaced by computational studies from 2000s onwards with renewed focus on nonlinear dynamics and the statistical analyses of energy converters (Abbasnia and Guedes Soares, 2018; Dou et al., 2020; Gomes et al., 2020), fish cages (Huang et al., 2018), ships (Abu Husain et al., 2019) and other floating or submerged bodies (Zhu and Chen, 2019).
- The subcluster termed "*Collision Risk and Marine Traffic*" emerged in the mid-2010s. The reason for this emergence is likely to be the shift of researchers from theoretical (or mathematical) methods towards using machine learning methods. This attracted the renewed attention of researchers in different fields of science and engineering (Greene, 2020).

Table 1 presents the most influential references of each subcluster and the citing papers with the highest coverage of those. For each subcluster the notations namely "*year duration of fundamental references (YR (ref))*", "*mean year of fundamental references (MY (ref))",* and "*mean year of citing papers (MY (citing))*" are presented. In addition, a "*Silhouette Score (SS)*", which describes the clustering quality is also presented. Here 1.0 is the highest value that SS can take.

The influential references for subclusters "*Renewable energy of Ocean: Conceptualization*", "*Hydrodynamic of OWC*", "*Hydrodynamics of tidal turbines*" and "*Hydrodynamics of offshore wind turbines*" are those presenting a general overview of ocean energy conversion devices, or a review of ocean energy resources (e.g., Clément et al., 2002; Coulling et al., 2013; Falcão, 2010; Falcão and Henriques, 2016; Falnes, 2002; Jonkman, 2010; Jonkman et al., 2009; Khan et al., 2009; Robertson et al., 2014, 2017; Roddier et al., 2010; Rourke et al., 2010; Setoguchi et al., 2001; Setoguchi and Takao, 2006; Torre-Enciso et al., 2009).

References of relevance to the subclusters on "*Dynamic control and path tracking of marine vehicles*", "*Hydroelastic motion of floating objects and marine vehicles*", "*CFD modelling of processes in upper oceanic boundary layer*", "*Freak waves and wave statistics*", "*Wave breaking and internal gravity waves*", and "*Theoretical and Statistical Analyses of Response of Structures to waves*", are seminal papers or books that provide theories or developed methods for modelling physical problems. These references may not be originally related to the field of ocean engineering. For example Hirt and Nichols, 1981 is one of the most important references of subcluster 2 namely "*CFD modelling of processes in upper oceanic boundary layer*". In this article, authors have presented the Volume of Fluid (VoF) method which is commonly used for simulating the air-water flow in CFD studies.

In the subcluster "*Hydrodynamics of tidal currents*", the focus of published papers is largely on tidal hydrodynamics. Most important references discuss models developed for ocean turbulence and tidal flows used for simulation of Earth processes and coastal region climate (e.g. Davies, 1991; Shchepetkin and McWilliams, 2005).

Citation bursts can demonstrate when and how significantly a fundamental reference may be cited in a subcluster over the years. Readers interested in the method used for calculation of the burst may refer to Kleinberg, 2003. Analysing a burst can show when a specific study attracts the attention of other researchers. In turn, this may help us to (i) understand the structure of the of the ocean engineering field, and (ii) predict whether any specific research in the future can potentially attract the attention of researchers. In this paper only bursts related to the subclusters that are steadily growing are analysed. On this basis the following observations can be drawn:

- Cruz, 2008 - burst strength, 20.5, over 2010–2014, Iglesias et al., 2009, - burst strength 16.74, over 2010–2015 Waters et al., 2009, - burst strength 16.32, over 2010–2015, de O. Falcão, 2007 - burst strength 15.58, over 2009–2016, Uihlein and Magagna, 2016, - burst strength 15.26, over 2016–2021 Magagna and Uihlein, 2015, - burst strength 14.4 over 2017–2021, Ringwood et al. (2014) - burst strength 13.88 over 2017–2021 are the fundamental references with the strongest burst in subcluster 0 ("*Renewable energy of Ocean: Conceptualization*"). These studies mostly forecast or present ocean renewable energy resources. As seen the earliest burst occurred in

2009. This relates to a paper that presents analysis on performance of an OWC (de O. Falcão, 2007). It matches with what was observed in Fig. 5 (e.g., subcluster 0 was seen to grow in 2000s). Interestingly, bursts of two documents are still on: Magagna and Uihlein, 2015 and Ringwood et al., 2014. The former presents an overview of the wave and tidal energy resources, and the latter presents a control method for optimization of the performance of wave energy converters. This shows how important the control of a wave energy device is as it may lead to optimization of the performance of a converter. *It is believed that the optimization of the performance of energy converters through control methods may turn into a subcluster in the future.*

- Fossen, 1994 - burst strength 65.04 over 1996–2012, Fossen, 2002, - burst strength 54.04 over 2005–2014, Krstic et al., 1995, - burst strength 31.13 over 1998–2010, Newman, 1977, - burst strength 29.88 over 1995–2012, Fossen, 2011, - burst strength 26.32 over 2016–2019 present fundamental research with the strongest burst in subcluster 1 (“*Dynamic control and path tracking of marine vehicles*”). All these references are textbooks presenting control methods for marine vehicles (Fossen, 1994, Fossen, 2002, Fossen, 2011), marine hydrodynamics (Newman, 1977), and theory of controls (Krstic et al., 1995). Except Fossen, 2011, bursts of these references started in the late 1990s. Presently, the burst of all documents in this cluster is over.
- Salvesen et al., 1970 - burst strength 26.08 over 2001–2011, Wehausen and Laitone, 1960, -burst strength 20.94, over 1988–2008, Watanabe et al., 2004, - burst strength 20.19, over 2005–2010, John, 1950, - burst strength 17.55 over 1992–2011 and Squire, 2007 - burst strength 17.44, over 2009–2013 are fundamental references with the strongest burst in subcluster 2 (“*Hydroelastic motion of floating objects and marine vehicles*”). The burst of all of them is over. Interestingly, two of these references are old; Salvesen et al., 1970 and Wehausen and Laitone, 1960. They present theories of water waves and ship motions (the burst of which did not last after 2011) and do not present any information on hydroelectricity theory of objects in the ocean. This indeed shows that this subcluster is basically built around the water wave motion theories and rigid body motion theories. Two of the other references (Watanabe et al., 2004 and Squire, 2007) present review studies on fluid-structure interactions of ice and very large floating structures (VLFS). Note that hydroelastic motions of these two floating objects are very similar (Squire, 2008a). The main motivation of researchers to study hyperelastic motion of VLFS is related to their growing development in late 1990s (e.g., Mega-Floats from Japan in 2000 discussed in Lamas-Pardo et al. (2015), and recent retreat of ice extent in Arctic discussed by Stroeve et al. (2008)).
- Jacobsen et al., 2012 - burst strength 14.96 over 2017–2021, Longuethiggins and Cokelet, 1976 - burst strength 14.7, over 2008–2014, Young, 2008, - burst strength 13.17, over 2010–2014, Carlton, 2012, - burst strength 12.76, over 2017–2021, Carrica et al., 2007, - burst strength 11.93, over 2007–2013 and Lin and Liu, 1998 - burst strength 10.02, over 2006–2014 are references with the strongest burst of subcluster 3 (“*CFD modelling of processes in upper oceanic boundary layer*”). Two of these references are addressing methods for wave generation in a computational domain. This clearly signals that there is a pressing need to carry out wave modelling by CFD simulations. The burst of the book of Carlton (2012) on marine propellers started in 2017 and is still ongoing. This shows that in recent years ocean engineering researchers using CFD methods have maintained interest in the traditional hydrodynamic modelling of propeller flows.
- Torre-Enciso et al., 2009 - burst strength 15.26 over 2016–2019, López et al., 2013 - burst strength 14.26 over 2016–2019, Ning et al., 2016, – burst strength 13.07, over 2017–2021, McCormick, 2007, - burst strength 11.81, over 2010–2017, Abramowitz and Stegun, 1965, - Burst strength 11.68 over 1999–2012, Raghunathan, 1995, - burst strength 11.15 over 1999–2006 are some of the fundamental references of subcluster 5 that have the strongest burst. Most of these references present the general idea of wave energy conversion (Torre-Enciso et al., 2009, López et al., 2013, McCormick, 2007) and were bursting until 2019. Perhaps this demonstrates that the idea of wave energy conversion is reaching maturity and accordingly authors find of lower importance to refer to studies on wave energy conversion. Ning et al., 2016 and Raghunathan, 1995, present analysis for wave energy conversion technologies. The latter presents an analysis on how a “*Wells Air Turbine*” can be used for of wave energy conversion. The burst of this reference is over. The former presents experimental analysis on an energy converter and its burst is still on. This suggests that researchers dealing with tidal turbines are now more interested to have benchmark data for their studies or are inspired by recent and novel studies to better understand their performance. The paper of Abramowitz and Stegun (1965) experienced a strong burst in between 1999 and 2006. This reference presents mathematical functions and is mostly used when theoretical methods are used to solve wave-structure interaction problems. As the burst of this document is over, one can conclude that researchers studying the hydrodynamics of OWC start showing less interest into the use of theoretical methods.
- Faltinsen and Timokha, 2009 - burst strength 15.19 over 2011–2015 Monaghan, 2005, - burst strength 14.88, over 2010–2015, Faltinsen, 2006, - burst strength 14.67, over 2009–2015) Cole, 1948, - burst strength 13.14, over 2008–2014) Mei et al., 1999, - burst strength 13.07, over 2013–2017, and Smagorinsky, 1963 - burst strength 11.13, over 2006–2012 are fundamental references of subcluster 7 with the strongest burst. This subcluster, is dominated by studies that use the SPH methods to solve the free surface (water wave propagation) problem. Amongst these fundamental studies, the burst of only one namely Monaghan, 2005 is over. The other references are textbooks or research papers presenting free surface problems, with emphasis mostly on water entry and sloshing (e.g. Faltinsen, 2006; Faltinsen and Timokha, 2009) or the computation of sea loads (e.g. Cao et al., 2014; Gotoh et al., 2014; Marsh et al., 2011; Shao et al., 2012). This observation fairly matches with what was observed in Fig. 2. The reference by Wendland, 1995 shown in Table 1 presents SPH related mathematical formulations and suggests that marine related work in this area starts becoming more rational and focused.
- The papers by Kuwata et al., 2014 - burst strength 9.94 over 2016–2019, Goerlandt and Kujala, 2011, - burst strength 9.29 over 2012–2015, Montewka et al., 2010, - burst strength 8.71, over 2011–2015, Tsou et al., 2010, - burst strength 5.96, over 2014–2017, Davis et al. (1980) - burst strength 5.15, over 2016–2019 present the strongest burst cases for subcluster 8. All these studies present methods or algorithms for the analysis of ship collision avoidance. The trend of this subcluster may depend on the emergence of AI algorithms many of which are constantly updated. It can be concluded that development of new methods for the analysis of ship collision avoidance may receive more attention by researchers.
- Bahaj et al., 2007a - burst strength 12.61, over 2012–2016, Khan et al., 2009, – burst strength 12.61, over 2012–2016, Rourke et al., 2010, - burst strength 11.91, over 2013–2017 and Bahaj et al., 2007b - burst strength 11.24, over 2012–2015 are fundamental references with the strongest burst in subcluster 11. Two of these references, present analysis on the performance of turbines that can be used for energy extraction (Bahaj et al., 2007a, 2007b). One of the other references reviews the literature (Khan et al., 2009) and the other presents an update on tidal energy (Rourke et al., 2010). The burst of all these references is over. This may signal that a new update of tidal energy and its use may be required. New analysis on performance of hybrid energy converters (extracting energy of tides and waves) may receive further attention by researchers in the near future (ES-Wave, 2021).
- Bathe, 1996 - burst strength 9.85 over 2007–2013, Bearman, 2011, - burst strength 8.89 over 2011–2016, Gabbai and Benaroya, 2005, -

burst strength 6.15 over 2013–2017, Williamson and Govardhan, 2004a, - burst strength 5.28, over 2017–2021 and Williamson and Govardhan, 2008 - burst strength 5.18 over 2017–2021 are the references with the strongest burst in subcluster 15. Some of these references (Bearman, 2011; Gabbai and Benaroya, 2005; Williamson and Govardhan, 2004a, 2008) present reviews on the problem of vortex-induced vibrations. The bursts of two of these review papers are still on (Williamson and Govardhan, 2004a, 2008), although they were published in 2000s. In the future, there may be a need to update their review and accordingly present progress that made over the last two decades.

An indicator, named, *"centrality"* is also presented in Table 1. This indicator shows how a node (i.e., a cited reference) representing fundamental research (see Fig. 5) can be cited broadly across various topics. For example, the classic references by Newman, 1977, Lamb, 1932, Pierson Jr. and Moskowitz, 1964, Cummins et al., 1962, Minorsky, 1958 and Gill, 1982 have the highest centrality amongst papers. The following points should be highlighted:

- The *Marine Hydrodynamics* book (Newman, 1977) and the *Hydrodynamics* book by Lamb, 1932 are fundamental references used in most of the ocean engineering studies. They may serve as key references for many researchers dealing with the physics of water waves, ship motions, fluid forces acting on a body in an unbounded fluid domain etc. It is therefore very reasonable that they enjoy the highest centrality in the field.
- Pierson Jr. and Moskowitz, 1964 in their article entitled "*A Proposed Spectral Form for Fully Developed Wind Seas Based on the Similarity Theory of S. A. Kitaigorodskii*" introduced the first wave spectrum representing the randomized sea. The method is still in use for reproducing the wave forcing condition by many researchers dealing with motions of objects in the ocean or wave propagation (Carlton, 2018).
- Cummins et al., 1962 in their study entitled "*The Impulse Response Function and Ship Motions*" introduced a method for analysing ship responses in the frequency domain, which has been turned into a fundamental method applied for seakeeping analysis of any floating object or marine vehicle. This research gained very noticeable centrality among all subclusters.
- Minorsky, 1958 presented an analysis for collision prediction of ships, which is one of the oldest ones in the whole field of ocean engineering. This reference received the attention of researchers dealing with "*Control and path tracking of Marine Vehicles*" (subcluster 1) and "*Collision Risk and Marine Traffic*" (subcluster 8).
- Gill, 1982 entitled "*Atmosphere-Ocean Dynamics*" authored a book that presents general formulation and theories related to ocean and atmosphere and the way their interact. The latter is very important in wave modelling, wave climate, wave statistics and energy dissipation, and it has reached a very high level in subclusters dealing with ocean waves (e.g., see subcluster 6 - *"wave breaking and internal gravity waves"*).

Assuming that research in any of the growing co-citation clusters follows an exponential function, it is predicted that studies falling into subclusters 0 ("*Renewable energy of Ocean: Conceptualization*"), 1 ("*Dynamic control and path tracking of marine vehicles*"), 2 ("*Hydroelastic motion of floating objects and marine vehicles*"), 3 ("*CFD modelling of processes in the upper oceanic boundary layer*"), 5 ("*Hydrodynamics of OWC*"), 7 ("*Smoothed Particle Hydrodynamics*"), 8 ("*Collision Risk and Marine Traffic*"), 10 ("*Theoretical and Statistical Analyses of Response of Structures to waves*"), 11 ("*Hydrodynamics of tidal turbines*"), 12 ("*Hydrodynamics of offshore wind turbines*") and 15 ("*Vortex Induced Vibrations: Modelling and Application*") increasingly grows. This is reasonable because of the pressing need to consider renewable energies and research on ship autonomy that interrelates to marine hydrodynamics (e.g. (Zheng et al., 2022)). Subclusters dealing with *"the control theory of energy conversion"* and *"marine hydrodynamics using data-driven models"* may emerge strongly in the future.

4. Conclusions

Ocean engineering is a vast and growing field of research with impact on our daily lives. Global trends and climate change imply the need to fully understand the structure and temporal progression of research undertaken in the field. With the latter in mind this paper attempted a review of the entire field of ocean engineering research over the last 50+ Years. Knowledge and management gaps, future challenges and the way forward were identified. Studying the evolution of research helped identify strategic research streams and how they evolved over decades. The discussion attempted to highlight which of the methods developed contributed to the pragmatic solutions of problems that emerged over time. They also questioned whether research topics are in line with societal expectations for a safer and sustainable world.

The bibliometric perspectives presented helped highlight six major ocean engineering divisions including "*Ocean Hydrodynamics*", "*Risk Assessment and Safety*", "*Ocean Climate and Geophysics: Field data and Models*", "*Control and Automation in the Ocean*", "*Structural Engineering and Manufacturing for the Ocean*", and "*Ocean Renewable Energy*". "*Renewable Energy of the Ocean*" emerges strongly as a theme in recently published papers. On the other hand, publications under the theme "*Climate: Field data and Models*" were seen to relate to past research. Computational models are visible in traditional streams of work related with "*Ocean Hydrodynamics*" and "*Structural Engineering and Manufacturing for the Ocean*". Terms such as *"3D printing"* and *"pandemics"* including COVID-19 did not emerge strongly. This suggests that well devoted studies are not evident. The former relates with new manufacturing methods that can be used for printing propellers, and ship elements as well as ship model tests, leading to more sustainable marine life. The latter highlights an emerging topic of cross-cutting research relevance (Haghani, 2022) that so far has not been at all in the focus of ocean engineering. Machine learning methods are an emerging topic. However, so far, they are largely used for finding solutions to problems linked to *"Risk Assessment and Safety"*. Evident research dealing with the emerging topics of *"Structural Engineering for Manufacturing for the Ocean"* is somehow limited to concurrent methods.

The possible reason for the success of studies dealing with "*Ocean Hydrodynamics*" is mainly the progress of the science underlying computational models and the emergence of modern experimental techniques. In addition, studies falling under the "*Risk Assessment and Safety*" cluster have been recently very successful in terms of introducing AI models for ship safety assessment. The parametrised equations (based on available big data records) used in climate modelling and the methods used for tracking climate evolution are believed to be the main reasons for the success of research dealing with ocean climate modelling and observation. The emergence of "*Control and Automation in the Ocean*" is possible because of advances in ship automation. Research studies under the cluster "*Structural Engineering and Manufacturing for the Ocean*" have been very successful in terms of modelling marine structures. As computational, analytical, and experimental methods become more mature and accurate for the analysis of structural responses it is expected that research in this field will become more impactful. A large body of research under the cluster of "*Renewable Energy of the Ocean*" is becoming increasingly more and more evident. This is because of the pressing need for clean energy. It is expected that in the years to come improved hydrodynamic models and the availability of climate data from field measurements will make even more possible the advancement of technologies for energy extraction from the ocean.

Analysis of the similarity map of all papers under the ocean engineering field highlighted a big gap between research dealing with *"Ocean Climate and Geophysics: Field data and Models"* and the studies related to "*Ocean Hydrodynamics*", "*Risk Assessment and Safety*", "*Control and Automation in the Ocean*", and "*Structural Engineering and Manufacturing for the Ocean*". This shows that most models used to analyse engineering processes relate to the ocean (e.g., shipping, installation of offshore platforms, etc.) do not address ocean climate. Thus, climate change effects are often overlooked throughout the design process of ships and floating offshore installations.

There is huge potential to use machine learning techniques in ocean engineering. Presently studies are somehow concentrated on ship collision avoidance that relates to "*Risk Assessment and Safety*". "*3D printing in the maritime industry", "mesh-free methods for structural analysis and hydroelastic simulations", and "the use of SPH in studying the performance of wave energy converters"* are suggested as potential research that can be done in the future. Research in advanced ventilation systems and air circulation processes for the avoidance of transmission of diseases onboard ships was identified as another emergent topic because of the COVID-19 pandemic.

Fundamental references, resulted in sixteen subclusters, named as the key sub-divisions of the field. Amongst those, "*Renewable energy of Ocean: Conceptualization*", "*Hydrodynamics of OWC", "Hydrodynamics of tidal turbines*", "*Hydrodynamics of offshore wind turbines*" and "*Vortex Induced Vibrations: Modelling and Application*" peaked up in late 2000s. This trend could be attributed to the growing demand for affordable and clean energy. The subclusters namely "*Dynamic control and path tracking of marine vehicles*" and "*CFD modelling of processes in upper oceanic boundary layer*" grew since 1990s. The latter could be attributed to the development of computational models for simulation of fluid problems and the rise of integrated navigation systems in the late 20th century. Growing interest in the use of machine learning in mid-2010s has been hypothesized to be the main reason behind intensifying research on "*Collision Risk and Marine Traffic*". The subcluster "*Theoretical and Statistical Analyses of Response of Structures to waves*" was seen to re-grow during the first decade of the 21st century. This could be attributed to its cross-cutting relevance.

Research and technology development or exploitation in the field of ocean engineering is expected to exponentially grow over time. Whereas growth may continue being significant within the subclusters identified in this paper new trends may also emerge. The application of neural networks in marine hydrodynamics, the emergence of control theory concepts for application in autonomous floating ships and FOI concepts, and the development of energy converters are possible examples. Extreme events with high societal impact (e.g., global warming patterns, wars and pandemics), may also highly affect strategic research trends. In any case, research justifying and enabling the utilisation of clean and renewable energy is expected to increase, and in particular research dealing with ocean renewable energy may bust leading to research subclusters beyond those currently foreseen.

Overall, research in the field of ocean engineering is in line with general demands such as environmental sustainability, clean and affordable energy, and absolute safety. Notwithstanding this the conceptual implementation of emerging technology capabilities (e.g., AI and 3D printing) and the potential impact of extreme events including pandemics ocean engineering and the society at large should be researched further. Development of computational based models (e.g., idealising fluids, solids and their interactions) in the late 20th century triggered research dealing with hydromechanics, hydroelasticity and wave modelling. Emerging model scale experiments based on 3D printed models and machine learning methods are not yet broadly used. Yet, their utilisation and development in the years to come is expected to have profound effects on the enhancement and validation of traditional methods.

The authors acknowledge that in the future, more bibliographic studies may be carried out with the aim to improve our technological and scientific know how. For example, research progress in the areas of "*Renewable Energy of the Ocean*" and "*Risk Assessment and Safety*" has been limited to the last two decades. Therefore, analyses of progress and research directions of these two clusters over the last 15 years may provide a meaningful understanding of additional strategic avenues for ocean engineering research.

CRediT authorship contribution statement

Sasan Tavakoli: Conceptualization, Investigation, Formal analysis, Visualization, Project administration, Writing – original draft. **Danial Khojasteh:** Conceptualization, Investigation, Formal analysis, Writing – original draft. **Milad Haghani:** Conceptualization, Visualization, Resources, Methodology, Writing – review & editing. **Spyros Hirdaris:** Conceptualization, Supervision, Resources, Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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