Process Safety and Environmental Protection 148 (2021) 437–461

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

Reliability of multi-purpose offshore-facilities: Present status and future direction in Australia

Vahid Aryai [a,b], Rouzbeh Abbassi [a,*], Nagi Abdussamie [b], Fatemeh Salehi [a], Vikram Garaniya [b], Mohsen Asadnia [a], Al-Amin Baksh [b], Irene Penesis [b], Hassan Karampour [c], Scott Draper [d], Allan Magee [e], Ang Kok Keng [e], Chris Shearer [f], Suba Sivandran [g], Lim Kian Yew [e], Denham Cook [h], Mark Underwood [i], Andrew Martini [i], Kevin Heasman [j], Jonathan Abrahams [k], Chien-Ming Wang [l]

[a] School of Engineering, Faculty of Science and Engineering, Macquarie University, Sydney, Australia
[b] National Centre for Maritime Engineering and Hydrodynamics, Australian Maritime College (AMC), University of Tasmania, Launceston, Australia
[c] School of Engineering and Built Environment, Griffith University, Gold Coast, Australia
[d] School of Civil, Environmental and Mining Engineering, University of Western Australia, Perth, Australia
[e] Department of Civil and Environmental Engineering, National University of Singapore, Republic of Singapore
[f] BMT Commercial Australia Pty Ltd
[g] BMT Singapore Pte Ltd
[h] Seafood Production Group, The New Zealand Institute for Plant & Food Research Limited, Port Nelson, New Zealand
[i] Engineering and Technology, CSIRO Oceans and Atmosphere Hobart, Hobart, Australia
[j] Cawthron Institute, Nelson, New Zealand
[k] DNV GL Australia Pty Ltd, Australia
[l] School of Civil Engineering, The University of Queensland, St Lucia, Australia

ARTICLE INFO

Article history:
Received 1 September 2020
Received in revised form 6 October 2020
Accepted 6 October 2020
Available online 14 October 2020

Keywords:
Blue economy
Ocean multi-use
Offshore platforms
Structural integrity
Reliability analysis

ABSTRACT

Sustainable use of the ocean for food and energy production is an emerging area of research in different countries around the world. This goal is pursued by the Australian aquaculture, offshore engineering and renewable energy industries, research organisations and the government through the "Blue Economy Cooperative Research Centre". To address the challenges of offshore food and energy production, leveraging the benefits of co-location, vertical integration, infrastructure and shared services, will be enabled through the development of novel Multi-Purpose Offshore-Platforms (MPOP). The structural integrity of the designed systems when being deployed in the harsh offshore environment is one of the main challenges in developing the MPOPs. Employing structural reliability analysis methods for assessing the structural safety of the novel aquaculture-MPOPs comes with different limitations. This review aims at shedding light on these limitations and discusses the current status and future directions for structural reliability analysis of a novel aquaculture-MPOP considering Australia's unique environment. To achieve

Abbreviations: AI, Artificial intelligence; AK-MCS, Active Learning Reliability Method with integrated Kriging and MCS; ARENA, Australian Renewable Energy Agency; AUV, Autonomous underwater vehicles; CBM, Condition-based monitoring; CSIRO, Commonwealth Scientific and Industrial Research Organisation; CSRV, Common source random variables; EGRA, Efficient Global Reliability Analysis; EMA, Experimental Modal Analysis; FBG, Fibre Bragg Grating; FDD, Frequency Domain Decomposition; FE, Finite element; FLNG, Floating Liquefied Natural Gas; FMEA, Failure Mode and Effects Analysis; FORM, First Order Reliability Method; FOWT, Floating offshore wind turbine; FPSO, Floating structures for production, storage and offloading; GI, Galvanised iron; GIS, Geographic information system; HDPE, High-Density Polyethylene; IS, Importance Sampling; LH, Latin Hypercube; LS, Line Sampling; MCS, Monte Carlo Simulation; MEMS, Microelectromechanical systems; MFS, Modular floating structures; MOB, Mobile offshore base; MPOP, Multi-Purpose Offshore-Platforms; NARMAX, Non-linear Auto-Regressive Moving Average with exogenous inputs model; NOAA, USA National Oceanic and Atmospheric Administration; NWW3, NOAA Wave Watch III; O&M, Operations and management; OMA, Operational Modal Analysis; OREDA, Off ;shore and Onshore Reliability Data database; OWT, Offshore wind turbine; PE, Polyethylene; PET, Polyethylene terephthalate; PES, Polyurethane polyester; PP, Polypropylene; PSP, Pneumatically Stabilized Platform; PVC, Polyvinyl Chloride; QRS, Quantum Resistive Sensors; RAMS, Reliability, Availability, Maintainability, and Safety; ROV, Remotely operated vehicles; RSM, Response Surface Method; SCADA, Supervisory Control and Data Acquisition; SES, Dragon and Seaweed Energy Solutions; SHM, Structural health monitoring; SORM, Second-Order Reliability Method; SS, Subset Simulation; SWAN, Simulating Waves Nearshore; VLFS, Very large floating structure; WEC, Wave energy converter; WSE, Wave Swell Energy.

* Corresponding author.
E-mail address: Rouzbeh.Abbassi@mq.edu.au (R. Abbassi).

https://doi.org/10.1016/j.psep.2020.10.016

this aim, challenges which exist at different stages of reliability assessment, from data collection and uncertainty quantification to load and structural modelling and reliability analysis implementation, are discussed. Furthermore, several solutions to these challenges are proposed based on the existing knowledge in other sectors, and particularly from the offshore oil and gas industry. Based on the identified gaps in the review process, potential areas for future research are introduced to enable a safer and more reliable operation of the MPOPs.

1. Introduction

The aquaculture sector delivers more than half of the world's seafood supply and is the major source of employment in many countries (FAO, 2018). Among different types of commercial fishing and aquaculture activities in Australia, marine aquaculture contributes 23.7 % of the employment (ABARES, 2018). Currently, the important seafood and marine products of aquaculture in the country are: mussels, oyster, pearl, tuna, abalone, lobsters, rainbow trout, Atlantic salmon and seaweed. In particular, the salmon aquaculture industry in south-east Tasmania is the most valuable fishery, which has seen an increase in value of 194 % in the past decade (ABARES, 2018). Sea cages, also known as fish pens, and mussel longlines are common methods of marine aquaculture in Australia (ABARES, 2018). Owing to its vast economic capacity and environmental adaptability, marine aquaculture is expected to significantly expand in the near future. In comparison with other developed countries, Australia is known to have a huge gap between its current aquaculture production and potential production capacity. As of 2018, the total fish production was 265,975 tonnes per year, while the potential production (if 1 % of the suitable marine area in the country was developed for low-density marine fish aquaculture) was estimated to be between 6,000 % and 9,000 % of that (Gentry et al., 2017; Australian Fisheries and Aquaculture Statistics 2018, 2019Australian Fisheries and Aquaculture Statistics 2018, 2019). Considering this huge potential, in 2018, the total value of exports from Australia was approximated at 1,575.1 M$, which was no more than 1 % of the global trade market (Australian Fisheries and Aquaculture Statistics 2018, 2019Australian Fisheries and Aquaculture Statistics 2018, 2019). Thus, the described gap, if properly filled, would enable the Australian fish market to compete with the top countries in the world in the global trade market. Pursuing this aim however, requires reliable infrastructures with minimal risks and high productivity. For instance, a recent study on the co-location of offshore wind and mussel cultivation facilities showed the possibility of 5 % reduction in the operations and management (O&M) costs of a wind farm (Buck et al., 2010). Furthermore, an analysis of shared moorings for a floating offshore wind farm has been performed by Connolly and Hall (2019), indicating a significant cost-saving opportunity (between 0.4 M$ and 12 M$ based on the water depth and mooring configuration) in the construction phase by sharing the mooring system. Further cost reduction is expected to occur because of shared resources and logistics in case of integration (Dalton et al., 2019). Also, better access to the spatially efficient production systems can significantly increase the production rate. A study on the integration of wind energy and mussel aquaculture showed an 8 % increase in spatial efficiency and a 207–230 % increase in the density of value generated by the cooperation between two firms in comparison with a wind farm alone (Griffin et al., 2015). As mentioned in the work of Jensen et al. (Jansen et al., 2016), the viability of the MPOP highly depends on the type of multi-use combinations and the price of the products (energy vs seafood and marine products). The study revealed that the price of mussels could determine whether an MPOP of mussel and wind farming is profitable or non-profitable. Therefore, different combinations of aquaculture and renewable energy devices must be assessed in terms of profitability and then combined through a reliable MPOP design to guarantee the safety, species compatibility and profitability of the whole system.

1.1. Multi-purpose offshore platforms (MPOPs)

Multi-use of the ocean by MPOPs can be achieved via two different approaches, namely co-location, and integration. Co-location mainly involves moving two or more platforms close together without physically connecting them to share benefits such as logistics, sea space, and the possibility of benefiting each other by supplying the energy demand required by the systems (e.g. electric power needed for aquaculture facilities can be provided by the offshore wind, wave or solar energy system located in the vicinity). Also, better structural and operational reliability can be achieved through proper co-location of offshore energy facilities. A study by Silva et al. (2018) showed that the wave energy converters can be used as the shelter for aquaculture installations to minimize the nearshore wave impact on the aquaculture cages. On the other hand, integration, is defined as a hybrid use of a single structure for multiple purposes, including infrastructure for aquaculture, wind turbine(s), and/or wave energy converter(s). Integration by itself can be realised by designing new hybrid structures or modifying the functionality of existing structures. Transformation of existing offshore oil and gas platforms for other activities such as aquaculture is also suggested as an appealing solution for MPOPs. Because of the enormous decommissioning costs of out-of-service offshore oil and gas platforms, transforming the functionality of these platforms to other activities such as aquaculture has always been an interesting topic of research (Sommer et al., 2019).

Shifting from fossil fuels to clean energy by the Australian and New Zealand governments is another reason behind the importance of repurposing offshore oil and gas platforms. Australia's and New Zealand's targets under the Paris Agreement is to reduce greenhouse gas emissions by 28 and 30 per cent, respectively, below current gross emissions by 2030 (About New Zealand's, 2020). In order to achieve this aim, several offshore oil and gas platforms need to be decommissioned. Consequently, after the deadline, the decommissioning of offshore oil and gas platforms around the country means that they could be effectively used for other activities in future. In Australia, many of the old oil and gas platforms (e.g. oil platforms on the North West Shelf of Australia) have been already turned into artificial reefs (Fujii et al., 2020), as the removal of such structures could cause massive damage to the surrounding environment (Chandler et al., 2017). Additionally, transforming the functionality of oil and gas platforms to hydrogen production platforms is a green option that is being supported by the Australian Government through a National Hydrogen Strategy (Group, 2019). The recent significant decline in oil price could tighten the deadlines for countries around the world including Australia; thereby reinforcing the importance of this research topic.

During the past decade, the ideas of co-location and integration were highly supported by the European Union (EU) during two major projects: *The Ocean of Tomorrow* and *Horizon 2020*

(Koundouri, 2017; Aguilar-Manjarrez, 2016). The available experience and knowledge gained through the EU projects can be of significant help for developing the MPOP concept in Australia. Australia is expected to launch its first offshore wind farm, through *the Star of the South* project, and has already started the development of a wave farm with the pilot project launched by Carnegie Wave Energy Limited in Western Australia (Australia's first proposed offshore wind farm, 2020; Energy, 2020a). Moreover, the Wave Swell Energy (WSE) is about to launch a wave energy converter in King Island, Tasmania by mid 2020 (Energy, 2020b). Consequently, there is huge potential for integrating the MPOPs into pilot projects which allows for collecting data on different operational and structural aspects of the MPOPs. This would eventually lead to the production of reliable and more efficient MPOPs. The possible integration comes with advantages and disadvantages that highly depend on the type of combination (co-location/integration), planned activities (aquaculture, wave, wind, solar, hydrogen, etc.) and the site location (offshore or nearshore). However, the regulatory framework to support aquaculture and renewable energy production in offshore waters does not yet exist. The two most common metrics are the minimum distance from shore (in nautical miles, nm) and minimum water depth (in meter, m). In Australia, based on the location of the energy and aquaculture activity the State/Territory governments (for <3 nm offshore) and the Federal government (for 3−200 nm offshore) are the assessment authorities, respectively for the multi-purpose activities. Additionally, the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) is the regulator for oil and gas activities in Commonwealth waters and in coastal waters (Australia's Offshore Energy Regulator, 2020). Also, the potential activities within the marine parks have been classified by the Australian Government's Department of the Environment and Energy (ERIN, 2020). The designated areas for energy and aquaculture activities include both deep and shallow waters which are considered as far-from shore and nearshore zones, respectively.

The potential advantages of moving aquaculture units further offshore, where renewable energy stations are located, include almost unlimited operational scale, better water quality, social license to operate, better waste management, and reduced risk of diseases associated with farming. Many of these merits are linked to the deeper offshore waters which provide stronger currents and higher rates of water exchange. Moreover, moving aquaculture units offshore may be inevitable in the long-term due to the foreseen negative impacts of climate change (Merino et al., 2012; Rice and Garcia, 2011). However, this comes with the design and technical challenges including more intensive structural stresses due to the presence of high-speed surface currents, wave actions and high wind, longer transit duration (or ship endurance) and many unknown operational (e.g. added costs from maintenance, spare parts lead times, etc.) and safety (e.g. crew transfer by helicopter rather than OSV, etc.) challenges. Owing to the lack of adequate structural strength, currently used nearshore aquaculture pens and mooring systems in Australia are not likely to operate safely in a harsh offshore environment. An alternative approach is to install renewable energy (fixed) platforms, such as wind farms in an appropriate nearshore/sheltered area, where aquaculture farms are currently operating. In doing so, the operational challenges related to the harsh offshore environment are minimised and better transportations and logistics are achieved. However, the operational scale limitations, environmental, and sustainability issues are amplified. In either of the abovementioned cases, the combination of aquaculture farms and renewable energy platforms affect the structural integrity of individual structures and the whole integrated system, and such an impact must be considered in the design phase of the integrated systems.

1.2. Importance of structural reliability

Innovative integration methods on a commercial basis are still in their infancy, as there are many unknown aspects and limitations regarding the operational and technical issues which may threaten human safety, the environment and assets. For instance, between 2012 and 2016 in Australia, 66 % of injury-related compensation claims of aquaculture workers have been recorded in the marine aquaculture sector (Mitchell and Lystad, 2019). A majority of those claims was associated with a lack of structural reliability and the extensive use of cranes in normal and maintenance activities (Holen et al., 2018). The failure of individual components of an MPOP (i.e. aquaculture or offshore renewable energy system) may have indirect impacts on the other components. A study by Horn and Leira (2019) revealed that fatigue damage accumulated faster in the foundations of a non-operating wind turbine. In case of failure of the aquaculture system, for instance, the wind turbine should be shut down for safety reasons. As a result, the non-operating wind turbine would be subjected to faster fatigue damage accumulation and eventually, a higher probability of failure. Consequently, it is vital to analyse the reliability of the integrated systems, ensuring the integrity of aquaculture and renewable energy structures and the safety of its personnel. This aim can be achieved through collecting structural and environmental data, realistic modelling of the forces and structural responses of the system and its components to those forces, identification and simulation of the degradation processes threatening the structural integrity, quantifying uncertainty that exists within the involved factors and ultimately, applying detailed reliability analysis. By using the results obtained from such a reliability analysis, engineers can adjust the design parameters to maximise the reliability and service-life of the integrated systems, and asset managers can use the results for better decision making.

1.3. The review scope and outline

This review intends to discuss the unique features of both offshore aquaculture and renewable energy systems by examining the main problems in having an integrated system from the viewpoint of structural reliability. The paper highlights the gaps in knowledge and proposes further research areas for structural reliability analysis of the integrated system. To achieve this aim, the related previous projects are reviewed in Section 2. Sections 3 and 4 discuss the challenges regarding essential components of a structural reliability assessment, from data collection to implementing reliability analysis methods. Based on the identified challenges, Section 5 recommends several topics for future research. Finally, Section 6 concludes the findings.

As for the literature review herein, whenever possible, MPOP's specific references are provided; otherwise, it is complemented with single-purpose aquaculture and renewable energy references and examples. To be specific and detailed in the discussions about renewable energy devices, examples of offshore wind turbine references are provided. The output of this study, as one of the major requirements, contributes to the design of a reliable integrated system by highlighting the challenges regarding structural reliability aspects of the integration.

2. Review of potential MPOP designs

This section provides reviews on recent attempts for multi-use of the ocean through the integration scheme of MPOPs. Co-location is ignored here since it does not alter the structural aspects of the co-located systems. Furthermore, several conceptual designs for an integrated system proposed within the reviewed research programs are highlighted.

Fig. 1. A prototype of solar and wind energy generator integrated into offshore oil and gas platform (Rosebro, 2006).

2.1. Transformation approach

All available offshore oil and gas structures can be broadly classified in terms of structural configuration as (i) fixed structures such as steel jackets, and gravity-based foundations, and (ii) floating structures such as tension leg platforms, semi-submersible platforms, spar-type platforms, drill ships, and floating structures for production, storage and offloading (FPSO). These facilities can be found in different locations with different water depths and environmental weather conditions. Modifying such platforms to be used as a multi-functional platform, such as a mooring point for aquaculture pens/cages or renewable energy devices, is among the transformation plans for oil and gas platforms being decommissioned (Fig. 1). The transformation procedure varies for different oil and gas platforms based on their next planned/intended functionality. Several conversion options such as transformation to a wave power station (Azimov and Birkett, 2017), a support structure for wind turbines (Maini, 2019), infrastructure for aquaculture (Buck et al., 2017a), and artificial reefs (Dafforn et al., 2015) have been explored in recent years, with the latter receiving special attention by governments and researchers through funded programs such as the Rigs-to-Reef program in the US (Rigs to Reefs, 2020).

Moreover, blue hydrogen production is considered a potential transformation candidate for exhausted offshore oil and gas platforms. In a survey of 1000 senior oil and gas professionals, in the fourth quarter of 2019 about their investment priorities and expectations for the year ahead, 21 % of participants mentioned that their organisation was already active in the hydrogen market (DVN-GL, 2020). 42 % of the participants indicated that their organisation intends to enter the market in 2020. The fact that the survey took place before the COVID-19 pandemic, and the significant drop in the oil price, adds more to the importance of hydrogen production for the oil and gas industry leaders. In general, the decline in the oil price reflects a reduced call for energy. This fact combined with increasing pressures on the oil and gas industry research and development budgets, driven by reduced profitability, may stifle short term development for offshore hydrogen. Since the industry is the current owner of the platforms available for decommissioning, the possible transformation to the offshore hydrogen production platform would be even more accessible in comparison with other activities such as wind and wave energy production. The Australian Renewable Energy Agency (ARENA) has highlighted hydrogen production as one of its three main priorities by dedicating $55 million to the hydrogen projects (Farmer, 2020). Because of the support provided by the government and the oil and gas industry such as BP and DVN-GL, the concept of transforming offshore rigs to hydrogen production platforms can soon be realised.

As already mentioned, the structural safety of the decommissioned platforms is an important challenge faced by structural engineers and asset managers. In general, the service-life of a production platform is constrained by the life of the production wells associated with an oil or gas reservoir/field. The engineers are potentially seeking to extend the life of these structures beyond what may have been expected at time of design or planned for within maintenance regimes and practices. Therefore, comprehensive knowledge of the current and ongoing integrity of the structure will be essential. Additionally, the industry is seeking to use platforms in a manner different to what the platform or structure was designed to deliver, and careful consideration of changed loads and fatigue regimes and monitoring the impacts of these will be important. For predicting the remaining/residual structural reliability of the platform, the Structural Health Monitoring (SHM) systems, and reliability analysis methods must be utilised. In this case, the data gathered from the structural health monitoring equipment attached to the hull, topside attachment, and the mooring/tethering systems are fed to the structural reliability assessment methods to predict the remaining service life of the platform. A brief review of the different SHM methods available for structural monitoring of offshore systems is presented in Section 3.1.3 which examines the transformation approach of the MPOP concept. Several potential candidates for the transformation of the decommissioning oil and gas platforms were introduced, and the relevant support schemes by the government and the industries were discussed. It can be concluded that hydrogen production and artificial reefs, should be considered as the transformation targets. Besides, the environmental-friendly nature of these activities makes them great candidates to operate in the vicinity of aquaculture facilities. The following section reviews the hybrid approach to develop the MPOP concept.

2.2. Hybrid design approach

Designing integrated (hybrid) systems is another idea for aquaculture MPOPs. Several design ideas for an integrated offshore platform have been proposed within the EU research programs, *the Ocean of Tomorrow* and *Horizon 2020*. The first program includes three main projects: *H2OCEAN*, *MERMAID* and *TROPOS*. The *H2OCEAN* project goal was to develop an open-sea wind-wave platform for hydrogen generation (Pirlet et al., 2014). A conceptual design proposed for MPOPs in this program is a floating shipping terminal that includes aquaculture facilities (Dalton et al., 2019). The concept is expected to be implemented by 2030 in Guyana (Port, 2020). On the other hand, *MERMAID* project proposed specific guidelines for optimal use of the ocean by different offshore industries through the concept of MPOPs. The guidelines covered some important environmental, economic and structural aspects of MPOPs for use by aquaculture, renewable energy and offshore oil and gas industries. Among several conceptual integration designs for MPOPs proposed within this program, a connected system of aquaculture units and offshore wind turbines with shared moor-

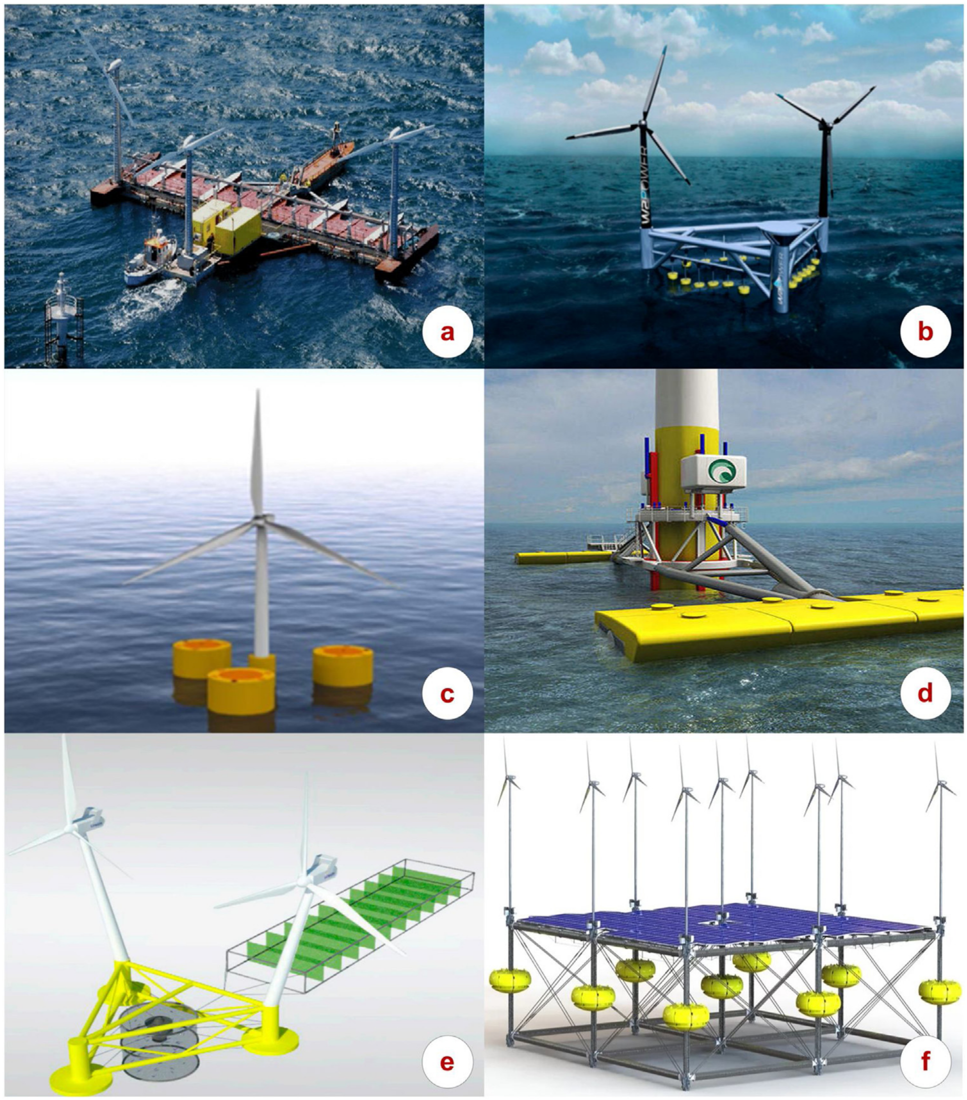

Fig. 2. a) Poseidon wind-wave platform that can produce 33 kW from wind, 50 kW from wave (Tethys, 2020) b) W2Power by Pelagic Power to achieve a rated power of 10 MW (Power, 2020) c) A wind-wave platform (MERMAID, 2020) d) The Green Ocean Energy Wave Treader to produce 500−700 kW (Energy, 2020c) e) A satellite unit proposed for TROPOS project (TROPOS, 2020) f) Each module of Ocean Hybrid Platform by SINN Power has the capacity of four WEC of 0.75 MW, 20 kW of solar energy and four wind turbine of 6kWp (Ocean Hybrid Platform, 2020). (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

ing systems received more attention. Some other design concepts proposed within this program include *Poseidon* wind-wave platform (Fig. 2a), a semi-submersible triangular platform with two or three wind turbines and point absorber wave energy converters (Fig. 2b), a wind-wave platform that utilises Oscillating Water Column technology for wave energy conversion (Fig. 2c), the Green Ocean Energy Wave Treader (Fig. 2d) and the modular Ocean Hybrid Platform by SINN Power (Fig. 2f) (Solutions, 2020; Power, 2020; Iturrioz et al., 2016; Energy, 2020c; Ocean Hybrid Platform, 2020).

In the *TROPOS* project (TROPOS, 2020), the idea of floating modular MPOPs has been proposed as the main conceptual design. A *TROPOS* platform consists of a central floating unit and several associated modules, called “satellites”. The satellites can be either moored to, or structurally separated from, the central unit (Papandroulakis et al., 2017). The conceptual design given by *TROPOS* is a fish aquaculture satellite unit comprising a triangular base with two 3.5 MW wind turbines and aquaculture cage while an algae aquaculture satellite unit was connected to the fish satellite (Fig. 2e). A farm of 30 units is expected to produce (assuming maximum production capacity) up to 750 tonnes of fish per week (Papandroulakis et al., 2017). Moreover, the algae production unit can produce up to 2000 tonnes of algae in a continuous biannual production cycle (Papandroulakis et al., 2017).

The idea of floating islands for integrating different ocean activities has been covered in different projects such as *TROPOS* and specifically, in Space@Sea program of the *Horizon 2020* project. Very large floating structure (VLFS) is not a new concept and has been applied previously in shallow and deep waters for different purposes from oil and gas explorations to leisure centres. Examples of large-scale floating islands which are currently in operation are floating oil storage modules at Kamigoto Island and Shirashima Island in Japan and Floating performance stage at Marina Bay in Singapore (Wang and Tay, 2011; Shell, 2020). Semi-submersibles and pontoon-type are two types of VLFS which are mainly used in deep and shallow waters, respectively. Mobile offshore base (MOB), Versabuoy and Pneumatically Stabilized Platform (PSP) are among the offshore VLFS design concepts, a review of which can be found in (Lamas-Pardo et al., 2015; Wang and Wang, 2015). Based on the location of the system, different mooring systems can be used. Examples include tension leg, chain and wire ropes, and rubber fender-dolphin (Wang and Wang, 2015). The design of the large floating structures is based on the nature of activities to be performed. Each design scenario comes with advantages and disadvantages; the review of which can be found in (Jak et al., 2019). The Prelude Floating Liquefied Natural Gas (FLNG) facility in Australia was in operation between December 2018 and February 2020 but has been shut down due to safety reasons after being identified by NOPSEMA as dangerous (World's largest floating, 2020). Incidents like this, fittingly indicate the importance of reliability assessment of MPOPs.

Outside of the EU supported programs, various conceptual designs have been proposed by offshore aquaculture and renewable energy companies. Hex Box (Fig. 3c) by Ocean Aquafarms is among the ambitious conceptual designs that have been adopted from the SALMAR's offshore fish pens (SALMAR, 2020; Aquafarms, 2020). The system employs a fixed-point mooring system for holding up to 10.140 m T Atlantic salmon, three 60 kW windmills, and two diesel generators. The company claims that the system can survive up to 10 m wave height which easily represents an offshore condition (Aquafarms, 2020). However, the Norwegian development license was refused in 2018 (Fisheries officials turn down Hex Box idea, 2018) and to the best knowledge of the authors, this concept has not yet been implemented elsewhere. Some other design concepts such as Hexicon's multi-wind turbine units (Fig. 3d) have not been originally designed for multi-use applications but can be considered as potential candidates for multi-use after modifications (Hexicon, 2020). This conceptual design is expected to produce up to 10 MW electricity by each unit. Wave Dragon and Seaweed Energy Solutions (SES) developed an MPOP that combines wave energy and offshore aquaculture systems. The design concept has been proposed initially through the MARIBE project and involves a wave energy converter device and longlines for seaweed cultivation (Fig. 3e). The pilot project of the system is in operation 3 miles offshore from the South West Wales coast, UK. The Wave Dragon is capable of being used as the foundation for multi-wind turbines. A Wave Dragon wave converter is expected to produce 4 MW energy, and an SES seaweed farm produces 80 tons per year from an approximately 4 ha' surface area farm (Dragon et al., 2020). Some other conceptual designs include a cubic wind-solar-aquaculture platform with four vertical axis turbines (Fig. 3a) (Zheng et al., 2020), Guangzhou Institute of Energy Conversion's semisubmersible aquaculture-wave platform with solar panel roof (Successfully, 2019), a Floating Offshore Wind Turbine, FOWT-aquaculture cage (Fig. 3b) and an aquaculture-solar-wind system for salmon farming by Grieg Seafood (Zheng and Lei, 2018; Lei et al., 2020; World-first as Grieg installs renewables at salmon farm, 2020).

This section reviewed the currently available design concepts for co-location/integration of aquaculture and renewable energy systems. To select a proper conceptual design for Australian offshore location, different environmental, structural, and financial factors must be considered within the decision-making framework. Unlike the Northern Europe environment, for which a majority of the available conceptual designs have been developed, Australia has some of the best conditions in the world for producing solar energy. Therefore, a design with the capability of solar panel installation can be beneficial for the Australian environment (i.e. Figs. 2e, 3a and 3f).

A similar design concept to the VLFS conceptual design, with a significantly smaller number of modules, is called modular floating structures (MFS). MFS has been proposed and implemented in the solar farm (Liu et al., 2020). The modular design can be added to an MPOP to provide the system with all the benefits of solar energy. The modular design of MFS solar panels causes less shading because of the open spaces available between the modules. As a result, algae growth beneath the modules would be less affected by the lack of direct sunlight in comparison with the conventional large-scale offshore solar farms. A major disadvantage of this conceptual design for the Australian environment is the expected accumulation of bird dropping on the solar panels. Because of the presence of the aquaculture facilities, more birds would be attracted to the system which results in faster dropping accumulation and eventually, an additional reduction in the efficiency of the system. Considering the developments in *the Star of the South* wind farm project, which is going to use FOWTs, the MERMAID design concept of directly connecting aquaculture systems and MFS-based solar panels to the FOWT can be a convenient option at this point. The implementation of this design in practice however, requires accurate reliability assessment of the conceptual system.

3. Reliability analysis of the integrated system

The former section revealed the lack of unified design criteria for MPOPs. Different projects proposed different conceptual designs based on their approach to the MPOP idea. The structural reliability of these designs (i.e. stability, safe structure and mooring, operation, etc.) would be affected over time, due to external loadings, deterioration phenomena, accidents, poor workmanship or natural hazards such as severe storms. The reliability of the system can be assessed quantitively and qualitatively by using structural reliability methods. Structural reliability may be expressed as the probability that a structure works with a predefined extent of safety throughout its service-life. The concept of the component reliability is relevant to the concept of system reliability which is the case when the reliability assessment of a group of interdependent components, e.g., an integrated system of aquaculture-MPOP, is intended. The reliability of the system is computed by using the failure probability of individual components and the correlation among the associated failures. The data collection is a prerequisite of structural reliability analysis. Therefore, the collected data is vital for identifying failure modes, uncertainty quantification and applying reliability analysis methods. The reliability varies for different types of systems. The following section reviews the challenges with regard to data collection for structural reliability assessment of aquaculture-MPOPs.

3.1. Data for structural planning, design and reliability assessment

Optimal design and reliability assessment of a novel MPOP structure requires using three types of databases, namely, operational (i.e. environmental and spatial) data, failure history data (of similar structures or experimental models) and structural health data obtained via SHM techniques (Fig. 4). Sections 3.1.1 to 3.1.3 discuss in detail the data sources and the process of obtaining such data. In addition, it is necessary to use a wide range of data (i.e. energy production, financial and economic data, etc.) for spatial planning stages of the project as well as fish-welfare data which is obtained by continuously monitoring the water quality and fish-welfare indicators inside and outside the cages. In general, the operator and the asset owner have access to SHM and failure history data of their assets. Environmental data is obtained from available data sources as mentioned in Table 1.

Among the operational data, the environmental data is essential for establishing the environmental force and excitation models, time-dependent reliability analysis and predicting the future condition of the structure. Furthermore, certain types of operational condition data are used for spatial planning of MPOPs such as data directly related to the structural design of the system. SHM databases are concerned with data recorded by different structural health monitoring sensors after the installation of SHM devices. On the other hand, failure history data include the detailed records of the failures that occur to a component through its service-life, including the time of failure, the extent of the failure, the assumed

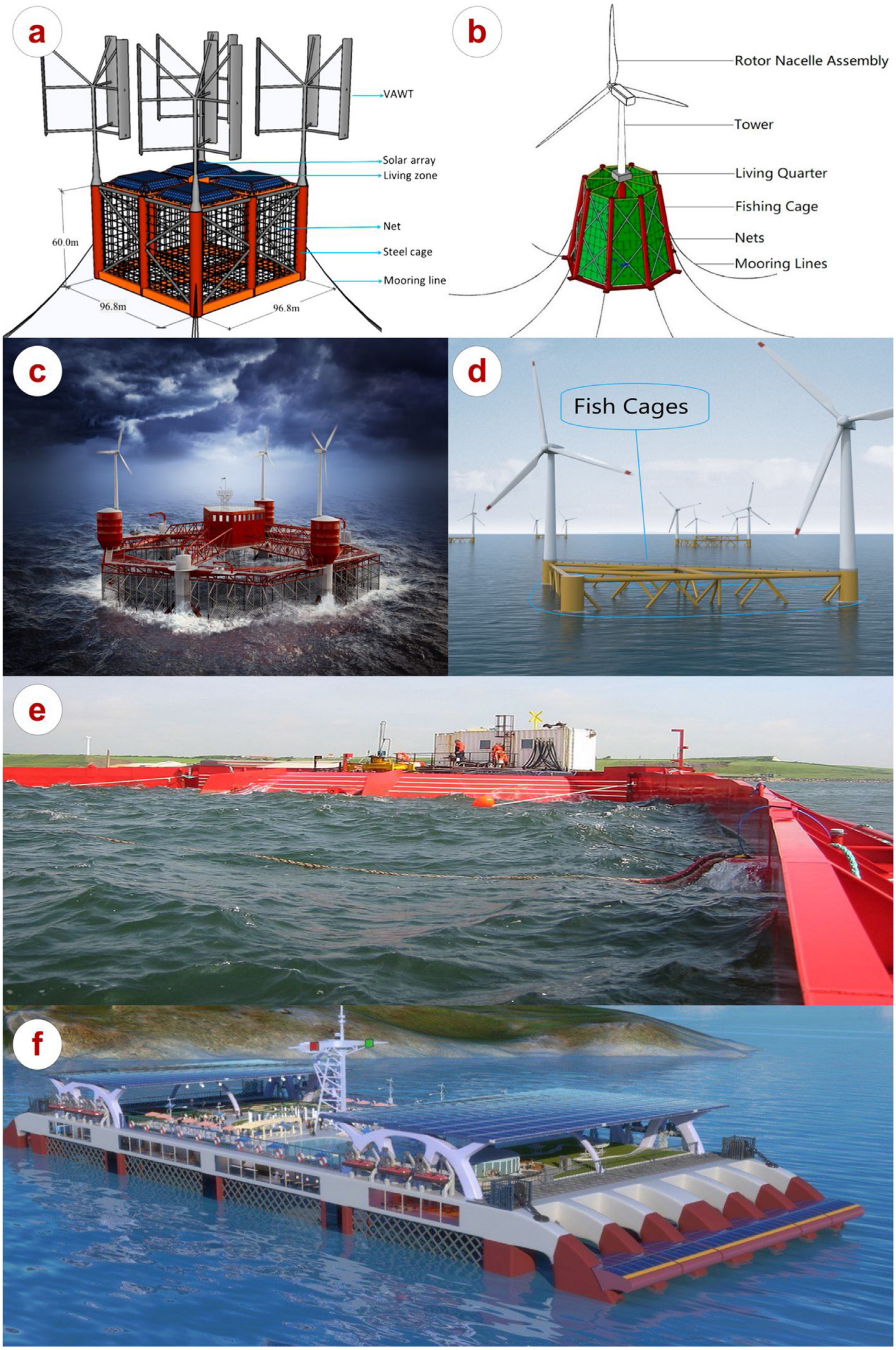

Fig. 3. a) Aquaculture (300,000 m^3 capacity), wind (12 MW capacity), and solar power (1.52 MW capacity) in a floating platform (Zheng et al., 2020) b) An integrated FOWT (NREL 5-MW) - aquaculture cage (200,000 m^3) moored with eight catenary chains (Zheng and Lei, 2018; Lei et al., 2020) c) Hex Box by Ocean & ((Aquafarms (2020))) d) A conceptual design with the capability of being used as an MPOP (Hexicon, 2020) e) Wave Dragon MPOP for wave, wind and aquaculture multi-use. f) Guangzhou Institute of Energy Conversion's semi-submersible wave powered (200 kW) aquaculture pen with seawater desalination plant on board and solar panel (50 kW) roof (Successfully, 2019).

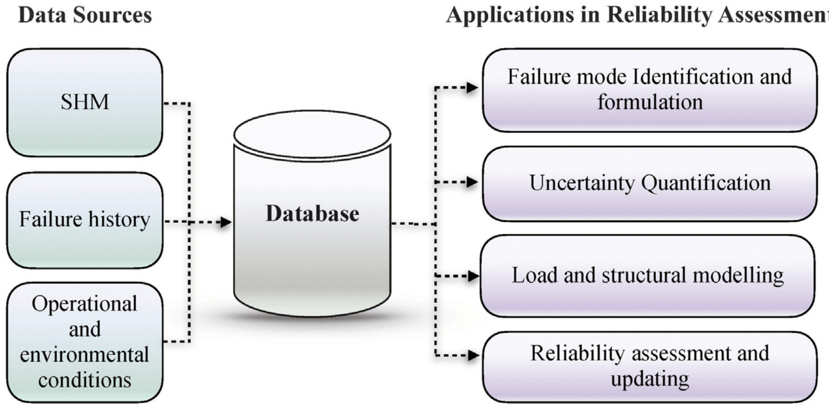

Fig. 4. Data sources and applications for structural reliability assessment of MPOPs.

type of failure(s) and the root causes. Failure history data is essential for identifying the failure modes threatening the structural integrity of the integrated system and for understanding the correlation among the failure modes identified. Also, failure history data is used to estimate the Mean Time to Repair (MTTR) which is an influential parameter in reliability modelling of the structure. The need for failure history data, does not mean that the structure must be failed to provide the analyst with such data. Instead the data related to failure in old structures, mainly because of lack of advanced SHM techniques in the early years of constructions, gathered so far, can serve the purpose.

3.1.1. Operational and environmental conditions data

In the pre-construction phase of the development, environmental and operational data is essential for identifying a appropriate location for the integration based on the limitations of potential system design. The structural integrity of a conceptual design candidate can be evaluated by using environmental models calibrated from the wind, wave, current, water temperature, and data collected from the potential site locations, and structural reliability analysis methods (Bore and Amdahl, 2017). Alternatively, essential adjustments can be applied to available design concepts, through reliability-based design optimisation methods, to make them suitable for a specific site location and/or the suitable fish types to be cultured within the system. The collected data is also employed in the different phases of the lifecycle including construction, operation, and decommissioning phases of the aquaculture-MPOP development for assuring a safe operation. Tables 1 and 2 summarise the required data for site selection of an MPOP from the viewpoint of structural and operational safety. The presented data can serve as the baseline for building complex extreme value statistics and probabilistic return period models essential for accurate structural design and reliability assessment of an aquaculture-MPOP.

Even though site selections of aquaculture-MPOPs have been extensively studied in the literature (Gimpel et al., 2015; Flocard et al., 2016; Cradden et al., 2016), only a few studies have focused on different frameworks for integrating the structural limitations of specific design concepts into the geographic information system (GIS)-based site selection tools. Falconer et al. (2013) considered technical limitations of four different aquaculture cages in a GIS-based site selection platform. On the other hand, Weiss et al. (2018) investigated a GIS-based site-selection module for an integrated system of wind-aquaculture while addressing the structural limitations of the system based on the Norwegian design codes. These studies conclude that different operational requirements of aquaculture, wind and wave farms are the main issues to be resolved at the site selection phase.

It is fortunate in this instance that parameters pertinent to the design and operation of MPOP systems are equally appropriate to the assessment, design and operation of an aquaculture facility although variables including noise/vibration, turbulence, chlorophyll concentrations, and depositional fields (relating to the dispersal of fish waste), will also need to be considered in addition to those parameters in Table 1. It is therefore entirely possible that a site with proper environmental conditions for the MPOP system will not be appropriate for culturing the desired culture organism or vice-versa (Flocard et al., 2016; Vasileiou et al., 2017). Salmon farming, for example, is not recommended in sites where the current speed is more than 1 m/s as the salmon has to use much of its energy to maintain its position (Chu et al., 2020) however the current speed in many sites with proper wind and wave condition for renewable energy production may exceed 1 m/s. Selecting proper fish species based on the environmental condition of a site (with adequate wind/wave condition) is an old solution for solving the issue. Alternatively, the problem can be effectively addressed by a novel MPOP design that (i) withstands harsh offshore environments, (ii) can control the current speed within the containment area, (iii) meets the specific needs of the intended culturing species to provide optimal conditions for growth (Davison and Herbert, 2013), and (iv) is easy to access and maintain. Each of these solutions-based approaches present potential opportunities for aquaculture and MPOP developments.

It should also be considered that the transition of aquaculture systems from sheltered to more exposed culture environments is in a relatively nascent stage of development – much is still to be learned about how animal welfare and system suitability is affected by these increasingly challenging environments, and novel approaches are continuously being developed. One such example is the present movement to submerge aquaculture systems in order to avoid highly energetic surface waters (Chu et al., 2020; He et al., 2018). Salmonids – a phsyostomus species – require access to surface conditions to ensure swim bladder inflation and normal swimming behaviour (Davison and Herbert, 2013; Oppedal et al., 2011). Designs and mechanisms to allow fish in submerged systems to access surface conditions vary (ranging from snorkel designs, air pockets to active buoyancy control of the whole cage system) and may also need to be considered during their integration (Korsøen et al., 2012; Stien et al., 2016; Scott and Muir, 2000).

3.1.2. Data for failure mode identification

Identification of potential failure modes is an important part of the design process. The identification is systematically performed by using data analysis and simulation. For new systems with limited available input data, the primary source of failure mode identifi-

Table 1
Environmental factors required for site selection from the structural reliability point of view.

Items	Parameters	Potential impacts	Data source
Seabed condition	Water depth, m Slope, % Substrate Sand grain angularity Grain size distribution Soil unit weight	Affect the foundation and mooring type selection (Perez et al., 2005). Also, affect structural integrity through different soil-structure interactions (Gallant, 2020; Barari et al., 2017). Impact the slope stability and hydraulic stability (Ding et al., 2015; Sedlacek et al., 2012).	• Australian Bathymetry and Topography Grid (Whiteway, 2009) and Lidar (for better resolutions) • USA National Oceanic and Atmospheric Administration (NOAA) Wave Watch III (NWW3) operational wave model (Tolman et al., 2002) • Simulating WAves Nearshore (SWAN) (Booij et al., 1999) • CSIRO Wave Energy Atlas (Hemer and Griffin, 2010) • AuSEABED (Surficial Sediments of the Australian Seabed) (Surficial sediments of the Australian seabed, 2006) • Integrated Marine Observing System (IMOS, 2020) • Australian Renewable Energy Mapping Infrastructure (Agency, 2020) • Global Wind Atlas (GWA, 2020)
Water condition	pH Dissolved Oxygen Water temperature, °C Salinity, psu	These parameters not only affect corrosion/Fatigue behaviour (Adedipe et al., 2016; Micone and De Waele, 2017; Soares and Parunov, 2019) but have direct impact on the fish welfare and the type of fishes to be cultured.	
Wave condition	Significant wave height, m Annual 50th percentile of the significant wave height, m Mean annual significant wave height Peak wave period Monthly average wave height Extreme wave height, m 50-year return period for the significant wave height, m	Direct impact on the structural integrity and stability of the structure by applying wave loads (Wei et al., 2014). Also, causes fatigue in the structure (Bai et al., 2018, 2016). May cause buckling failure in floating collars (Li et al., 2013; Fu and Moan, 2012; Huang et al., 2016a; Jensen et al., 2007).	
Tides and currents	Mean tidal range, m Max tidal current, cm/s Mean and max spring and neap velocities, m/s 50-year return period for current velocity, m/s	Impact the corrosion (Zve et al., 2015). Causing uneven load distribution and scour in the foundation (Chen et al., 2014a; Goseberg et al., 2012; Chen et al., 2014b). Changing the cage volume by deforming the nets and collar in flexible fish pens (Moe et al., 2010; Zhao et al., 2019a).	
Wind condition	Wind speed at 10 m height, m/s Mean annual wind speed, m/s Monthly average wind speed, m/s 50-year return period for wind speed, m/s	Direct impact on the structural integrity and stability of the structure by applying wind loads, i.e. causing gaps in the foundation sections, loosen bolts, and studs (Wei et al., 2014; Márquez et al., 2016). Also, causes fatigue and corrosion in the structure. (Dong et al., 2012; Chou and Tu, 2011)	

Table 2
Operational condition data for spatial planning.

Items	Parameters	Potential impacts	Data source
Operational limitations	Distance to deployment port, km Distance to O&M port, km Distance to grid, km Distance to shoreline, km Distance to other offshore activity centres, i.e. oil and gas extraction, military activities, submarine archaeology, navigation routs, km Distance to birds and animals' migration routes, m Air temperature, °C Required duration of O&M actions, hour Required time for towage, hour Required time for installation of different parts of the system, hour Expected noise and vibration in the location, dB Biofouling condition in the location Animal species living in the site Hours inaccessible at maximum wave and wind condition, hour The capacity of the location for dissolving the pollutions Access to emergency Access to helicopter landing site Marine navigation compliance Aviation and radar compliance in the site	Direct impact on the safety of personnel, i.e. physical, chemical, biological, ergonomic and psychological impacts and the efficiency of operation (Mitchell and Lystad, 2019; Lovatelli et al., 2013).	• Integrated Marine Observing System (IMOS, 2020)

cation includes simulation, experts' opinions and experience from other industries. The findings can be validated and updated by using the collected data from relevant pilot projects. The procedures for failure mode identification include bottom-up and top-down analysis which break down the system into smaller components and studying the causes and effects of a failure related to each component. Among different methods, Failure Mode and Effects Analysis (FMEA) (Stamatis, 2003) and its modification, correlation-FMEA (Kang et al., 2017) are applied for aquaculture systems and offshore wind turbines. For further information, the reader is referred to the work of Leimeister and Kolios (2018), where the commonly used practices were reviewed for the failure mode identification. After identifying the failure modes related to each critical component of the system, the required data for inspecting the failure modes and studying their correlations can be obtained by using SHM techniques.

3.1.3. SHM data for material and structural failure assessment

One of the key requirements for the development of MPOPs is the structural integrity of the integrated systems. SHM techniques are widely used for acquiring data on the structural integrity of ships and offshore structures (Mieloszyk and Ostachowicz, 2017; Martinez-Luengo et al., 2016; Srinivasan, 2019). SHM minimises the uncertainty through gaining better insight into the performance of the structure being monitored and eventually, results in reduced risks. A reliable SHM framework includes damage detection, damage localisation, and damage quantification (Caspeele et al., 2019). The first two involve data collection from the structure, while the latter includes the analysis of the collected data by using relevant software tools for prediction purposes. Table 3 summarises the commonly used non-destructive SHM methods for offshore structures. The methods listed in Table 3 are used for monitoring the deterioration in both material (changes in material properties) and structure (changes to geometric properties). Bridging the relationship between the degradation in the material and the structure is an emerging field of research which requires advanced data fusion, signal processing, AI-based trend detection algorithms and the reliability analysis methods. Data fusion herein refers to combining the data gathered from different SHM sensors by using data fusion algorithms for better damage diagnosis (Eleftheroglou et al., 2018). The following paragraphs discuss the typical materials used in the structural design of aquaculture, renewable energy and the MPOPs.

In finfish aquaculture, widely used cage structures (including floating flexible, and floating rigid cages) can be divided into three main components, namely, the floating collar and/or frame, nets and the mooring system (Scott and Muir, 2000). The materials for the floating collar are typically selected based on the operational location of the cage from cages with relatively flexible High-Density Polyethylene (HDPE) frames for deployment in the nearshore area to rigid steel frames for the harsh offshore environment. Other materials used in the production of cage frames are Galvanised iron (GI), PVC, etc. Numerous novel designs are also currently being investigated, each of which may ultimately present opportunities for integration with MPOP's, and with differing structural health monitoring frameworks (Chu et al., 2020). In Australia, the cages are mostly made up of two uni-central HDPE pipes as the floating collar. Nets are mainly made up of synthetic material including nylon, glass fibre reinforced nylon, polyethylene terephthalate PET, Polyurethane polyester PES, polypropylene PP, Polyethylene PE, high-modulus PE such as Spectra™ or Dyneema™, aramid, vectran and zylon. These materials differ with respect to tensile modulus, the mass of net panel, density, etc. and must be used in net production so that the breaking strength of the net pens does not fall below 65 % of the initial strength of the net (Myrli and Khawaja, 2019). As the tensile strength of the submerged nets reduces over time, the aging nets must be replaced after a certain time. For example, the life span of new PET nets is estimated to be up to 20 years (AKVA, 2020). Nylon nets are economically convenient, but lightweight and eventually need more added weight to the ballast pipes. The net is known to have the highest load contribution in the form of drag forces generated by currents and wave action (Balash et al., 2009). Consequently, the selection of net material must be made in accordance to the structural capacity of the floating collar and the mooring system, elongation (in accordance to ISO 3790), the environmental conditions (currents, waves, etc.) and the intended net cleaning process. If not, then the failure of the containment system leads to fish escape or higher stresses imposing on the fish inside the pen (Yang et al., 2020).

Generally, the mooring system for sea cages consists of ropes, chains, mooring connectors and anchors. Mooring ropes are made from synthetic fibre, nylon, PES, PP, PE and high-modulus PE in a braided or twisted arrangement. Chains that connect different parts of an aquaculture system, such as chains to ropes, are made in different steel grades (from Carbon steel to heat-treated alloy chains). Technical requirements in the selection of steel grade for aquaculture applications can be found in (Steel chains, 2012). Deadweight and drag embedment anchors are the common anchoring equipment in the aquaculture industry (Fredriksson and Beck-Stimpert, 2019) and the design requirement which must be met in accordance with DNVGL RP E302 (Thompson et al., 2012). Unanchored cage systems have also been trialled but are not in commercial use (Sims and Key, 2011).

Different materials are used for manufacturing different components of the offshore renewable energy platforms for integration into an MPOP. Different parts of the OWTs include rotor blades, tower, hub, transition piece, foundation and substructure. Reinforced concrete and steel are the most commonly used materials for manufacturing the foundation and substructure of the OWTs. Steel is commonly used material in the construction of the tower (Association, 2012). The steel grades and concrete characteristics to be used in the manufacturing of OWT must comply with the requirements of the EN10025, DNV-OS-C401 and DNV-OS-J101 standards (Igwemezie et al., 2018; Veritas, 2004). The hub is mainly made up of cast iron or forged steel, and the blades are made from composite materials, fibre (i.e. glass and carbon fibres, aramid and basalt fibres and natural fibres) reinforced polyester and epoxy adhesive as specified in DNVGL-ST-0376 and IEC61400-23 standards (Mishnaevsky et al., 2017). Review of the SHM techniques in the monitoring of composite structures and specifically for wind turbine blades can be found in the works of Güemes et al. (2020) and Schubel et al. (2013) respectively. The materials used in offshore wave energy converters mostly include steel, the selection of which follows the same standards for other floating offshore structures such as OWT. Since there exists no specific standard for the material selection of MPOPs, the abovementioned standards should be considered for the design of the desired novel integrated systems. The currently available MPOP pilot projects such as Wave Dragon, utilise the same guidelines. Wave Dragon foundation, is manufactured using reinforced concrete under the DNV-GL standards for structural design (Dragon et al., 2020).

This section outlines different SHM methods for structural assessment of offshore platforms. Additionally, the common material types used in the construction of offshore aquaculture and renewable energy systems and their conforming selection standards are examined briefly. The SHM methods are used for ensuring the safety and reliability of the structure and materials used for constructing the MPOP. The selection of a proper SHM method must be made in accordance with the material type, experience, known failure modes of the structure and the limitations of the SHM sensors and devices. The data gathered by the SHM techniques are the inputs to the reliability analysis of novel MPOPs, and therefore, they have a significant impact on the accuracy of the failure probability estimation. The proper implementation of such techniques however, requires dealing with several challenges. The following section examines the challenges in SHM of novel MPOPs.

3.1.4. Challenges and future direction

The former section briefly provides the main approaches for structural health monitoring of offshore structures and reported on the advantages and disadvantages of each method. An important issue relates to the harsh environment and harmonic excitations, thereby making it difficult to extract desirable data from the collected data (Magagna et al., 2018). Offshore renewable energy devices are equipped with a condition-based monitoring (CBM) system such as Supervisory Control and Data Acquisition (SCADA) system. The data gathered from SHM techniques are applied to

Table 3
Structural health monitoring methods used for offshore systems.

Purpose	Method/Principle	Advantages	Limitations	Ref
Monitoring excessive deformations, corrosion, fatigue crack propagation	Acoustic emission	High-resolution (up to microscale), easy to use and cost-effective monitoring	Sensitivity of these methods to the background noise limits their applicability in offshore environments; limited distance between measurement point and damage location.	(Jüngert, 2008; Tziavos et al., 2020; Liu et al., 2018; DeCew et al., 2013)
Strain monitoring	Strain gauge, Fibre Bragg Grating (FBG), Quantum Resistive Sensors (QRS), Fibre optic cables	Easy to install sensors must be placed within the critical parts of a component to obtain data on the micro-level damages	Short service-life of the sensors, sensitivity to misalignment and lack of robustness	(Ziegler et al., 2019; Maes et al., 2016) (Mieloszyk and Ostachowicz, 2017)
Detection of cracks and corrosion	Ultrasonic techniques	Non-contact, with the capability of being used with drones. Minimal preparation time and fast to obtain results, high penetration depth waves and accurate imaging	Sensitivity to misalignment of sensors, expertise, and labour intensity and calibration difficulties in the absence of relevant standards	(Gunn et al., 2019; Brett et al., 2018)
Detecting the anomalies, damages and cracks	Thermal imaging or thermography methods utilise thermochromic coatings and liquid crystal sheets, infrared cameras and thermocouples	Non-contact and can be used with drones in an automated inspection	Sensitivity of the thermal sensors to temperature variations, the minimum detectible defect size and the need for post-processing algorithms. These methods have limited application in the offshore environment.	(Gao et al., 2016; Chatzakos et al., 2010; Newman, 2016)
Modal monitoring and fatigue	Operational Modal Analysis (OMA), Experimental Modal Analysis (EMA), Frequency Domain Decomposition, Natural Frequency shift using: piezoelectromechanical and microelectromechanical systems (MEMS), Velocimeters Accelerometers Linear displacement sensor	Reliable and easy to implement for non-operating (offshore) and onshore platforms	Large amount of uncertainty induced by the involved external parameters such as wind and wave loading and scouring effect. Also, in offshore environment it is difficult to measure the wave and wind loads.	(Pacheco et al., 2017; Devriendt et al., 2014) (Devriendt et al., 2014; Antoniadou et al., 2015)

the aquaculture facility and the offshore renewable energy device structure by using data fusion techniques. Combining this data with the data gathered from SCADA would assist in extracting useful dataset from raw data. The solution is obtained through analysing a huge flow of data recorded by SCADA and a combination of SHM methods for identifying the correlation existing among the gathered data. This aim cannot be achieved without utilising efficient big-data management techniques, AI-based feature extraction algorithms and a high-quality database (Pliego et al., 2018).

Transferring the collected data by SHM methods to the server is another challenge to cope with. Because of the high costs of satellite connectivity for data transferring and absence of cellular connectivity in offshore locations, many offshore platforms need the data to be physically transported from the server to land in batches. In the oil and gas industry, communication cables using MQ Telemetry Transport or Message Queuing Telemetry Transport (MQTT) protocols for packet streaming are used to stream data. Internet of things (IoT) connectivity technologies, are expected to provide MPOPs with reliable, robust, and scalable data collection and transferring soon. An IoT-based solution to the issue is Low Power Wide Area Networks (LPWAN) (Mekki et al., 2019). This low-rate long-range radio communication technology has already been proposed commercially for structural monitoring of offshore platforms (IoT Applications for Offshore Monitoring in Oil and Gas, 2020). However, to the author's best knowledge, practical implementation of the technology for offshore platforms has not yet been reported.

The use of unmanned vehicles for inspection purposes has always been a topic of research, specifically for the aquaculture industry. Several researchers investigated different options for minimising human intervention in aquaculture farms by use of Remotely Operated Vehicles, (ROV) and Autonomous Underwater Vehicles (AUV) (Livanos et al., 2018; Tao et al., 2018; Osen et al., 2017; Hval, 2012; Capocci et al., 2017) and in offshore wind turbines by Autonomous Aerial Vehicles (UAV) (Aquilina et al., 2019; Chung et al., 2020). Some companies such as BioSort and Cermaq already offer robotic solutions for morphological features and farms' operation parameters, and monitoring fish activities, such as number of fishes and their size, and number of fishes with sea lice (Canada, 2019). Applications of unmanned vehicles for monitoring missions in the offshore environment can be found in (Verfuss et al., 2019). Combination of SHM techniques based on the unique features of the integrated system (number of components, environmental conditions, etc.) with unmanned vehicle technologies can likely solve issues relevant to the structural health monitoring of the integrated system. It will assist with SHM techniques that require changing reference points around the structure, specifically imaging and acoustic techniques. The technology, also minimises the human interference and error, and maximises reachability of the sensors to different components of the system (e.g. components deep in the water, or at heights).

The inclusion of SHM in the condition monitoring standards and guidelines is another area of further research. Although the offshore wind industry standards have focused on SHM of rotating machinery, there is no comprehensive guideline for utilisation of SHM for the OWT and aquaculture components as a whole system (Martinez-Luengo and Shafiee, 2019). The SHM of such systems is different when compared to machinery condition monitoring. It requires localisation of the damage before deciding on further predictive and assessment tools, and consequently, available standards for machinery condition monitoring are not applicable in this case (Worden et al., 2015). Moreover, the integration of SHM equipment into the structure must be considered at the design stage of the system to address the discrepancy between the initial values of the structural parameters and those provided by the designer company. This discrepancy arises from the fact that the design information provided by the designers is usually obtained from laboratory evaluations, which are different from those of the real operational conditions (Tewolde et al., 2018). As a short-term solution to this issue, obtaining the relationship between these laboratory-extracted information and real case initial values can be an interesting area of future research. Such information provides the baseline for comparing the structural health of the system at each point of time and estimating the extent of reduction in reliability of the system.

An idea to model the reliability of MPOPs comprehensively considering all the internal (e.g. deteriorations process, geometric deformations, etc.) and external factors (e.g. presence of personnel, the living products, etc.) affecting the reliability of the system is realised through using the Digital Twins concept. The digital twins of an MPOP can be defined as its digital equivalent, which enables assessing its reliability under different service conditions. The data collected by SHM equipment in real-time are used to make a digital twin of the MPOP and evaluate its real-time reliability. The digital twins concept provides the possibility of real-time surveillance of the system through the combined use of SHM techniques, the internet of things, mathematical modelling, failure history databases and reliability analysis methods. This concept has first been utilised in the aerospace industry for service-life management of airplanes. Several use cases which used the digital twins for life-cycle management of different systems have been examined in the work of Macchi et al. (2018). Examples of such cases used in different industries include (i) Optimised maintenance planning and decision making on the structure subjected to different failure modes (Kampczyk, 2020; Wang et al., 2019; Xiao et al., 2019), (ii) System life-cycle modelling (Kaewunruen and Lian, 2019; Lim et al., 2019), and (iii) System performance optimisation (Zhang et al., 2017; Guerra et al., 2019).

Digital twins is not a new concept however, the recent advances in sensor design and the internet of things enhanced the applicability of the concept for solving real-world problems. The offshore industry has already started using the digital twins for operation optimisation, predictive maintenance, anomaly detection and fault isolation purposes (Demystifying digital twins, 2020; Wanasinghe et al., 2020). Several usages of the digital twins concept for reliability assessment of MPOPs can be realised in the future. For system performance optimisation, one can first build a digital twin of the MPOP and then study the variations of parameters, to see which ones have the most influence on the reliability of the system. For example, parameters such as collar wall thickness, diameter, member length tolerance of aquaculture sub-system, and anchor placement, line length and soil characteristics of the mooring subsystem of the digital twin can be changed to examine the impact on the reliability of the MPOP system. Also, the digital twin serves to check the actual performance against design calculations to help remove conservatism for future designs, thereby improving reliability predictions. In addition, the concept helps with monitoring the stress throughout the structure. This approach would be beneficial both for long-term fatigue and transfer functions if environmental conditions can be monitored also using proper monitoring sensors. Furthermore, by correlating the monitored stress at a few selected locations with the most critical dynamic response modes, the digital twin can provide a picture of the entire loading distribution throughout the structure, including hot spots. This way, the digital twin concept bridges monitoring and modelling and eventually allows the use of data analytics and artificial intelligence-based prediction techniques to make real-time predictions of future behaviour and reliability. Examples of the combined use of artificial intelligence-based models and digital twins in offshore industry can be found in the works of Ellefsen et al. (2019); Shirangi et al. (2020); Tygesen et al. (2019); Augustyn et al. (2019), and Kirschbaum et al. (2020). Additional examples implemented in other fields, such as manufacturing industries are provided by Cronrath et al. (2019); Min et al. (2019), and Jaensch et al. (2018).

3.1.5. Transferable knowledge from the offshore energy industry

There are many similarities between the offshore industry platforms and the innovative MPOPs in terms of construction technology and building materials. The experience and technology gained by the oil and gas industry were broadly adopted by the offshore wind and aquaculture industry. Hywind was the first large scale FOWT in the world and it was installed by Statoil (now called Equinor), which is primarily a petroleum company (Castro-Santos and Diaz-Casas, 2016). Bucket foundations, jackets, tension leg platforms, semi-submersibles, and spars used in OWT and FOWT were originally designed by the oil and gas industry (Wu et al., 2019; Wang et al., 2018; Perez-Collazo et al., 2018). In the aquaculture industry, the research on size and shape of vessels, mooring systems, cranes, the stability of the platforms, manoeuvring of service vessels around the sea cages, ship collisions etc., together with validation and verification of the models/results highly depends on the findings by the oil and gas industry (Yu et al., 2019; Veritas, 2010; Moan et al., 2019). Differences also exist between the structures utilised by the two sectors in terms of fatigue load magnitude, different loading conditions, design return periods, complex wake interactions, higher dynamics of the system, welfare of marine products, waste management-based limitations, and case-specific failure modes (Castro-Santos and Diaz-Casas, 2016; Wu et al., 2019).

This section reviews solutions to the mentioned issues relating to data scarcity and SHM technology immaturity for structural reliability assessment of novel aquaculture-MPOPs. The proposed solutions, potential capabilities and the justifications are summarised in Table 4.

3.2. Load and structural response modellings

The realistic modelling of environmental forces on the structure is essential for reliability assessment of an aquaculture-MPOP. In order to study the response of the structure of an integrated system under environmental forces and/or collision forces, different models representing the external forces such as wind, wave and current, and the structure must be coupled (Moan et al., 2020; Feng et al., 2019). Furthermore, an MPOP perfectly exemplifies a multi-physics system exposed to different fluid-structure-soil interactions. These multi-physics components must be coupled in time and space for simulating the motions of the system. This is an emerging field of research with considerable evolutions in recent years because of the advances in computer sciences and hardware development. Several commercial and open source software codes, such as FAST, Orcaflex, HAWC2, ABAQUS, ANSYS, SESAM.DeepC, etc., have been used in the literature for modelling dynamic environmental loadings and structural responses. Liu et al. (2016) reviewed the features of several widely used software packages for modelling hydrodynamic, aerodynamic and structural responses of offshore structures. To the best of the authors' knowledge, a single software package which can adequately model fully coupled, fluid-structure-soil interactions does not exist. The following sub-sections explain the challenges arising from the integration of aquaculture and offshore renewable energy systems from the viewpoint of structural and environmental dynamic analysis.

Table 4
Possible areas of knowledge transfer from the oil and gas industry to address the issues regarding data collection and data availability.

Limitations of aquaculture-MPOP systems	Available opportunities in offshore oil and gas industry	Justifications	Ref
Implementation of SHM methods in offshore industry	• Eliminating the need for costly, time-consuming, and labour-intensive laboratory testing stage of SHM. • Providing expert opinion to minimise the installation and maintenance of SHM equipment challenges.	30 years of experience in the offshore oil and gas industry. The industry started applying SHM techniques such as vibration monitoring in 1980s and corrosion monitoring using ultrasonic guided waves in 1990s and recently acoustic emission and thermography. More than 81.9 % of the global corrosion monitoring market is dedicated to the oil and gas industry.	(Coppolino and Rubin, 1980; Shahrivar and Bouwkamp, 1986) (Mudge et al., 1997; Alleyne et al., 1997) (Shamsudin, 2019) (Doshvarpassand et al., 2019)
Use of robotics in SHM	• Reduce the costs, mortality, and human related errors by eliminating the need for saturation diving, addressing issues related to the short weather windows and to guarantee the flow of online inspection data for reliability assessment and reliability-based maintenance planning of the system.	Application of unmanned vehicles in the oil and gas industry goes back to the early 1990s. Industrial applications of robotics and unmanned vehicles for inspection of offshore oil and gas platforms involve subsea equipment inspection and leak detection. Some examples include inspecting welded joints of jacket structures subjected to fatigue damage and corrosion in underwater pipelines by ROVs and AUVs.	(Johnston et al., 1986; Budiyono, 2009; Zhang et al., 2012; Zeng et al., 2012; Onoufriou, 1999; Khan et al., 2017)
Software requirements in SHM	• Available specialised post-processing and predictive algorithms can be used for aquaculture-MPOPs. • Available IoT-based platforms developed by oil and gas industry can be used for data storing and analysis of MPOPs.	Oil and gas industry has been involved in software development for analysing SHM data for decades. For example, Non-linear Auto-Regressive Moving Average with exogenous inputs model, NARMAX, one of the first and most powerful techniques for detection of nonlinearities in time-series data was introduced in 1985 and since then, has been extensively used and modified by the industry for predicting unknown forces induced to the offshore structure by surrounding environmental forces. Another powerful predictive module available with the oil and gas industry has been developed within the Monitas Joint Industry Project. This project introduced a prediction software called OCTOPUS-Monitas that can predict confidence bounds for future fatigue accumulation in offshore structures with high accuracy. Many of the IoT-based data storing and analysis platforms have already been available with the oil and gas industry. BMT Deep, for example, captures vast amounts of Big Data from IoT devices and securely stores and processes the data in a Cloud platform allowing one to monitor an asset's response to the environment real-time, remotely and safely.	(Leontaritis and Billings, 1985; Mai et al., 2016; Spiridonakos and Chatzi, 2015; Worden et al., 2018; Welcome to BMT Deep, 2020; MONITAS, 2020)
Lack of failure database	• Transferring information and knowledge between industries is expected to occur through building a Reliability, Availability, Maintainability, and Safety (RAMS) database. Such a database is built through collaboration among military, offshore oil and gas, offshore wind, offshore wave and tidal energy, aquaculture and nuclear energy sector.	Oil and gas industry has access to an Off ;shore and Onshore Reliability Data database, OREDA. Other databases available with the industry include: • Metocean sensors data • Environmental sensors data • Structural sensors data • Subsea interfaces data • Telecoms equipment data • Navigation aids data • Remote power systems data	(OREDA, 2020)

3.2.1. Multi-scale modelling

The dynamic behaviour of interconnected floating bodies is studied through the multi-body dynamic analysis concept. This approach examines the dynamic behaviour of the interconnected bodies by using the equilibrium of applied forces and the change in the momentum (Jin et al., 2016). The dynamic analysis of the intended integrated system is a multi-body, multi-scale problem composed of several different components from a very small net twine (in the order of millimetre in diameter) to very large components such as the foundation of a wind turbine (in the order of meters in size). This multi-scale nature of the problem increases the modelling complexity and consequently the analysis computational cost. As an example, complex modelling and analysis of wake interactions associated with different components with various scales are of great importance, since such phenomena may increase the non-linear failure rate of offshore systems.

3.2.2. Hydroelasticity modelling

The Australian aquaculture industry commonly uses the HDPE made floating collars and longlines which are flexible and deform under wave action (Gagnon and Bergeron, 2017; Bi et al., 2020; Bore et al., 2017). Unlike the common practice in floating structures of the oil and gas industry, the dynamic analysis of such integrated system, must consider the hydroelastic nature of the structure because of the considerable impact of structural deformations (Fu et al., 2007; Leble and Barakos, 2016; Faltinsen and Shen, 2018). One of the main areas of research that accounts for the hydroelastic behaviour of flexible floating systems involves discretising the structure into several rigid modules (plates or beams) which are connected by Euler-Bernoulli beam elements (Lu et al., 2019). Although there exist some rare examples of the integrated systems of wave energy converters and also the systems of multi aquaculture cages, to the best of the authors' knowledge, the integration of aquaculture systems with other offshore renewable energy platforms, such as OWT, has never been addressed in previous studies (Fu and Moan, 2012; Zhang et al., 2018, 2019a; Lamei and Hayatdavoodi, 2020). Two main approaches for the hydrodynamic analysis of multi-modular floating systems include modal expansion and two-step approach (Feng and Bai, 2017). The first method applies frequency-domain analysis while considering the multi-body system as a single deformable body, while the latter applies the frequency domain analysis to obtain the required coefficients which are utilised in a time-domain analysis (Ó'Catháin et al., 2008; Wei et al., 2017). Both methods were developed based on frequency-domain analysis, and therefore, neither can simulate the non-linear dynamic behaviour of the system and the transient effects. It is expected that the desirable system experiences a high degree of non-linearity due to the flexible parts of the system and the shallowness of water (in case of the nearshore location of the system) (Zhao et al., 2019b; Zhang et al., 2019b). However, a fully coupled time-domain numerical tool specially developed for an integrated system of aquaculture-MPOPs has not been reported in the literature. Consideration of non-linear coupling between the modules in a time-domain simulation is also a future area of research.

3.2.3. Limitations of simplified models

In the majority of the abovementioned studies, only the connectors are assumed deformable and the modules of the system are considered as rigid bodies with relatively small deformations (Ren et al., 2019). However, this is not the case for systems with elastic/flexible floating components. Further assumptions, such as uniform mass distribution and the consideration of the pitching axis on the water surface made the applicability of these methods questionable for dynamic analysis of the intended integrated system.

Another issue to tackle is unidirectionality of forces as considered within the design standards. Current standards adopted the conservative assumption of the unidirectionality of environmental forces which represents a worst-case scenario. Such an assumption can adversely affect the accuracy of fatigue analysis, reliability analysis and also the dynamic analysis of MPOPs with complex geometries, e.g., the direct attachment of an aquaculture cage to the foundation of an OWT) (Sørum et al., 2019).

3.2.4. Motion effect on energy production

Motions of the floating platform not only impact the structural reliability of the system but also affect the energy production capability of the renewable energy platform and the welfare of fish being farmed offshore. For instance, FOWTs can experience reduced power generation due to the rigid-body motions of the support structure (Wen et al., 2018). This may imply that aquaculture cages integrated into the FOWT could be useful in this case due to the higher damping effect provided by the nets. Similarly, a study on the use of WECs as damping devices for improving the performance of FOWTs confirms the applicability of this idea (Borg et al., 2013). Furthermore, the results of a study indicate the higher energy extraction capability of an array configuration of WECs in comparison with the same number of isolated WECs (Lee et al., 2018). Damping effect of the cages and longlines (that is increased over time because of biofouling) on the structural reliability and energy production rate of the FOWTs and WECs is among the important issues which must be studied through realistic simulation of external forces and the structure. As a novel practical method for evaluating different motion effects, robotic towing tanks recently have received much attention (Intelligent Towing Tank propels human-robot-computer research, 2019). This new model testing technique allows machine learning algorithms to map a complex function over a given parameter space (Fan et al., 2019). Using this approach, it is possible to let the machine decide which simulation to run next. Such a functionality can be beneficial for reliability analysis of the MPOP using simulation-based reliability approaches (e.g. Monte-Carlo Simulation) where different motion types are randomly and repeatedly selected in each trial.

Simulation of external forces is an essential stage of reliability-based controller design (Salic et al., 2019). In a reliability-based controller design, a controller is designed by minimising the probability of violating the failure threshold through solving a reliability-based multi-objective optimisation problem (Crespo and Kenny, 2005). As an emerging field of research, reliability-based controller design of MPOPs would make it possible for better reliability of the system in terms of energy production, fish welfare and reduced fatigue damage (Horn et al., 2017a).

3.2.5. Scaling effect

Results predicted by numerical methods must be validated using experimental data obtained through testing in laboratory and/or in the intended deployment field using scaled models and/or prototypes, respectively. Utilising Wind Tunnel Testing as a reliable way for understanding loading (topsides and current loading) on offshore structures and validating the numerical models has always been a common practice in offshore oil and gas and wind industries (Sivandran, 2015). A problem to tackle while using the model test data for validation is scaling issues. The currently acceptable practice is that models are scaled-down in size, and hence difficulties in extrapolating/translating the results obtained from the scaled-down models to full-scale due to those scaling effects are unknown and difficult to quantify (Day et al., 2015). For instance, the Froude scaling law and Reynolds similarity law cannot be guaranteed simultaneously when scaling is applied for hydrodynamic experiments. Individually following Froude's scaling law or Reynolds Similarity law would ignore some essential influencing effects such as viscosity, compressibility, and surface tension of water. This inconsistency between Reynolds and Froude scaling in existing wind-wave simulation facilities is an important obstacle yet to be tackled for physical modelling of FOWT as well as the integrated aquaculture-OWT systems. The Cauchy similitude law, which is mainly used for elastic structures (e.g. mooring lines), on the other hand, must be analysed with precaution when the materials used for the prototype and the real structure are relatively different.

3.3. Uncertainty quantification

Integrated system operates in an extremely uncertain offshore or nearshore environment. The uncertainty of the influencing parameters such as wave and wind models must be considered in deriving the stress distribution caused by the environmental forces over the structural components. Other than such external parameters, material properties such as the structural capacity thresholds may have a degree of uncertainty that must be captured properly. Hou et al. (2019a) studied the impact of uncertainty of the allowable strength in reliability assessment of aquaculture cage's grid mooring system. These uncertain parameters were proved to be the determining factors in the reliability and service-life of renewable energy and aquaculture systems (Yeter et al., 2019; Hou

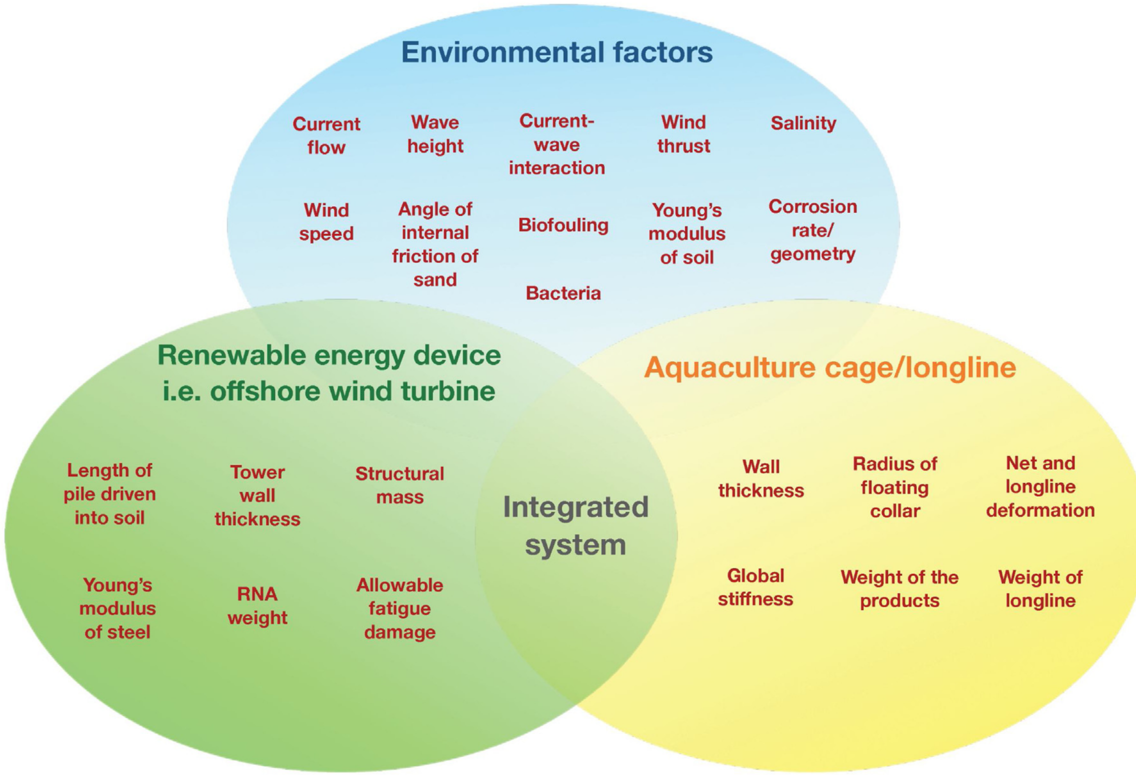

Fig. 5. Examples of random parameters affecting the reliability of an integrated floating system (aqua-wind system). (For interpretation of the references to colour in the Figure, the reader is referred to the web version of this article).

et al., 2018). As an example, Fig. 5 lists some of the influencing stochastic parameters in reliability assessment of the offshore wind turbines and aquaculture structures. Other influencing stochastic parameters and processes include the random change in the contact collision force due to the uncertainty in the connection gaps, the initial angle between a mooring line and horizontal plane, the length of the mooring line, the drag coefficient of the cage, the geometric uncertainty of the structures (e.g., the wetted surface area) and the corrosion allowance (He et al., 2019; Melchers, 2013). It should also be noted that the integrated system is subjected to more uncertainty parameters in comparison with individual systems of the renewable energy and aquaculture units. Among these uncertainty parameters, some (e.g. material properties) can be effectively modelled using its probability distribution, while others (e.g. soil condition, corrosion topology) must be represented using sophisticated probabilistic models such as random fields. Modelling the influential uncertainty parameters requires statistical analysis of collected data from laboratory experiments (i.e. accelerated corrosion experiments) and real case samples (i.e. samples collected from an in-service, or possibly failed offshore structure), while the involved stochastic processes cannot be modelled without utilising advanced mathematical modelling techniques, such as spatial-temporal correlated models.

3.3.1. Uncertainty in environmental and material parameters

Environmental factors are among the critical stochastic parameters in reliability analysis of an offshore system. Mostly because of their simplified physics, wave-forecast models are associated with a high degree of uncertainty. The uncertainty in these models depends on their forcing fields. It has been shown that an error in wind speed estimation may lead to at least two times larger error in the estimation of wave height (Stopa, 2018). The same issue occurs for wind speed and surface current models. Because of the poor-quality control and assurance, lack of competency, and inconsistency in the manufacturing process, structural design parameters, such as the dimensions of a floating collar, wall thickness, and elasticity modulus are also random variables with respective uncertainties. Uncertainty in the measurements of wave, wind and other environmental parameters and structural health data transfers uncertainty into the reliability assessment outcome and therefore, needs to be accounted for. Also, the correlation between different environmental and material uncertainties must be captured and reflected in the reliability analysis of MPOPs (Horn et al., 2017b).

3.3.2. Uncertainty in spatial and temporally variable processes

Not all the uncertain factors in reliability assessment of offshore structures can be described with a random number. In many cases, the uncertainty in a parameter changes with time and/or space. Among these stochastic processes, corrosion and fatigue damage (Veritas and SE, 2015) are of great significance here. Owing to its direct impact on the reduction of structural strength and also its cumulative impact with fatigue, corrosion is known to be an important parameter in the failure of renewable energy platform's foundation and tower (Martinez-Luengo et al., 2016) and aquaculture systems (specifically rigid cages and mooring systems) (Kang et al., 2017; Hou et al., 2017). Because of the presence of wind and the cumulative impact of wind gust and wave, studying corrosion-fatigue in the integrated systems of aquaculture-OWT would differ from that of oil and gas platforms. Therefore, the available offshore standards cannot be used directly in this case (Adedipe et al., 2016). While the industry utilises effective coatings for protecting the offshore structures from corrosion, rigid aquaculture cages, wave energy converters, and OWTs are still subjected to corrosion due to partial removal of the coating through periodic maintenance actions such as regular cleaning for mitigating marine growth. Service vessels moored directly to the structure can also remove the coating, which eventually leads to localised pitting corrosion. This issue is more significant in FOWT because a larger part of the structure is located close to the splash zone.

The integration is anticipated to accelerate the corrosion in the unprotected areas of steel structures (especially those located in the splash zones) (Momber, 2016) of both sub-systems (van den Burg et al., 2020; Klijnstra et al., 2017). Apart from the increased microorganisms' activities because of the presence of fish pens, more accidental platform impacts (by crane operations, maintenance, inspection, and repair activities) are expected because of increased activities around the turbines and cages that augment the corrosion damage in both sub-systems. Currently, the literature has adopted simplified corrosion models and unjustified assumptions, such as linear corrosion models (Wang and Zhao, 2016), uniform corrosion reduction (Hou et al., 2017) and spatially uncorrelated models (Moghaddam et al., 2019). The corrosion is however, a non-linear spatial and temporally correlated process that results in non-uniform reduction of the metallic surface. Therefore, there is a need for developing sophisticated probabilistic corrosion models to represent the stochastic yet spatially and temporally correlated evolutions of the corrosion process.

In addition to corrosion, there exist other phenomena exclusive to each design concept which can reduce the reliability of an MPOP. Consider the MERMAID's conceptual design (Buck et al., 2017b) that involves connecting the aquaculture longline to the foundations of two FOWT units in a wind farm. Within the proposed design, the distance between the two units on the farm is estimated at between 700 m and 2500 m (Buck et al., 2017b). The connection of intact longline would change the dynamic behaviour and the distribution of loading, which changes over time due to the increase in the weight of shellfish within the structure and the mooring lines. These time-dependent spatially varying parameters must be modelled for reliability assessment of the conceptual integration system.

The phenomena, such as deterioration processes, material properties and loadings are not only random but spatially varying. The farms, such as that proposed within the TROPOS project, would have several km^2 of surface area. Many of the environmental parameters, such as soil characteristics would take different but correlated values at different locations of the farm. Existing reliability methods commonly model such uncertain spatially variable phenomena by using random fields (Aryai and Mahmoodian, 2017; Stewart, 2012; Hajializadeh et al., 2016). In order to minimise the computational cost, the random fields are discretised first, and then the discretised fields are incorporated into the analysis. In the case of the intended integrated system, homogeneous random fields have proved to be useful when data scarcity was the case, since they allow representation of the spatially variable phenomena across a large-scale structure with limited input data.

3.3.3. Capturing the uncertainty in reliability standards

Considering the traditional deterministic reliability approach, in the design phase of offshore renewable energy and aquaculture systems, safety factors are widely used to incorporate the uncertainty of the design parameters and the targeted reliability indices into the design. The currently available safety factors (e.g., fatigue safety factors) in OWT standards for example, have been calibrated in accordance with the operational conditions of these structures, where very limited traffic and human interference are expected. However, an integrated system of OWT and aquaculture dictates more traffic and requires more maintenance actions and human activity around the system. The safety factors for aquaculture systems, on the other hand, were mostly calibrated for nearshore conditions with a relatively calm environment. In either case, within the available standards, the partial safety factors were commonly calibrated by using probabilistic models, which eventually, caused inconsistency in the reliability levels associated with different components (wind turbines and aquaculture farms).

The adjustment of the safety factors for new offshore systems based on the oil and gas industry standards is technically justifiable, since similar materials (except for blade and net materials), technologies, and modelling techniques (i.e. soil-structure models, corrosion models, etc.) are used by the oil and gas and other offshore industries (Faulstich et al., 2009). The approach allows pilot projects to start operating with a non-optimal (usually much higher than required, also known as "overdesigned") acceptable reliability. Over time, the operation of pilot projects would provide the initial data for calibration of the structural models and safety factors specifically for renewable energy devices, aquaculture systems and the integrated systems.

Despite their feasible computational cost, safety factor methods used in deterministic reliability approach, cannot capture the realistic random nature of the influencing parameters. Hence there is a need for pure probabilistic modelling of the parameters for probabilistic reliability analysis of innovative MPOP design. To achieve this, it is necessary to quantify the uncertainty associated with the input parameters as well as the uncertainty in the models. Incorporating uncertainty in a probabilistic reliability approach (e.g. using FE-reliability methods) can be an overwhelming task, due to the huge computational burden of such an analysis and limitations of available software packages. An approach for dealing with this issue has been proposed by (Aryai et al., 2020; Teixeira et al., 2013), where a pure probabilistic time-dependent Finite Element (FE) based reliability analysis was performed by using coupled MATLAB and ANSYS simulations. Applicability of such techniques for reliability assessment of large-scale systems, such as the intended system herein, is limited due to the huge computational cost of the FE-based reliability methods. Consequently, novel methods must be developed for efficient yet accurate probabilistic time-dependent reliability assessment of the integrated system, considering the stochastic parameters and processes threatening the reliability of the system.

3.4. Failure modes and limit-states

To perform a structural reliability analysis, the uncertain factors discussed in the previous section are incorporated into the mathematical formulation of the structural components' failure modes. Aquaculture systems and the offshore renewable energy platforms have their own failure modes, and the integration is expected to affect these failure modes while causing new ones. Table 5 summarises the common failure modes used in the structural reliability analysis of the aquaculture and OWT systems. New failure modes are induced due to the damping effect of the aquaculture systems, uneven load distribution over the sub-systems, relative motions of the platforms, impact of aquaculture cages on OWT scour process, etc. Offshore renewable energy platforms, such as wind turbines have a predefined service-life and must be decommissioned after a certain time (e.g. 25 years) (Luengo and Kolios, 2015). New failure modes can, therefore, potentially reduce this service-life and eventually reduce the profitability of the entire project. As a result, it is essential to consider the impact of the integration on individual sub-systems' failure modes as well as the new failure modes arising because of the integration. All these failure modes must be modelled mathematically using the limit-state concept.

In previous studies, the effects of the failure modes on the structural reliability of aquaculture, OWT, and FOWT systems have been studied without considering the cumulative impact of the involved failure modes (Shittu et al., 2020; Hallowell et al., 2018). These failure modes threatening the structural reliability are correlated, and the occurrence of each affects the incidence of others. Ignoring the correlation among the failure modes has been proved to

Table 5
Common failure modes used for the structural reliability assessment of aquaculture equipment and offshore wind turbines.

	Sub-system/Assembly/Component	Studied limit-states	Description	Ref
Aquaculture	Grid mooring system for net cage system	• Fatigue	Direct integration by assuming a worst-case scenario: extreme-value event method	(Hou et al., 2019a, b)
	Floating collar	• Tensile strength • Buckling • Fatigue	Static, vibration and fatigue analysis of a Finite Element (FE) model. Estimating fatigue life from fatigue laws (S-N curves) (potentially non-linear HDPE fatigue and strength behaviour)	(Bai et al., 2018; Zhao et al., 2019a; Liu et al., 2019a)
	Mooring chains	• Ultimate strength	First Order Reliability Method (FORM) for Time-dependent reliability assessment of mooring chains subjected to corrosion.	(Hou et al., 2017)
Offshore Wind Turbine	Foundation	• Fatigue • Buckling • Ultimate Strength	Reliability analysis using two methods, Monte Carlo Simulation (MCS) with Latin Hypercube Sampling and FORM.	(Shittu et al., 2020; Kolios and Wang, 2018; Morató et al., 2019)
		• Crack growth	Multi-failure system reliability analysis using FORM and SORM.	(Yeter et al., 2016)
	Anchors	• Ultimate Strength	System reliability using MCS	(Hallowell et al., 2018)
	Blade	• Excessive displacement of blade tip • Overload of blade root • Fatigue	Uncorrelated limit-state exceedance probability calculation	(Liu et al., 2019b; Zhang, 2018)
	Gears	• Fatigue • Corrosion	Reliability analysis using FORM and MCS	(Dong et al., 2020; Scheu et al., 2017)
	Mooring line	• Fatigue • Ultimate strength	Reliability analysis using MCS and FORM/ Second Order Reliability Method (SORM)	(Wandji et al., 2016; Hallowell and Myers, 2017; Kang et al., 2016a)

underestimate the failure probability of the structure. On the upper scale, the failure of a sub-system structure induces failure in the other sub-systems and so on. The determination of these correlations requires statistical analysis of the recorded failure history data from experiments and real-world cases. The accessibility to such data is becoming easier daily, mainly due to the increasing number of operating platforms as well as effective collaboration between different offshore energy sectors as previously discussed. An alternative approach to deal with the case of unknown correlation information is to use extreme-value event methods (Hou et al., 2019a). These methods however, only provide the worst-case scenario analysis and cannot be used for a comprehensive analysis of the system.

Joint-failure probability of the failure modes must be calculated to enter the correlated failure modes into a reliability analysis. The correlation between failure modes due to a common source of hazard (e.g., extreme weather) makes the derivation of the joint-failure probability among the failure modes a daunting task because the joint-probabilities can no longer be obtained by the multiplication of the components' probabilities (marginal probabilities). Coccon et al. (2017) addressed the statistical dependence between the failure modes by identifying common source random variables (CSRV), assuming a conditional independence between the failure modes. The applicability of the method to the case of an aquaculture-MPOP, where a large number of CSRV are involved, is highly limited. Park et al. (2015) and Aryai (2019) utilised copula for capturing the dependence between failure modes. The selection of appropriate copula types is still under progress.

3.5. Reliability analysis methods

After obtaining the limit-state functions and stochastic parameters and processes, the reliability of the structure for a predefined failure threshold can be obtained by using reliability analysis methods such as First-Order Reliability Method (FORM) (Hu et al., 2016), Second-Order Reliability Method (SORM) (Dimitrov et al., 2017), Outcrossing methods (Li et al., 2016), and Monte Carlo Simulation (MCS) (Melchers and Beck, 2018). Different reliability analysis methods have their own pros and cons and in general, must be selected based on the desired reliability precision and the available computational power. Table 6 reviews different reliability analysis methods and their advantages/disadvantages. So far, the industry (specifically the offshore renewable energy industry) has considered discrete analysis of the components and limited data are exchanged between the engineers working on the design stage of different components of the system (Lemmer et al., 2020). The current level of reliability in OWT and aquaculture systems has been achieved by setting reliability constraints at the component level. However, the reliability constraints must be considered at the system level to achieve the cost-saving goal.

To the authors' best knowledge, multi-failure analysis and structural system reliability of an integrated system of aquaculture-MPOPs have not been addressed in the literature. The same argument is valid for individual renewable energy and aquaculture systems. For example, although the reliability of rotor blades, mooring systems, foundation and gearbox were extensively studied in the offshore wind farm literature, very few researchers examined the structural reliability of an offshore wind turbine as a whole (Liu et al., 2019b; Su and Kam, 2020; Pourazarm et al., 2016; Leong et al., 2019).

Aside from the fully coupled dynamic design tools, there is a need for comprehensive multi-scale system reliability of the whole systems by considering all the structural components as an interconnected system of sub-systems and components. This aim cannot be achieved using computationally expensive methods such as MCS. The bound estimation methods, on the other hand, do not

Table 6
Different reliability analysis methods.

Category	Description	Methods	Advantages	Disadvantages	Refs
Simulation Methods	Numerically solve the reliability integration by generating a large number of trials and estimating the probability of failure using the fraction of the points occurring within the failure domain over the total number of generated trials.	Crude Monte-Carlo Simulation and its complementary techniques such as: • Subset Simulation (SS) • Latin Hypercube (LH), Importance Sampling (IS) and Line Sampling	Provides accurate estimation of failure probability. In many cases, if the number of trials is high enough, the results can be considered as the exact solution. Moreover, it can deal with any type of limit-state function and any reliability analysis problem.	MCS requires a large number of trials for evaluating the performance function and therefore, is computationally expensive. Other methods such as LH, SS and IS can be incorporated to decrease the computational burden of MCS.	(Aryai and Mahmoodian, 2017; Fu et al., 2018; Graf et al., 2018; Leheta et al., 2017)
Transformation/Approximation Methods	Approximate the failure domain mainly using first or higher order Taylor expansion at the design point.	FORM, SORM and Response Surface Method (RSM)	Easy to implement and computationally efficient.	Provide an estimation of failure probability and not an exact solution. Cannot be used effectively for the case of problems with multiple local or global solutions or highly non-linear limit-state functions. Very high accuracy cannot be guaranteed using these methods.	(Hu et al., 2016; Dimitrov et al., 2017; Su and Kam, 2020; Kim and Lee, 2015)
Metamodel-based Reliability Methods	Utilise surrogate models (Mostly Kriging and Gaussian Process model) for representing the limit-state and then, apply simulation methods for estimating the failure probability.	Efficient Global Reliability Analysis (EGRA) and Active Learning Reliability Method with integrated Kriging and MCS (AK-MCS)	Provide the advantages of MCS with an acceptable computational cost. Moreover, the methods can deal with non-linear and/or implicit limit-state functions.	The accuracy and efficiency of surrogate models highly depends on the complexity of the limit-state function (high dimensional reliability problems). Also, it is not easy to quantify the accuracy of these models in terms of error in calculation of failure probability.	(Fauriat and Gayton, 2014; Huang et al., 2016b; Peijuan et al., 2017; Bichon et al., 2008; Zhu et al., 2020)
Outcrossing Methods	Simulating the reduction/increase in the strength/stress using stochastic processes and calculating the probability of the first passage of the stochastic process from the predefined threshold	Different closed-form formula for outcrossing of stochastic processes	Accurately predict the failure probability by realistic simulation of structural strength evolutions. If the closed-form solution exists, the method is easy to implement and very accurate.	In many cases, the proper closed-form solution for the outcrossing rates is not available (e.g. for the case of non-normal stochastic processes or joint-outcrossing rates for system reliability analysis)	(Aryai et al., 2020; Li et al., 2016; Sudret, 2008; Jiang et al., 2017)
Knowledge-based Methods	Direct calculation of the failure probability from available failure databases using AI-based methods	Variety of AI-based methods (machine learning and deep learning)	Provide with very accurate predictions. Are easy to implement and can be used for any sort of limit-sate functions	Requires large number of input data which is not readily available for real-world reliability problems. The accuracy of predictions highly depends on the quality of the input data. The results cannot be generalised to other cases	(Stern et al., 2017; Behnia et al., 2016; Kang et al., 2016b; Amaya-Gomez et al., 2016)

Process Safety and Environmental Protection 148 (2021) 437–461

calculate the narrowest possible bound, even if all the components' probabilities (marginal probabilities) are known. As a result, they are not applicable for practical uses (Melchers and Beck, 2018). The-state-of-the-art methods based on surrogate models and neural networks proved to be efficient and easy to implement (Xiao et al., 2018; Zhang et al., 2019c; Oparaji et al., 2017). The majority of these methods however, do not consider the dependency between components and/or are difficult to be extended to time-dependent system reliability cases (Yuan et al., 2020; Jiang et al., 2020). The utilisation of surrogate models for multi-failure analysis along with cross-validation and uncertainty quantifications of these models require further research. Other alternatives, such as Matrix-based System Reliability (MSR) and its modifications (Aryai, 2019; Byun and Song, 2017) proved to be of practical use if the marginals and joint-failure probabilities are known. Outcrossing methods are known as one of the most accurate reliability analysis methods. Modelling the structural deterioration using stochastic process (or correlated stochastic processes) and studying the probability of their outcrossing from predefined thresholds is a tremendous task for complex offshore platforms and is an area for future research.

As described in Section 3.2, an MPOP consists of different sub-systems with different scales and structural features. From the system-reliability point of view, individual sub-systems can be represented using multi-level models (Kumar et al., 2015). A floating collar as an example can be modelled at different levels associated with material degradation, cross-section reduction, structural strength and other MPOP-scale features. These levels are described with state variables which are representative of different properties or any desirable quality or quantity (such as different reliability measures) of the sub-system or the main MPOP system (Kumar et al., 2015). Several researchers investigated multi-level modelling of the structural systems by employing AI-based methods (Cong et al., 2009), dynamic Bayesian networks (Luque and Straub, 2016), subset-simulation (Schneider et al., 2017), and random-fields (Aryai, 2019; Dogandzic and Zhang, 2006). These researches however, did not consider the correlation between different levels and inhomogeneity of the levels in space. ((Xu and Gardoni (2020a))) addressed this issue by employing multi-variate non-stationary random fields. The required data for multi-level modelling of MPOPs would be collected through different SHM sensors attached to different components of the system. Because of the issues discussed in Section 3.1.3, multi-level modelling of an MPOP can be subjected to the incomplete data issue. Xu and Gardoni (2020b) proposed a methodology for calibrating the random-fields describing multi-level system models using incomplete data. Because of the difficulties in modelling (see Section 3.2), the input data availability and quality (see Section 3.1), and the high degrees of uncertainty associated with the environmental and structural parameters (see Section 3.3), application of the abovementioned methodology for modelling an MPOP would be challenging and requires further investigations.

Finally, the reliability modelling for risk assessment and in general, risk-based design approaches can come to the aid of asset owners for selecting the best MPOP conceptual design, and/or optimal operational location of the MPOP considering different types of risks (i.e. environmental, social, financial, structural, etc.) defined for the system. Using these probabilistic techniques, one can propagate the risk of different component-level events for the system and observe the resultant system-level impacts. Different techniques for risk-based reliability modelling have been reported in the literature, among which, Bayesian statistics-based approaches and particularly Bayesian networks are of great importance. Several applications of Bayesian networks for probabilistic reliability assessment of offshore systems can be found in works of Li et al. (2020); Abaei et al. (2018a), b and Arzaghi et al. (2020) for floating offshore wind turbines, general floating offshore platforms, ship groundings and subsea pipelines, respectively.

4. Optimising reliability standards

From the structural design viewpoint, the over-reliance of offshore renewable industry on the standards produced by the oil and gas industry can be seen through the list of technical standards and requirements imposed by the certification authorities such as DNV-GL and Lloyds Register, which include oil and gas industry's specific standards such as ISO 19901-6 (Petroleum and natural gas industries. Specific requirements for offshore structures, Part 6: marine operations), ISO 19905-1 (Petroleum and natural gas industries. Site-specific assessment of mobile offshore units, Part 1: Jack-ups), API RP-2A-WSD/LRFD (American Petroleum Institute, Recommended Practice), etc. This huge reliance on the oil and gas industry's standards and design codes is challenging, with known and unknown drawbacks in the long-term, even though such standards and design codes make it possible for launching initial pilot offshore renewable energy and aquaculture farm projects.

In the abovementioned standards and many other offshore structure design standards, such as Eurocode and DNVGL-OS-C101, system reliability is not explicitly considered (Melchers, 2013; Stopa, 2018). This issue, however, causes the reliability threshold levels to be determined without considering the system limitations and features. This ultimately leads to the loss of resources due to over-design of the system. In practice, the reliability threshold for individual component/sub-systems is different from the condition where the integral component/sub-system is part of a marine system. This implies the necessity of considering the system reliability concept in preparation of the standards for new MPOPs.

The aforementioned design standards ignore the impact of deterioration (except for fatigue) on the structural integrity of offshore systems. In other words, the standards consider the structure intact throughout its lifetime, even after applying a maintenance action to the structure. In reality, because of the imperfection of the maintenance actions, the general structural integrity of a structure is decreased over time, and the structure cannot be perfectly restored to its installation date condition (as-new condition). This unrealistic approach applies to new operating structures, but it cannot assure the safety of the structure several years after its commissioning. Addressing this issue requires the incorporation of structural deterioration models together with the time-dependent reliability analysis methods, examples of which can be found in works of Aryai et al. (2020) and Teixeira et al. (2013).

In order to ensure long-term safety of the MPOP, case-specific design codes must be established to address the unique technical, structural, and environmental features of the system. Adapting the available offshore oil and gas industry's OREDA, Europa's pilot offshore wind and aquaculture projects database, considering Australia's environmental conditions is only a short-term solution to address the issue. In the long-term, the proposed RAMS database in conjunction with system reliability-based design optimisation methods would allow for establishment of the first set of Australian, case-specific optimised standards and design codes for the desirable integrated systems.

5. Recommendations for future research

The previous sections discussed the gaps in the current field of knowledge for reliability assessment of MPOPs. Based on these identified gaps, several recommendations for future research are listed in Table 7.

Table 7
Recommendations for future research.

Topic	Recommended area for further research
Data collection and analysis	• Integrating the reliability precautions and structural limitations of specific design concepts into the GIS-based site selection tools • Developing advanced data fusion, signal processing, AI-based trend detection algorithms for bridging the relationship between the degradation in the material and the structure. • Use of ROVs and AUVs for autonomous inspection tasks. • Improving the durability of SHM sensors for offshore implementations. • Inclusion of SHM in the condition monitoring standards and guidelines. • Addressing big-data issues for developing real-time data collection and analysis frameworks.
Load and structural modelling	• Considering the inherent multi-scale features in dynamic analysis of an MPOP. • Accurate multi-physics simulation of MPOPs by studying realistic fluid-soil-structure interactions. • Addressing non-linear coupling between the components of a modular design MPOP in a time-domain simulation. • Tackling issues regarding force unidirectionality in the current design standards. • Studying the impact of platform motions on energy production. • Examining the effect of platform motions on fish welfare. • Tackling the scaling-effect issues in the scaled-down models. • Developing robotic intelligent towing tanks for model testing purposes.
Uncertainty quantification	• Quantification of existing uncertainty in the influential factors. • Determining the key failure drivers and proposing mitigation measures. • Developing stochastic spatial-temporal models for time and space varying influential phenomena such as product growth, corrosion, seabed and material properties variations. • Dealing with the issues related to the safety factor approach used in the current design standards by employing probabilistic reliability analysis methods.
Failure modes	• Identification of design-specific failure modes. • Capturing the correlation existing between different failure modes. • Incorporating the dependence between failure modes into system reliability analysis approaches.
Reliability analysis	• Proposing a system-based reliability analysis approach within the design standards. • Multi-failure system reliability analysis of different MPOP designs. • Representing an MPOP system using correlated multi-level models. • Entering time- and space-dependent degradation phenomena into the system reliability analysis of MPOPs. • Amending the current offshore oil and gas industry-based reliability standards based on the unique features of the designed MPOPs. • Combining different reliability approaches such as human-based, production-based, operational and structural reliability approaches for the design and operation of MPOPs. • Using risk-based reliability modelling techniques for assessing the suitability of conceptual designs considering different types of risk. • Using the digital twins in conjunction with reliability modelling techniques to develop predictive algorithms for real-time reliability assessment of MPOPs.

6. Concluding remarks

This review paper discusses the challenges related to structural reliability analysis of aquaculture-MPOP in consideration of Australia's environmental and technological conditions. To this end, the reliability analysis of the system has been divided into its related sub-topics including data availability, data collection, failure modes, uncertainty quantification, and reliability analysis methods. The following pertinent points may be drawn from this review:

- Data scarcity is an intrinsic problem of novel designs. To deal with this issue, several possible solutions based on the available knowledge in the offshore oil and gas industry have been proposed. It can be concluded that the huge database available from the offshore oil and gas industry may not fully replace the missing data from similar novel aquaculture-MPOPs. However, it can serve as the baseline for constructing a RAMS database based on the unique features of Australia.
- Based on probabilistic reliability analysis approaches, one can assess the reliability of the intended system with very limited data already available. Accuracy of the results obtained from probabilistic system reliability approaches will improve over time with updates in the RAMS database and the utilization of reliability updating methods.
- Accurate reliability assessment of MPOPs would not be possible without dealing with challenges regarding flexibility of structural components, unique structural features of renewable energy and aquaculture systems, high level of non-linearity, multi-scale features, etc. that make load analysis of the intended system difficult.
- Failure modes specific to the novel design must be identified, formulated, and studied considering the dependencies among the corresponding failure mechanisms.
- Uncertainties which exist within the models, environmental and design parameters, deterioration processes, and geometries must be quantified and incorporated into the reliability assessment.
- The current design standards being used in the design of MPOPs must be revised to include a system-based reliability approach based on the specific requirements of aquaculture and offshore renewable energy industries. The revised standards would differ from the conventional offshore oil and gas industry standards in terms of construction materials, structural features, failure modes, health monitoring requirements and reliability targets of the MPOPs.
- By incorporating the reliability analysis results into a decision-making framework, asset managers would be provided with a powerful, accurate and easy-to-interpret tool to decide on the maintenance planning of their assets in both the short and the long-term.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgments

The authors acknowledge the financial support of the Blue Economy Cooperative Research Centre (CRC), established and supported under the Australian Government's CRC Program, grant number CRC-20180101. The CRC Program supports industry-led collaborations between industry, researchers and the community.

References

Abaei, M.M., et al., 2018a. Reliability assessment of marine floating structures using Bayesian network. Appl. Ocean. Res. 76, 51–60.
Abaei, M.M., et al., 2018b. Dynamic reliability assessment of ship grounding using Bayesian Inference. Ocean. Eng. 159, 47–55.
ABARES, 2018. Australian fisheries and Aquaculture Statistics. Australian Government Department of Agriculture and Water Resources.
About New Zealand's emissions reduction targets. 2020 [cited 2020 Jul 2020]; Available from: https://www.mfe.govt.nz/climate-change/climate-change-and-government/emissions-reduction-targets/about-our-emissions.
Adedipe, O., Brennan, F., Kolios, A., 2016. Review of corrosion fatigue in offshore structures: present status and challenges in the offshore wind sector. Renew. Sustainable Energy Rev. 61, 141–154.
Agency, A.R.E. AREMI. 2020 [cited 2020 May]; Available from: https://nationalmap.gov.au/renewables/about.html.
Aguilar-Manjarrez, J., 2016. Horizon 2020: Promoting Sustainable Aquaculture. FAO Aquaculture Newsletter, pp. 26 (54).
AKVA. Pens and nets. 2020 [cited 2020 March]; Available from: https://www.akvagroup.com/pen-based-aquaculture/pens-nets.
Alleyne, D.N., et al., 1997. The lamb wave inspection of chemical plant pipework. In: Review of Progress in Quantitative Nondestructive Evaluation. Springer, pp. 1269–1276.
Amaya-Gomez, R., Sánchez-Silva, M., Muñoz, F., 2016. Pattern recognition techniques implementation on data from in-line Inspection (ILI). J. Loss Prev. Process Ind. 44, 735–747.
Antoniadou, I., et al., 2015. Aspects of structural health and condition monitoring of offshore wind turbines. Philos. Trans. Math. Phys. Eng. Sci. 373 (2035), 20140075.
Aquafarms, O., [cited 2020 May]; Available from: 2020. Hex Box. http://www.oceanaquafarms.com/.
Aquilina, J.P., Farrugia, R.N., Sant, T., 2019. On the Energy Requirements of UAVs Used for Blade Inspection in Offshore Wind Farms. in 2019 Offshore Energy and Storage Summit (OSES). IEEE.
Aryai, V., 2019. Spatio-temporal Reliability Analysis of Pipeline.
Aryai, V., Mahmoodian, M., 2017. Spatial-temporal reliability analysis of corroding cast iron water pipes. Eng. Fail. Anal. 82 (Supplement C), 179–189.
Aryai, V., et al., 2020. Time-dependent finite element reliability assessment of cast-iron water pipes subjected to spatio-temporal correlated corrosion process. Reliab. Eng. Syst. Saf., 106802.
Arzaghi, E., et al., 2020. Pitting corrosion modelling of X80 steel utilized in offshore petroleum pipelines. Process. Saf. Environ. Prot.
Association, W.S., [cited 2020 July 2020]; Available from: 2012. Steel Solutions in the Green Economy. https://www.worldsteel.org/en/dam/jcr:41f65ea2-7447-4489-8ba7-9c87e3975aab/Steel+solutions+in+the+green+economy:+Wind+turbines.pdf.
Augustyn, D., et al., 2019. Data-driven design and operation of offshore wind structures. In: The 29th International Ocean and Polar Engineering Conference, International Society of Offshore and Polar Engineers.
Australia's first proposed offshore wind farm. 2020 [cited 2020 May]; Available from: http://www.starofthesouth.com.au/.
Australia's Offshore Energy Regulator. 2020 [cited 2020 Auguest]; Available from: https://www.nopsema.gov.au/.
Australian Fisheries and Aquaculture Statistics 2018, 2019. Australian Bureau of Agricultural Resource.
Azimov, U., Birkett, M., 2017. Feasibility study and design of an ocean wave power generation station integrated with a decommissioned offshore oil platform in UK waters. Int. J. Energy Environ. 8 (2), 161–174.
Bai, X.-D., et al., 2016. Fatigue assessment for the floating collar of a fish cage using the deterministic method in waves. Aquac. Eng. 74, 131–142.
Bai, X., et al., 2018. Probabilistic analysis and fatigue life assessment of floating collar of fish cage due to random wave loads. Appl. Ocean. Res. 81, 93–105.
Balash, C., et al., 2009. Aquaculture net drag force and added mass. Aquac. Eng. 41 (1), 14–21.
Barari, A., et al., 2017. Embedment effects on vertical bearing capacity of offshore bucket foundations on cohesionless soil. Int. J. Geomech. 17 (4), 04016110.
Behnia, A., et al., 2016. Failure prediction and reliability analysis of ferrocement composite structures by incorporating machine learning into acoustic emission monitoring technique. Constr. Build. Mater. 122, 823–832.
Bi, C.-W., et al., 2020. An efficient artificial neural network model to predict the structural failure of high-density polyethylene offshore net cages in typhoon waves. Ocean. Eng. 196, 106793.
Bichon, B.J., et al., 2008. Efficient global reliability analysis for nonlinear implicit performance functions. AIAA journal 46 (10), 2459–2468.
Booij, N., Ris, R.C., Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions: 1. Model description and validation. J. Geophys. Res. Oceans 104 (C4), 7649–7666.
Bore, P.T., Amdahl, J., 2017. Determination of environmental conditions relevant for the ultimate limit state at an exposed aquaculture location. In: in International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers.
Bore, P.T., Amdahl, J., Kristiansen, D., 2017. Modelling of hydrodynamic loads on aquaculture net cages by a modified morison model. In: MARINE 2017 Computational Methods in Marine Engineering VII.
Borg, M., Collu, M., Brennan, F.P., 2013. Use of a wave energy converter as a motion suppression device for floating wind turbines. Energy Procedia 35, 223–233.
Brett, C., et al., 2018. Development of a technique for inspecting the foundations of offshore wind turbines. Insight-Non-Destructive Testing Condition Monitoring 60 (1), 19–27.
Buck, B.H., Ebeling, M.W., Michler-Cieluch, T., 2010. Mussel cultivation as a co-use in offshore wind farms: potential and economic feasibility. Aquac. Econ. Manag. 14 (4), 255–281.
Buck, B.H., et al., 2017a. Offshore and multi-use aquaculture with extractive species: seaweeds and bivalves. In: Aquaculture Perspective of Multi-use Sites in the Open Ocean. Springer, Cham, pp. 23–69.
Buck, B.H., et al., 2017b. The german case study: Pioneer projects of aquaculture-wind farm multi-uses. In: Aquaculture Perspective of Multi-Use Sites in the Open Ocean. Springer, Cham, pp. 253–354.
Budiyono, A., 2009. Advances in Unmanned Underwater Vehicles Technologies: Modeling, Control and Guidance Perspectives.
Byun, J., Song, J., 2017. In: Kiureghian, Armen Der, Gardoni, P. (Eds.), Structural System Reliability, Reloaded, in Risk and Reliability Analysis: Theory and Applications. Springer International Publishing: Cham., pp. 27–46, In Honor of Prof.
Canada, Go., [cited 2020 May]; Available from: 2019. State of Salmon Aquaculture Technologies. http://dfo-mpo.gc.ca/aquaculture/publications/ssat-ets-eng.html.
Capocci, R., et al., 2017. Inspection-class remotely operated vehicles—a review. J. Mar. Sci. Eng. 5 (1), 13.
Caspeele, R., Taerwe, L., Frangopol, D.M., 2019. Life-cycle analysis and assessment in civil engineering. In: in 6th International Symposium on Life-Cycle Civil Engineering (IALCCE 2018), Taylor & Francis Group.
Castro-Santos, L., Diaz-Casas, V., 2016. Floating Offshore Wind Farms. Springer International Publishing.
Chandler, J., et al., 2017. Engineering and legal considerations for decommissioning of offshore oil and gas infrastructure in Australia. Ocean. Eng. 131, 338–347.
Chatzakos, P., et al., 2010. Autonomous infrared (IR) thermography based inspection of glass reinforced plastic (GRP) wind turbine blades (WTBs. In: in 2010 IEEE Conference on Robotics, Automation and Mechatronics, IEEE.
Chen, H.-H., Yang, R.-Y., Hwung, H.-H., 2014a. Study of hard and soft countermeasures for scour protection of the jacket-type offshore wind turbine foundation. J. Mar. Sci. Eng. 2 (3), 551–567.
Chen, H.-H., et al., 2014b. Study on multi-use of an integrated offshore wind turbine foundation and coastal cage net. Coast. Eng., 2.
Chou, J.-S., Tu, W.-T., 2011. Failure analysis and risk management of a collapsed large wind turbine tower. Eng. Fail. Anal. 18 (1), 295–313.
Chu, Y., et al., 2020. Review of cage and containment tank designs for offshore fish farming. Aquaculture 519, 734928.
Chung, H.-M., et al., arXiv preprint arXiv:2006.08326 2020. Placement and Routing Optimization for Automated Inspection with UAVs: a Study in Offshore Wind Farm.
Coccon, M.N., et al., 2017. A new approach to system reliability analysis of offshore structures using dominant failure modes identified by selective searching technique. KSCE J. Civ. Eng. 21 (6), 2360–2372.
Cong, Q., Chai, T., Yu, W., 2009. Modeling wastewater treatment plant via hierarchical neural networks. Control Theory & Applications 26 (1), 8–14.
Connolly, P., Hall, M., 2019. Comparison of pilot-scale floating offshore wind farms with shared moorings. Ocean. Eng. 171, 172–180.
Coppolino, R., Rubin, S., 1980. Detectability of structural failures in offshore platforms by ambient vibration monitoring. In: in Offshore Technology Conference, Offshore Technology Conference.
Cradden, L., et al., 2016. Multi-criteria site selection for offshore renewable energy platforms. Renew. Energy 87, 791–806.
Crespo, L.G., Kenny, S.P., 2005. Reliability-based control design for uncertain systems. J. Guid. Control. Dyn. 28 (4), 649–658.
Cronrath, C., Aderiani, A.R., Lennartson, B., 2019. Enhancing digital twins through reinforcement learning. In: 2019 IEEE 15th International Conference on Automation Science and Engineering (CASE), IEEE.
Dafforn, K.A., et al., 2015. Marine urbanization: an ecological framework for designing multifunctional artificial structures. Front. Ecol. Environ. 13 (2), 82–90.
Dalton, G., et al., 2019. Feasibility of investment in Blue Growth multiple-use of space and multi-use platform projects; results of a novel assessment approach and case studies. Renew. Sustainable Energy Rev. 107, 338–359.
Davison, W., Herbert, N., 2013. Swimming-enhanced Growth, in Swimming Physiology of Fish. Springer, pp. 177–202.

Day, A., et al., 2015. Hydrodynamic modelling of marine renewable energy devices: a state of the art review. Ocean. Eng. 108, 46–69.
DeCew, J., et al., 2013. Field measurements of cage deformation using acoustic sensors. Aquac. Eng. 57, 114–125.
Demystifying digital twins. 2020 [cited 2020 August]; Available from: https://www.bmt.org/insights/demystifying-digital-twins/.
Devriendt, C., et al., 2014. Structural health monitoring of offshore wind turbines using automated operational modal analysis. Struct. Health Monit. 13 (6), 644–659.
Dimitrov, N., Bitsche, R., Blasques, J., 2017. Spatial reliability analysis of a wind turbine blade cross section subjected to multi-axial extreme loading. Struct. Saf. 66, 27–37.
Ding, H., et al., 2015. Model tests on the bearing capacity of wide-shallow composite bucket foundations for offshore wind turbines in clay. Ocean. Eng. 103, 114–122.
Dogandzic, A., Zhang, B., 2006. Distributed estimation and detection for sensor networks using hidden Markov random field models. IEEE Trans. Signal Process. 54 (8), 3200–3215.
Dong, W., Moan, T., Gao, Z., 2012. Fatigue reliability analysis of the jacket support structure for offshore wind turbine considering the effect of corrosion and inspection. Reliab. Eng. Syst. Saf. 106, 11–27.
Dong, W., et al., 2020. Structural reliability analysis of contact fatigue design of gears in wind turbine drivetrains. J. Loss Prev. Process Ind., 104115.
Doshvarpassand, S., Wu, C., Wang, X., 2019. An overview of corrosion defect characterization using active infrared thermography. Infrared Phys. Technol. 96, 366–389.
Dragon, W., A WEC and aquaculture MPOP. 2020 [cited 2020 16 Jun]; Available from: http://www.wavedragon.net/.
DVN-GL. Hydrogen. 2019 [cited 2020 17 Jun]; Available from: https://www.dnvgl.com/oilgas/hydrogen/index.html.
Eleftheroglou, N., et al., 2018. Structural health monitoring data fusion for in-situ life prognosis of composite structures. Reliab. Eng. Syst. Saf. 178, 40–54.
Ellefsen, A.L., et al., 2019. A comprehensive survey of prognostics and health management based on deep learning for autonomous ships. IEEE Trans. Reliab. 68 (2), 720–740.
Energy, C.C. CETO 5 – Perth (WA). 2020 [cited 2020 May]; Available from: https://www.carnegiece.com/project/ceto-5-perth-wave-energy-project/.
Energy, T.W.S. Uniwave. 2020 [cited 2020 July 2020]; Available from: https://www.waveswell.com/.
Energy, G.O., [cited 2020; Available from: 2020c. The Green Ocean Energy Wave Treader Project, UK. https://www.power-technology.com/projects/greenoceanenergywav/.
ERIN, E.R.I.N., [cited 2020 March]; Available from: 2020. Australian Marine Parks. https://parksaustralia.gov.au/marine/maps/.
Falconer, L., et al., 2013. Using physical environmental parameters and cage engineering design within GIS-based site suitability models for marine aquaculture. Aquac. Environ. Interact. 4 (3), 223–237.
Faltinsen, O.M., Shen, Y., 2018. Wave and current effects on floating fish farms. J. Mar. Sci. Appl. 17 (3), 284–296.
Fan, D., et al., 2019. A robotic Intelligent Towing Tank for learning complex fluid-structure dynamics. Sci. Robot. 4 (36).
FAO, [cited 2020 March]; Available from: 2018. The State of the World Fisheries and Aquaculture. http://www.fao.org/state-of-fisheries-aquaculture.
Farmer, M., [cited 2020 17 Jun]; Available from: 2020. BP Invests $1.76m in Australian Hydrogen Study. https://www.offshore-technology.com/news/bp-invests-australian-hydrogen-geraldton/.
Faulstich, S., et al., 2009. Proc. of European Offshore Wind Reliability of offshore turbines–identifying the risk by onshore experience, 69.
Fauriat, W., Gayton, N., 2014. AK-SYS: an adaptation of the AK-MCS method for system reliability. Reliab. Eng. Syst. Saf. 123, 137–144.
Feng, X., Bai, W., 2017. Hydrodynamic analysis of marine multibody systems by a nonlinear coupled model. J. Fluids Struct. 70, 72–101.
Feng, A., Magee, A.R., Price, W., 2019. Two dimensional wave-current-structure interaction with flat or sloping seabed environment in a linearized framework. Ocean. Eng. 173, 732–747.
Fisheries officials turn down Hex Box idea. 2018 [cited 2020 August]; Available from: https://salmonbusiness.com/fisheries-officials-turn-down-hex-box-idea/.
Flocard, F., Ierodiaconou, D., Coghlan, I.R., 2016. Multi-criteria evaluation of wave energy projects on the south-east Australian coast. Renew. Energy 99, 80–94.
Fredriksson, D.W., Beck-Stimpert, J., 2019. Basis-of-Design Technical Guidance for Offshore Aquaculture Installations In the Gulf of Mexico.
Fu, S., Moan, T., 2012. Dynamic analyses of floating fish cage collars in waves. Aquac. Eng. 47, 7–15.
Fu, S., et al., 2007. Hydroelastic analysis of flexible floating interconnected structures. Ocean. Eng. 34 (11–12), 1516–1531.
Fu, Z., et al., 2018. Reliability analysis of condition monitoring network of wind turbine blade based on wireless sensor networks. IEEE Trans. Sustain. Energy 10 (2), 549–557.
Fujii, T., et al., 2020. Seafloor heterogeneity: artificial structures and marine ecosystem dynamics. Front. Mar. Sci.
Gagnon, M., Bergeron, P., 2017. Observations of the loading and motion of a submerged mussel longline at an open ocean site. Aquac. Eng. 78, 114–129.
Gallant, A., 2020. Assessing Helical Anchors for Aquaculture Applications.
Gao, B., et al., 2016. Multidimensional tensor-based inductive thermography with multiple physical fields for offshore wind turbine gear inspection. IEEE Trans. Ind. Electron. 63 (10), 6305–6315.
Gentry, R.R., et al., 2017. Mapping the global potential for marine aquaculture. Nat. Ecol. Evol. 1 (9), 1317–1324.
Gimpel, A., et al., 2015. A GIS modelling framework to evaluate marine spatial planning scenarios: co-location of offshore wind farms and aquaculture in the German EEZ. Mar. Policy 55, 102–115.
Goseberg, N., Franz, B., Schlurmann, T., 2012. The potential co-use of aquaculture and offshore wind energy structures. in Proceedings of the Sixth Chinese-German Joint Symposium on Hydraulic and Ocean Engineering (CGJOINT 2012).
Graf, P., et al., 2018. Adaptive stratified importance sampling: hybridization of extrapolation and importance sampling Monte Carlo methods for estimation of wind turbine extreme loads. Wind Energy Science (Online) 3, NREL/JA-2C00-72435.
Griffin, R., Buck, B., Krause, G., 2015. Private incentives for the emergence of co-production of offshore wind energy and mussel aquaculture. Aquaculture 436, 80–89.
Group, C.E.C.H.W., 2019. Australia's National Hydrogen Strategy. Commonwealth of Australia.
Güemes, A., et al., 2020. Structural health monitoring for advanced composite structures: a review. J. Compos. Sci. 4 (1), 13.
Guerra, R.H., et al., 2019. Digital twin-based optimization for ultraprecision motion systems with backlash and friction. IEEE Access 7, 93462–93472.
Gunn, D., et al., 2019. Ultrasonic testing of laboratory samples representing monopile wind turbine foundations. Insight-Non-Destructive Testing and Condition Monitoring 61 (4), 187–196.
GWA, [cited 2020 July]; Available from: 2020. The Global WInd Atlas. https://globalwindatlas.info/.
Hajializadeh, D., et al., 2016. Spatial time-dependent reliability analysis of reinforced concrete slab bridges subject to realistic traffic loading. Struct. Infrastruct. Eng. 12 (9), 1137–1152.
Hallowell, S., Myers, A., 2017. Site-specific variability of load extremes of offshore wind turbines exposed to hurricane risk and breaking waves. Wind. Energy 20 (1), 143–157.
Hallowell, S.T., et al., 2018. System reliability of floating offshore wind farms with multiline anchors. Ocean. Eng. 160, 94–104.
He, Z., et al., 2018. The influence of fish on the mooring loads of a floating net cage. J. Fluids Struct. 76, 384–395.
He, K., et al., 2019. Stochastic dynamic response analysis of submerged multi-body structure considering the uncertainty of connection gap. Noise Vib. Worldw. 50 (8), 254–263.
Hemer, M., Griffin, D., 2010. The wave energy resource along Australia's southern margin. J. Renew. Sustain. Energy 2 (4), 043108.
Hexicon, W. 2020 [cited 2020 May]; Available from: https://www.wunderhexicon.es/newpage#OIPS.
Holen, S.M., et al., 2018. Occupational safety in aquaculture–part 2: fatalities in Norway 1982–2015. Mar. Policy 96, 193–199.
Horn, J.-T., Leira, B.J., 2019. Fatigue reliability assessment of offshore wind turbines with stochastic availability. Reliab. Eng. Syst. Saf. 191, 106550.
Horn, J.-T., Leira, B.J., Amdahl, J., 2017a. A preliminary study of reliability-based controller scheduling in offshore wind turbines. In: EERA DeepWind'2017, 14th Deep Sea Offshore Wind R&D Conference, Trondheim, Norway.
Horn, J.-T.H., Krokstad, J.R., Amdahl, J., 2017b. Joint probability distribution of environmental conditions for design of offshore wind turbines. In: International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers.
Hou, H.-M., et al., 2017. Time-dependent reliability analysis of mooring lines for fish cage under corrosion effect. Aquac. Eng. 77, 42–52.
Hou, H.-M., et al., 2018. Fatigue reliability analysis of mooring system for fish cage. Appl. Ocean. Res. 71, 77–89.
Hou, H.-M., et al., 2019a. System reliability evaluation of mooring system for fish cage under ultimate limit state. Ocean. Eng. 172, 422–433.
Hou, H.-M., Dong, G.-H., Xu, T.-J., 2019b. Fatigue damage distribution and reliability assessment of grid mooring system for fish cage. Mar. Struct. 67, 102640.
Hu, W., Choi, K., Cho, H., 2016. Reliability-based design optimization of wind turbine blades for fatigue life under dynamic wind load uncertainty. Struct. Multidiscip. Optim. 54 (4), 953–970.
Huang, X.-H., et al., 2016a. Numerical simulation of deformations and forces of a floating fish cage collar in waves. Aquac. Eng. 74, 111–119.
Huang, X., Chen, J., Zhu, H., 2016b. Assessing small failure probabilities by AK–SS: an active learning method combining Kriging and Subset Simulation. Struct. Saf. 59, 86–95.
Hval, M.N., 2012. Modelling and Control of Underwater Inspection Vehicle for Aquaculture Sites. Institutt for marin teknikk.
Igwemezie, V., Mehmanparast, A., Kolios, A., 2018. Materials selection for XL wind turbine support structures: a corrosion-fatigue perspective. Mar. Struct. 61, 381–397.
IMOS, [cited 2020 May]; Available from: 2020. Integrated Marine Observing System. http://imos.org.au/.
Intelligent Towing Tank propels human-robot-computer research. 2019 [cited 2020 August]; Available from: https://news.mit.edu/2019/intelligent-towing-tank-propels-research-1209.
IoT Applications for Offshore Monitoring in Oil and Gas. 2020 [cited 2020 August]; Available from: https://behrtech.com/blog/5-iot-applications-for-offshore-monitoring-in-oil-and-gas/.
Iturrioz, A., et al., 2016. Experimental and numerical design of a combined wind-wave concept. In: Progress in Renewable Energies Offshore: Proceedings of the

2nd International Conference on Renewable Energies, (RENEW2016). 2016. Taylor & Francis Books Ltd.
Jaensch, F., et al., 2018. Digital twins of manufacturing systems as a base for machine learning. In: 2018 25th International Conference on Mechatronics and Machine Vision in Practice (M2VIP), IEEE.
Jak, R., et al., 2019. Outline of Concepts for Aquaculture on Floating Modular Islands: D8. 1. European Commission.
Jansen, H.M., et al., 2016. The feasibility of offshore aquaculture and its potential for multi-use in the North Sea. Aquac. Int. 24 (3), 735–756.
Jensen, Ø., et al., 2007. Finite element analysis of tensegrity structures in offshore aquaculture installations. Aquac. Eng. 36 (3), 272–284.
Jiang, C., et al., 2017. An outcrossing rate model and its efficient calculation for time-dependent system reliability analysis. J. Mech. Des. 139 (4).
Jiang, C., et al., 2020. Real-time estimation error-guided active learning Kriging method for time-dependent reliability analysis. Appl. Math. Model. 77, 82–98.
Jin, X., et al., 2016. System safety analysis of large wind turbines. Renewable Sustainable Energy Rev. 56, 1293–1307.
Johnston, I., Young, H., Huntington, J., 1986. Toward unmanned oil and gas production offshore. In: European Petroleum Conference, Society of Petroleum Engineers.
Jüngert, A., 2008. Damage Detection in wind turbine blades using two different acoustic techniques. NDT Database J. (NDT).
Kaewunruen, S., Lian, Q., 2019. Digital twin aided sustainability-based lifecycle management for railway turnout systems. J. Clean. Prod. 228, 1537–1551.
Kampczyk, A., 2020. Measurement of the geometric center of a turnout for the safety of railway infrastructure using MMS and total station. Sensors 20 (16), 4467.
Kang, B.-J., Kim, J.-H., Kim, Y., 2016a. Engineering criticality analysis on an offshore structure using the first-and second-order reliability method. Int. Jounal Nav. Archit. Ocean. Eng. 8 (6), 577–588.
Kang, F., Xu, Q., Li, J., 2016b. Slope reliability analysis using surrogate models via new support vector machines with swarm intelligence. Appl. Math. Model. 40 (11–12), 6105–6120.
Kang, J., et al., 2017. Risk assessment of floating offshore wind turbine based on correlation-FMEA. Ocean. Eng. 129, 382–388.
Khan, A., et al., 2017. Visual feedback–based heading control of autonomous underwater vehicle for pipeline corrosion inspection. Int. J. Adv. Robot. Syst. 14 (3), p. 1729881416658171.
Kim, D.H., Lee, S.G., 2015. Reliability analysis of offshore wind turbine support structures under extreme ocean environmental loads. Renew. Energy 79, 161–166.
Kirschbaum, L., et al., 2020. AI-driven maintenance support for downhole tools and electronics operated in dynamic drilling environments. IEEE Access 8, 78683–78701.
Klijnstra, J., et al., 2017. Technical risks of offshore structures. In: Aquaculture Perspective of Multi-Use Sites in the Open Ocean. Springer, Cham, pp. 115–127.
Kolios, A., Wang, L., 2018. Advanced reliability assessment of offshore wind turbine monopiles by combining reliability analysis method and SHM/CM technology. In: The 28th International Ocean and Polar Engineering Conference, International Society of Offshore and Polar Engineers.
Korsøen, Ø.J., et al., 2012. Atlantic salmon (Salmo salar L.) in a submerged sea-cage adapt rapidly to re-fill their swim bladders in an underwater air filled dome. Aquac. Eng. 51, 1–6.
Koundouri, P., 2017. The Ocean of Tomorrow. Springer.
Kumar, R., Cline, D.B., Gardoni, P., 2015. A stochastic framework to model deterioration in engineering systems. Struct. Saf. 53, 36–43.
Lamas-Pardo, M., Iglesias, G., Carral, L., 2015. A review of very large floating structures (VLFS) for coastal and offshore uses. Ocean. Eng. 109, 677–690.
Lamei, A., Hayatdavoodi, M., 2020. On motion analysis and elastic response of floating offshore wind turbines. J. Ocean. Eng. Mar. Energy, 1–20.
Leble, V., Barakos, G., 2016. Demonstration of a coupled floating offshore wind turbine analysis with high-fidelity methods. J. Fluids Struct. 62, 272–293.
Lee, H., Poguluri, S.K., Bae, Y.H., 2018. Performance analysis of multiple wave energy converters placed on a floating platform in the frequency domain. Energies 11 (2), 406.
Leheta, H.W., Elhanafi, A.S., Badran, S.F., 2017. Reliability analysis of novel stiffened panels using Monte Carlo simulation. Ships Offshore Struct. 12 (5), 640–652.
Lei, Y., et al., 2020. Effects of fish nets on the nonlinear dynamic performance of a floating offshore wind turbine integrated with a steel fish farming cage. Int. J. Struct. Stab. Dyn. 20 (03), 2050042.
Leimeister, M., Kolios, A., 2018. A review of reliability-based methods for risk analysis and their application in the offshore wind industry. Renew. Sustainable Energy Rev. 91, 1065–1076.
Lemmer, F., et al., 2020. Multibody modeling for concept-level floating offshore wind turbine design. Multibody Syst. Dyn., 1–34.
Leong, D., Low, Y.M., Kim, Y., 2019. An efficient system reliability approach against mooring overload failures. In: International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers.
Leontaritis, I., Billings, S.A., 1985. Input-output parametric models for non-linear systems part I: deterministic non-linear systems. Int. J. Control 41 (2), 303–328.
Li, L., Fu, S., Xu, Y., 2013. Nonlinear hydroelastic analysis of an aquaculture fish cage in irregular waves. Mar. Struct. 34, 56–73.
Li, C.-Q., Firouzi, A., Yang, W., 2016. Closed-form solution to first passage probability for nonstationary lognormal processes. J. Eng. Mech. 142 (12), 04016103.
Li, H., Soares, C.G., Huang, H.-Z., 2020. Reliability analysis of a floating offshore wind turbine using Bayesian Networks. Ocean. Eng. 217, 107827.
Lim, K.Y.H., Zheng, P., Chen, C.-H., 2019. A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives. J. Intell. Manuf., 1–25.
Liu, Y., et al., 2016. Developments in semi-submersible floating foundations supporting wind turbines: a comprehensive review. Renew. Sustainable Energy Rev. 60, 433–449.
Liu, G., et al., 2018. Damage detection of offshore platforms using acoustic emission analysis. Rev. Sci. Instrum. 89 (11), 115005.
Liu, H.-Y., et al., 2019a. Evaluation of the structural strength and failure for floating collar of a single-point mooring fish cage based on finite element method. Aquac. Eng. 85, 32–48.
Liu, L., et al., 2019b. Reliability analysis of blade of the offshore wind turbine supported by the floating foundation. Compos. Struct. 211, 287–300.
Liu, H., Kumar, A., Reindl, T., in WCFS2019 2020. The Dawn of Floating Solar—Technology, Benefits, and Challenges. Springer, pp. 373–383.
Livanos, G., et al., 2018. Intelligent navigation and control of a prototype Autonomous underwater vehicle for automated inspection of aquaculture net pen cages. In: in 2018 IEEE International Conference on Imaging Systems and Techniques (IST), IEEE.
Lovatelli, A., Aguilar-Manjarrez, J., Soto, D., 2013. Expanding Mariculture Farther Offshore. Technical, Environmental, Spatial and Governance Challenges. FAO Technical Workshop, Orbetello, Italy, 22-25 March 2010. FAO Library.
Lu, D., et al., 2019. A method to estimate the hydroelastic behaviour of VLFS based on multi-rigid-body dynamics and beam bending. Ships Offshore Struct. 14 (4), 354–362.
Luengo, M.M., Kolios, A., 2015. Failure mode identification and end of life scenarios of offshore wind turbines: a review. Energies 8 (8), 8339–8354.
Luque, J., Straub, D., 2016. Reliability analysis and updating of deteriorating systems with dynamic Bayesian networks. Struct. Saf. 62, 34–46.
Macchi, M., et al., 2018. Exploring the role of digital twin for asset lifecycle management. IFACPapersOnLine 51 (11), 790–795.
Maes, K., et al., 2016. Dynamic strain estimation for fatigue assessment of an offshore monopile wind turbine using filtering and modal expansion algorithms. Mech. Syst. Signal Process. 76, 592–611.
Magagna, D., et al., 2018. Workshop on identification of future emerging technologies in the ocean energy sector: JRC Conference and workshop reports. In: in JRC Conference and Workshop, European Commission* Office for Official Publications of the European Union.
Mai, C., et al., 2016. Surrogate modelling for stochastic dynamical systems by combining NARX models and polynomial chaos expansions. arXiv preprint arXiv:1604.07627.
Maini, R., 2019. Conversion of Moveable Offshore Drilling Platforms to a Wind Turbine Installation Unit, Google Patents.
Márquez, F.P.G., et al., 2016. Identification of critical components of wind turbines using FTA over the time. Renew. Energy 87, 869–883.
Martinez-Luengo, M., Shafiee, M., 2019. Guidelines and cost-benefit analysis of the structural health monitoring implementation in offshore wind turbine support structures. Energies 12 (6), 1176.
Martinez-Luengo, M., Kolios, A., Wang, L., 2016. Structural health monitoring of offshore wind turbines: a review through the Statistical Pattern Recognition Paradigm. Renew. Sustainable Energy Rev. 64, 91–105.
Mekki, K., et al., 2019. A comparative study of LPWAN technologies for large-scale IoT deployment. ICT express 5 (1), 1–7.
Melchers, R.E., 2013. Long-term corrosion of cast irons and steel in marine and atmospheric environments. Corros. Sci. 68, 186–194.
Melchers, R.E., Beck, A.T., 2018. Structural Reliability Analysis and Prediction. John Wiley & Sons.
Merino, G., et al., 2012. Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? Glob. Environ. Chang. Part A 22 (4), 795–806.
MERMAID, [cited 2020 May]; Available from: 2020. Innovative Multi-purpose Offshore Platforms: Planning, Design & Operation. http://www.vliz.be/projects/mermaidproject/.
Micone, N., De Waele, W., 2017. Evaluation of methodologies to accelerate corrosion assisted fatigue experiments. Exp. Mech. 57 (4), 547–557.
Mieloszyk, M., Ostachowicz, W., 2017. An application of Structural Health Monitoring system based on FBG sensors to offshore wind turbine support structure model. Mar. Struct. 51, 65–86.
Min, Q., et al., 2019. Machine learning based digital twin framework for production optimization in petrochemical industry. Int. J. Inf. Manage. 49, 502–519.
Mishnaevsky, L., et al., 2017. Materials for wind turbine blades: an overview. Materials 10 (11), 1285.
Mitchell, R.J., Lystad, R.P., 2019. Occupational injury and disease in the Australian aquaculture industry. Mar. Policy 99, 216–222.
Moan, T., Amdahl, J., Ersdal, G., 2019. Assessment of ship impact risk to offshore structures-New NORSOK N-003 guidelines. Mar. Struct. 63, 480–494.
Moan, T., et al., 2020. Recent advances in integrated response analysis of floating wind turbines in a reliability perspective. J. Offshore Mech. Arct. Eng. 142 (5).
Moe, H., Fredheim, A., Hopperstad, O., 2010. Structural analysis of aquaculture net cages in current. J. Fluids Struct. 26 (3), 503–516.
Moghaddam, B.T., et al., 2019. Numerical analysis of pitting corrosion fatigue in floating offshore wind turbine foundations. Procedia Struct. Integr. 17, 64–71.
Momber, A., 2016. Quantitative performance assessment of corrosion protection systems for offshore wind power transmission platforms. Renew. Energy 94, 314–327.
MONITAS. [cited 2020 August]; Available from: https://www.marin.nl/jips/monitas.

Morató, A., Sriramula, S., Krishnan, N., 2019. Kriging models for aero-elastic simulations and reliability analysis of offshore wind turbine support structures. Ships Offshore Struct. 14 (6), 545–558.
Mudge, P.J., Lank, A.M., Alleyne, D., 1997. A long range method of detection of corrosion under insulation in process pipework. J. JSNDI 46, 314–319.
Myrli, O.E., Khawaja, H., 2019. Fluid-Structure Interaction (FSI) Modelling of Aquaculture Net Cage.
Newman, J.W., 2016. System and Method for Ground Based Inspection of Wind Turbine Blades, Google Patents.
Ó'Catháin, M., et al., 2008. A modelling methodology for multi-body systems with application to wave-energy devices. Ocean. Eng. 35 (13), 1381–1387.
Ocean Hybrid Platform. 2020 [cited 2020 July]; Available from: https://www.sinnpower.com/floatingplatform.
Onoufriou, T., 1999. Reliability based inspection planning of offshore structures. Mar. Struct. 12 (7–8), 521–539.
Oparaji, U., et al., 2017. Robust artificial neural network for reliability and sensitivity analyses of complex non-linear systems. Neural Netw. 96, 80–90.
Oppedal, F., Dempster, T., Stien, L.H., 2011. Environmental drivers of Atlantic salmon behaviour in sea-cages: a review. Aquaculture 311 (1-4), 1–18.
OREDA, 2020. Onshore Reliability Data Database.
Osen, O.L., et al., 2017. A Novel Low Cost ROV for Aquaculture Application. In OCEANS 2017 - Anchorage.
Pacheco, J., et al., 2017. Wind turbine vibration based SHM system: influence of the sensors layout and noise. Procedia Eng. 199, 2160–2165.
Papandroulakis, N., et al., 2017. TROPOS, in Aquaculture Perspective of Multi-Use Sites in the Open Ocean. Springer, Cham., pp. 355–374.
Park, C., Kim, N.H., Haftka, R.T., 2015. The effect of ignoring dependence between failure modes on evaluating system reliability. Struct. Multidiscip. Optim. 52 (2), 251–268.
Peijuan, Z., et al., 2017. A new active learning method based on the learning function U of the AK-MCS reliability analysis method. Eng. Struct. 148, 185–194.
Perez, O.M., Telfer, T.C., Ross, L.G., 2005. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. Aquac. Res. 36 (10), 946–961.
Perez-Collazo, C., Greaves, D., Iglesias, G., 2018. A novel hybrid wind-wave energy converter for jacket-frame substructures. Energies 11 (3), 637.
Pirlet, H., et al., 2014. The Mermaid Project—Innovative Multi-Purpose Offshore Platforms. Flanders Marine Institute (VLIZ), Ostend, Belgium, pp. 20.
Pliego, A., de la Hermosa, R.R., Márquez, F.P.G., 2018. Big data and wind turbines maintenance management. In: Renewable Energies. Springer, pp. 111–125.
Port, G., [cited 2020 19 May]; Available from: 2020. The Offshore Port of Guyana. http://www.portdeguyane.fr/projets/port-offshore-guyane/.
Pourazarm, P., et al., 2016. Perturbation methods for the reliability analysis of wind-turbine blade failure due to flutter. J. Wind. Eng. Ind. Aerodyn. 156, 159–171.
Power, P., [cited 2020; Available from: 2020. Combining Wind and Wave Power to Meet the Energy Demands of Tomorrow. http://www.pelagicpower.no/about.html.
Ren, N., et al., 2019. Hydrodynamic analysis of a modular multi-purpose floating structure system with different outermost connector types. Ocean. Eng. 176, 158–168.
Rice, J.C., Garcia, S.M., 2011. Fisheries, food security, climate change, and biodiversity: characteristics of the sector and perspectives on emerging issues. ICES J. Mar. Sci. 68 (6), 1343–1353.
Rigs to Reefs. 2020 [cited 2020 May]; Available from: https://www.bsee.gov/what-we-do/environmental-focuses/rigs-to-reefs.
Rosebro, J., [cited 2020 May]; Available from: 2006. Fossil-Fuel Platform Runs on Renewable Energy. https://www.greencarcongress.com/2006/04/fossilfuel_plat.html.
Salic, T., et al., 2019. Control strategies for floating offshore wind turbine: challenges and trends. Electronics 8 (10), 1185.
SALMAR, [cited 2020 March 2020]; Available from: 2020. Offshore Fish Farming. https://www.salmar.no/en/offshore-fish-farming-a-new-era/.
Scheu, M.N., et al., 2017. Influence of statistical uncertainty of component reliability estimations on offshore wind farm availability. Reliab. Eng. Syst. Saf. 168, 28–39.
Schneider, R., Thöns, S., Straub, D., 2017. Reliability analysis and updating of deteriorating systems with subset simulation. Struct. Saf. 64, 20–36.
Schubel, P., et al., 2013. Review of structural health and cure monitoring techniques for large wind turbine blades. Renew. Energy 51, 113–123.
Scott, D., Muir, J., 2000. Offshore cage systems: a practical overview. In: Option Mediterraneennes-International Centre for Advanced Mediterranean Agronomic Studies., pp. 79–89.
Sedlacek, G., et al., 2012. Geotechnical stability of gravity Base foundations for offshore wind turbines on granular soils. In: in ASME 2012 31st International Conference on Ocean, Offshore and Arctic Engineering, American Society of Mechanical Engineers Digital Collection.
Shahrivar, F., Bouwkamp, J., 1986. Damage Detection in Offshore Platforms Using Vibration Information.
Shamsudin, M.Fb., 2019. Structural Health Monitoring of Fatigue Cracks Using Acoustic Emission Technique. Brunel University London.
Shell, [cited 2020 May 2020]; Available from: 2020. First LNG Cargo Shipped From Prelude FLNG. https://www.shell.com/media/news-and-media-releases/2019/first-lng-cargo-shipped-from-prelude-flng.html.
Shirangi, M.G., et al., 2020. Digital twins for drilling fluids: advances and opportunities. In: IADC/SPE International Drilling Conference and Exhibition, Society of Petroleum Engineers.
Shittu, A.A., et al., 2020. Comparative study of structural reliability assessment methods for offshore wind turbine jacket support structures. Appl. Sci. 10 (3), 860.
Silva, D., Rusu, E., Guedes Soares, C., 2018. The effect of a wave energy farm protecting an aquaculture installation. Energies 11 (8), 2109.
Sims, N.A., Key, G., 2011. Fish without Footprints. In OCEANS'11 MTS/IEEE KONA. IEEE.
Sivandran, S., [cited 2020 August]; Available from: 2015. Validating FLNG Design. https://www.engineerlive.com/content/validating-flng-design.
Soares, C.G., Parunov, J., 2019. Trends in the analysis and design of Marine structures. In: Proceedings of the 7th International Conference on Marine Structures (MARSTRUCT 2019, Dubrovnik, : CRC Press, Croatia, 6-8 May 2019).
Sørum, S.H., Krokstad, J.R., Amdahl, J., 2019. Wind-wave directional effects on fatigue of bottom-fixed offshore wind turbine. J. Phys. Conf. Ser., IOP Publishing.
Solutions, B.W., [cited 2020 19 May]; Available from: 2020. Floating Power Plant. https://www.betterworldsolutions.eu/floating-power-plant/.
Sommer, B., et al., 2019. Decommissioning of offshore oil and gas structures–Environmental opportunities and challenges. Sci. Total Environ. 658, 973–981.
Spiridonakos, M.D., Chatzi, E.N., 2015. Metamodeling of dynamic nonlinear structural systems through polynomial chaos NARX models. Comput. Struct. 157, 99–113.
Srinivasan, C., 2019. Structural Health Monitoring With Application to Offshore Structures. World Scientific.
Stamatis, D.H., 2003. Failure Mode and Effect Analysis: FMEA from Theory to Execution. Quality Press.
Steel chains. 2012 [cited 2020 March]; Available from: https://www.astm.org/Standards/steel-standards.html.
Stern, R.E., Song, J., Work, D.B., 2017. Accelerated Monte Carlo system reliability analysis through machine-learning-based surrogate models of network connectivity. Reliab. Eng. Syst. Saf. 164, 1–9.
Stewart, M.G., 2012. Spatial and time-dependent reliability modelling of corrosion damage, safety and maintenance for reinforced concrete structures. Struct. Infrastruct. Eng. 8 (6), 607–619.
Stien, L.H., et al., 2016. 'Snorkel'sea lice barrier technology reduces sea lice loads on harvest-sized Atlantic salmon with minimal welfare impacts. Aquaculture 458, 29–37.
Stopa, J.E., 2018. Wind forcing calibration and wave hindcast comparison using multiple reanalysis and merged satellite wind datasets. Ocean Model. 127, 55–69.
Su, H., Kam, T., 2020. Reliability analysis of composite wind turbine blades considering material degradation of blades. Compos. Struct. 234, 111663.
Successfully, G.I.E.C., [cited 2020 July]; Available from: 2019. Built the First Semisubmersible Open Sea Aquaculture Platform "Penghu". http://english.giec.cas.cn/ns/rp/201908/t20190809_213996.html.
Sudret, B., 2008. Analytical derivation of the outcrossing rate in time-variant reliability problems. Struct. Infrastruct. Eng. 4 (5), 353–362.
Surficial sediments of the Australian seabed. 2006 [cited 2020 May]; Available from: http://www.geosci.usyd.edu.au/users/you/auseabed/auSEABED_USIMS.html.
Tao, Q., et al., 2018. Omnidirectional Surface Vehicle for Fish Cage Inspection. in OCEANS 2018 MTS/IEEE Charleston. IEEE.
Teixeira, A.P., Guedes Soares, C., Wang, G., 2013. Probabilistic modelling of the ultimate strength of ship plates with non-uniform corrosion. J. Mar. Sci. Technol. 18 (1), 115–132.
Tethys, [cited 2020 May]; Available from: 2020. Poseidon Floating Power. https://tethys.pnnl.gov/project-sites/poseidon-floating-power-poseidon-37.
Tewolde, S., et al., 2018. Lessons learned from practical structural health monitoring of offshore wind turbine support structures in the North Sea. FINAL CONFERENCE 2018.
Thompson, D., et al., 2012. Handbook for Marine Geotechnical Engineering. NAVAL FACILITIES ENGINEERING COMMAND PORT HUENEME CA ENGINEERING SERVICE CENTER.
Tolman, H.L., et al., 2002. Development and implementation of wind-generated ocean surface wave Modelsat NCEP. Weather. Forecast. 17 (2), 311–333.
TROPOS, [cited 2020 May]; Available from: 2020. The Tropos Project. http://www.troposplatform.eu/.
Tygesen, U., et al., 2019. State-of-the-art and future directions for predictive modelling of offshore structure dynamics using machine learning. Dynamics of Civil Structures, 2. Springer, pp. 223–233.
Tziavos, N.I., et al., 2020. Structural health monitoring of grouted connections for offshore wind turbines by means of acoustic emission: an experimental study. Renew. Energy 147, 130–140.
van den Burg, S.W., et al., 2020. Governing risks of multi-use: seaweed aquaculture at offshore wind farms. Front. Mar. Sci.
Vasileiou, M., Loukogeorgaki, E., Vagiona, D.G., 2017. GIS-based multi-criteria decision analysis for site selection of hybrid offshore wind and wave energy systems in Greece. Renewable Sustainable Energy Rev. 73, 745–757.
Verfuss, U.K., et al., 2019. A review of unmanned vehicles for the detection and monitoring of marine fauna. Mar. Pollut. Bull. 140, 17–29.
Veritas, D.N., Det Norske Veritas 2004. DNV-OS-J101-Design Of Offshore Wind Turbine Structures.
Veritas, D.N., 2010. Recommended Practice DNV-RP-C205: Environmental Conditions and Environmental Loads. DNV, Norway.
Veritas, D.N., SE, G.L., 2015. DNVGL-RP-C210: Probabilistic Methods for Planning of Inspection for Fatigue Cracks in Offshore Structures. Det Norske Veritas & Germanischer Lloyd SE, Oslo, Norway.
Wanasinghe, T.R., et al., 2020. Digital Twin for the Oil and Gas Industry: Overview, Research Trends, Opportunities, and Challenges. IEEE Access.

Wandji, W.N., Natarajan, A., Dimitrov, N., 2016. Development and design of a semi-floater substructure for multi-megawatt wind turbines at 50+ m water depths. Ocean. Eng. 125, 226–237.
Wang, C.M., Tay, Z., 2011. Very large floating structures: applications, research and development. Procedia Eng. 14, 62–72.
Wang, C.M., Wang, B.T., 2015. Large floating structures. In: Ocean Engineering & Oceanography. Springer, pp. 3.
Wang, X., et al., 2018. A review on recent advancements of substructures for offshore wind turbines. Energy Convers. Manage. 158, 103–119.
Wang, J., et al., 2019. Digital Twin for rotating machinery fault diagnosis in smart manufacturing. Int. J. Prod. Res. 57 (12), 3920–3934.
Wang, K., Zhao, M.-j., 2016. Mathematical model of homogeneous corrosion of steel pipe pile foundation for offshore wind turbines and corrosive action. Adv. Mater. Sci. Eng. 2016.
Wei, K., Arwade, S.R., Myers, A.T., 2014. Incremental wind-wave analysis of the structural capacity of offshore wind turbine support structures under extreme loading. Eng. Struct. 79, 58–69.
Wei, W., et al., 2017. A discrete-modules-based frequency domain hydroelasticity method for floating structures in inhomogeneous sea conditions. J. Fluids Struct. 74, 321–339.
Weiss, C.V., et al., 2018. Co-location opportunities for renewable energies and aquaculture facilities in the Canary Archipelago. Ocean Coast. Manag. 166, 62–71.
Welcome to BMT Deep. 2020 [cited 2020 August]; Available from: https://www.bmt.org/deep/default.aspx.
Wen, B., et al., 2018. The power performance of an offshore floating wind turbine in platform pitching motion. Energy 154, 508–521.
Whiteway, T., Geoscience Australia, Canberra 2009. Australian Bathymetry and Topography Grid.
Worden, K., et al., 2015. Structural health monitoring: from structures to systems-of-systems. IFACpapersonline 48 (21), 1–17.
Worden, K., et al., 2018. On the confidence bounds of Gaussian process NARX models and their higher-order frequency response functions. Mech. Syst. Signal Process. 104, 188–223.
World's largest floating LNG factory remains in shutdown — at just three years old. 2020 [cited 2020 August]; Available from: https://mobile.abc.net.au/news/2020-08-21/worlds-largest-floating-lng-factory-remains-in-shutdown/12565490.
World-first as Grieg installs renewables at salmon farm. 2020 [cited 2020 August]; Available from: https://www.fishfarmingexpert.com/article/world-first-for-grieg-as-it-installs-renewable-power-at-salmon-farm/.
Wu, X., et al., 2019. Foundations of offshore wind turbines: a review. Renewable Sustainable Energy Rev. 104, 379–393.
Xiao, N.-C., Zuo, M.J., Zhou, C., 2018. A new adaptive sequential sampling method to construct surrogate models for efficient reliability analysis. Reliab. Eng. Syst. Saf. 169, 330–338.
Xiao, L., et al., 2019. Long-term predictive opportunistic replacement optimisation for a small multi-component system using partial condition monitoring data to date. Int. J. Prod. Res., 1–18.
Xu, H., Gardoni, P., 2020a. Multi-level, multi-variate, non-stationary, random field modeling and fragility analysis of engineering systems. Struct. Saf. 87, 101999.
Xu, H., Gardoni, P., 2020b. Conditional formulation for the calibration of multi-level random fields with incomplete data. Reliab. Eng. Syst. Saf., 107121.
Yang, X., Utne, I.B., Holmen, I.M., 2020. Methodology for hazard identification in aquaculture operations (MHIAO). Saf. Sci. 121, 430–450.
Yeter, B., Garbatov, Y., Guedes Soares, C., 2016. Reliability of offshore wind turbine support structures subjected to extreme wave-induced loads and defects. In: ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering, American Society of Mechanical Engineers Digital Collection.
Yeter, B., Garbatov, Y., Soares, C.G., 2019. Uncertainty analysis of soil-pile interactions of monopile offshore wind turbine support structures. Appl. Ocean. Res. 82, 74–88.
Yu, Z., et al., 2019. Numerical analysis of local and global responses of an offshore fish farm subjected to ship impacts. Ocean. Eng. 194, 106653.
Yuan, K., et al., 2020. System reliability analysis by combining structure function and active learning kriging model. Reliab. Eng. Syst. Saf. 195, 106734.
Zeng, W.-J., et al., 2012. Robotics VisionBased system of autonomous underwater vehicle for an underwater pipeline tracker. J. Shanghai Jiaotong Univ. 46 (2), 178–183, + 189.
Zhang, C., 2018. Reliability-based Fatigue Damage Assessment and Optimum Maintenance Strategy of Offshore Horizontal Wind Turbine Blades. University of Greenwich.
Zhang, T.-d., et al., 2012. Vision-based system of AUV for an underwater pipeline tracker. China Ocean. Eng. 26 (3), 547–554.
Zhang, H., et al., 2017. A digital twin-based approach for designing and multi-objective optimization of hollow glass production line. IEEE Access 5, 26901–26911.
Zhang, X., et al., 2018. The maximum wave energy conversion by two interconnected floaters: effects of structural flexibility. Appl. Ocean. Res. 71, 34–47.
Zhang, X., et al., 2019a. Numerical investigation of the dynamic response and power capture performance of a VLFS with a wave energy conversion unit. Eng. Struct. 195, 62–83.
Zhang, C., et al., 2019b. Experimental and numerical study on the resonance in the narrow gap between a simplified floating hydrocarbon storage tank system. In: in The 29th International Ocean and Polar Engineering Conference, International Society of Offshore and Polar Engineers.
Zhang, J., et al., 2019c. A combined projection-outline-based active learning Kriging and adaptive importance sampling method for hybrid reliability analysis with small failure probabilities. Comput. Methods Appl. Mech. Eng. 344, 13–33.
Zhao, Y.-P., et al., 2019a. Deformation and stress distribution of floating collar of net cage in steady current. Ships Offshore Struct. 14 (4), 371–383.
Zhao, H., et al., 2019b. An optimization method for stiffness configuration of flexible connectors for multi-modular floating systems. Ocean. Eng. 181, 134–144.
Zheng, X.Y., Lei, Y., 2018. Stochastic response analysis for a floating offshore wind turbine integrated with a steel fish farming cage. Appl. Sci. 8 (8), 1229.
Zheng, X., et al., 2020. An offshore floating wind–solar–aquaculture system: concept design and extreme response in survival conditions. Energies 13 (3), 604.
Zhu, X., Lu, Z., Yun, W., 2020. An efficient method for estimating failure probability of the structure with multiple implicit failure domains by combining Meta-IS with IS-AK. Reliab. Eng. Syst. Saf. 193, 106644.
Ziegler, L., et al., 2019. Structural monitoring for lifetime extension of offshore wind monopiles: verification of strain-based load extrapolation algorithm. Mar. Struct. 66, 154–163.
Zve, E.S., Loukogeorgaki, E., Angelides, D.C., 2015. Effect of zoning corrosion on the life-time structural reliability of a jacket offshore structure. In: in The Twenty-Fifth International Ocean and Polar Engineering Conference, International Society of Offshore and Polar Engineers.