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ON COMMON RESEARCH NEEDS FOR THE NEXT GENERATION OF FLOATING SUPPORT STRUCTURES

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ABSTRACT

The world is facing several industrial and societal challenges, such as providing enough renewable energy and enough safe and healthy food as formulated in the United Nations sustainable development goals. Using floating stationary structures, the ocean can contribute to solving several of the challenges. New applications need new types of structures, with which we have limited experience. These support structures will be diverse, but also have essential research needs in common.

Design of novel floating structures need reliable descriptions of the marine environment. This is particularly challenging for semi-sheltered coastal regions, with complex topography and bathymetry. Novel structures are likely to be compliant, modular and/or multi-body, requiring increased understanding and rational models for wave-structure interaction. Structures with sustainable, safe, and cost-efficient use of materials, including untraditional ones, must be developed. Smart, affordable, and reliable mooring systems and anchors for novel applications are necessary for station keeping. Digital solutions connecting the various stages of design and operation, as well as various design disciplines, researchers, and innovators, will be necessary. Sustainability will be an integral part of any new design.

To unlock the potential of novel floating structures, we need to understand the requirements of the applications, as well as the associated technology gaps and knowledge and research needs. This paper highlights research needs for innovation within floating offshore wind, floating solar power plants, novel aquaculture structures, and coastal infrastructure.

Keywords: floating support structures, offshore wind, floating solar, aquaculture, coastal infrastructure

1. INTRODUCTION

The ocean can contribute with solutions to several global challenges, as highlighted for instance by the UN High Level Panel for A Sustainable Ocean Economy [1]. The transition to zero emission societies demands a dramatic shift from fossil energy sources to renewable energy. Wind and solar energy are predicted to have largest growth in production and to be the largest sources of renewable energy in the future [2]. This growth will happen both on land and in the ocean. The ocean has the potential to host massive upscaling of wind and solar energy due to the natural resources and the large areas available for development. Further, the ocean provides food through capture of wild fish as well as through farming. The potential for increased food production is largest for fish farming [3]. With a large portion of the global population living close to the coast, resilient and robust solutions for infrastructure and urban development are needed.

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FIGURE 1: ILLUSTRATION OF SEVAN SSP'S CONCEPT FOR FLOATING OFFSHORE WIND. CREDIT: SEVAN SSP

Floating support structures will be important for realization of the ocean´s potential to solve global challenges. Such structures will be varied, and they will bring new needs in terms of function, costs (capital and operational expenditures, environmental and societal), safety, operability, and sustainability. To contribute significantly, these developments must be of sufficient scale – requiring large areas. This will call for technological development, but also for development of policies and ocean management. The consequences for nature and environment need to be understood to create low-impact solutions. Sustainability will be a prerequisite. Several industries (for instance wild capture fisheries and energy production) will prefer the same areas and coexistence will be required.

In order to address the above, SINTEF, NTNU, NGI, and MET Norway, with industry partners, have established a centre for research-based innovation focusing on floating structures for the next generation of ocean industries, SFI BLUES. The centre comprises ten industry partners and five research partners. The industry partners represent end users, engineering companies and technology providers. The research partners have strong competence within hydrodynamics, structures, materials, geotechnics and metocean. The centre is funded by the Research Council of Norway and the partners and has funding for 8 years, starting from 2021.

In this paper we present the background and motivation for the research centre SFI BLUES. We first outline the potential for floating structures for applications within energy, food, and coastal infrastructure. Within energy, we focus on floating offshore wind and floating solar. Ocean based food production will mainly be centred around farming of salmon. Coastal infrastructure encompasses floating bridges or submerged floating tube bridges, as well as floating structures for development of residential or industrial areas. For each application we highlight the status of industrial development, the technical potential, as well as the main marine technological research needs. Common areas of research across applications are then discussed.

2. TECHNICAL POTENTIAL AND INDUSTRIAL STATUS

2.1 Floating wind turbines

According to the International Energy Agency, offshore wind turbines can potentially deliver 18 times the world's energy consumption [4] (2018 values). However, 80 % of the global offshore wind resources are in areas with water depths larger than 60 m. These are areas where bottom-fixed wind turbines become economically or technically infeasible. European ambitions for offshore wind are 450 GW in 2050, whereof between 100 and 150 GW are likely to be floating turbines [5] (an example of a floating wind turbine is shown in Fig. 1). Assuming a turbine size of 15 MW this corresponds to up to 10 000 floating wind turbines in European waters alone in 2050. Development plans outside Europe comes in addition. The potential and the ambitions for floating offshore wind are massive, but floating wind is still an emerging technology.

The first full-scale floating wind turbine (FWT), Hywind Demo (now Unitech Zefyros), was deployed outside of Karmøy at METCentre, Norway, in 2009. Since then, a handful of other full-scale demonstrators have been successfully installed around the world, including Portugal, Japan, and France. Floating wind is now at a precommercial stage and the first full-scale floating wind pilot farm, Hywind Scotland, was commissioned in 2017 with five spar floating wind units, and more pilot parks have recently been installed or are under construction (e.g., WindFloat Atlantic, Kincardine and Hywind Tampen). All the above concepts are based on single-unit, traditional horizontal-axis wind turbines with capacity ranging from 2 to 9.5 MW. Larger turbines are believed to contribute to cost reductions and a publicly available 15 MW reference turbine was recently made

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available by IEA [6]. The Flagship project, funded by Horizon 2020, will develop and demonstrate a floating 10 MW semi-submersible wind turbine also at the METCentre, off the West coast of Norway [7]. Even if most of the more mature concepts are spar-type substructures or semi-submersibles, other floating substructures are also being developed, such as various barges and TLPs. Turbine concepts include multi-rotor wind turbines or vertical-axis wind turbines.

Existing floating wind turbines have individual mooring systems, typically with three mooring lines and three anchors each. Such solutions do not scale well with the large number of planned FWTs. There are therefore efforts in reducing the number off mooring lines and anchors per FWT. At Hywind Tampen, up to three mooring lines will share anchors, reducing the number of anchors to 19 for 11 FWTs. Mooring concepts for shared mooring lines are also under development, see e.g. [8].

2.2 Floating solar

Solar energy has been predicted to have a share equal to wind energy in a future energy mix [2]. Most of this will be land-based, but energy production from floating photovoltaic (FPV) structures has gained increasing interest over the past years and this industry is growing rapidly [9]. There are several advantages of FPV compared to land-based PV. Terrestrial areas are in many places scarce resources; placing solar panels on floating support structures eliminates the need for valuable land area. It is also a promising way to optimise the utilization of marine space in combination with offshore wind and can contribute to mitigate the effects of wind variability on power output [10]. Proximity to consumers of electricity is another important advantage. According to the United Nations, about 40 % of the world's population live less than 100 km from the coast. Floating PV structures enable energy production close to consumers without the need for long transmission lines. An additional benefit is that the photovoltaic performance is enhanced due to cooling effect of the water [11].

FPV structures are being developed in several parts of the world, and such installations are now in operation worldwide, mainly in Asia, but even in a high-latitude country such as Norway. Most FPV systems are located in inland water bodies such as lakes and reservoirs, but nearshore areas are also being developed. The installed capacity of floating photovoltaics worldwide was 1.3 GWp[1] per December 2018. The global potential for FPV in man-made dams and reservoirs is about 400 GWp, assuming that 1 % of the area of such water bodies are covered [9]. The technical potential for nearshore and offshore areas is obviously a lot larger. A first estimate of possible areas world-wide is presented in [12].

The exploitation of floating PV in nearshore and offshore areas will depend on cost-efficient designs capable of surviving in waves. Most of today's technology is developed for inland water bodies. These structures are often modular systems based on buoyancy elements made from plastic materials and moored to the shore or with quite simple mooring arrangements. Technology for more exposed environments have been under development for some years. Two main trends are seen with respect to support structures. Figure 2 shows an example of a structure based on a floating collar from aquaculture, equipped with a membrane supporting the PV panels. Similar concepts based on multiple floating collars have also been studied [12]. Other concepts for exposed FPV are based on modularity, with several rigid body buoyancy elements interconnected, see Fig. 3.

FIGURE 2: ILLUSTRATION OF OCEAN SUN'S FLOATING PV STRUCTURE. CREDIT: OCEAN SUN

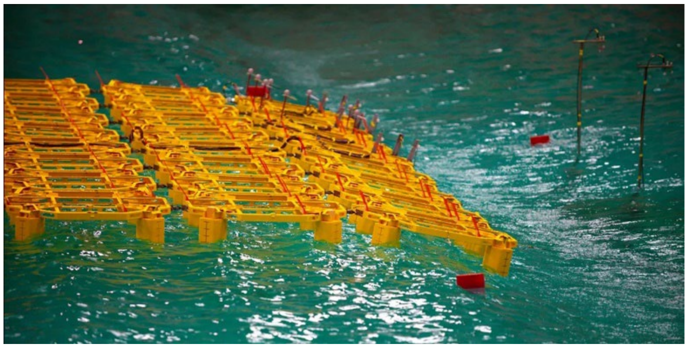

FIGURE 3: FLOATING PV STRUCTURE FROM MOSS MARITIME TESTED AT SINTEF OCEAN. CREDIT: MOSS MARITIME / SINTEF OCEAN.

2.3 Ocean-based aquaculture

The World Resource Institute [13] points out three main challenges in order to feed the world's population in 2050: to produce enough food (the food gap), to have enough area to produce food (the land gap) and to reduce greenhouse gas (GHG) emissions (the GHG gap). Aquaculture of finfish is likely to be one of the solutions to close these gaps [3]. As an example, offshore farming of Atlantic salmon in Norway has been estimated to have a growth potential from almost zero in 2020 to an annual production between 500.000 and 1.800.000 tonnes in

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[1] GWp = Gigawatt at peak power

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2050 [14]. This is equivalent to the production from between 75 and 270 copies of the Ocean Farm 1.

Open net-based cages with circular polyethylene (PE) or rectangular steel floating collars, are the most common structures for cultivation of finfish such as salmonoids, carps, and tilapia. A typical fish farm consists of several cages moored to a subsea mooring frame through mooring lines attached to mooring buoys (for PE cages) or directly to the floating collar (for steel cages). The mooring lines are composed of fibre ropes and steel chains and fixed to the seabed with drag-embedded or gravity anchors. The nets are often made of nylon. Open net cages have been under constant development since the 1970s and have proven to be reliable and cost-efficient structures. However, aquaculture faces several challenges, such as diseases and parasites, operations at exposed locations, personnel safety, and escapees [15]. In 2015, the Norwegian government introduced a financial instrument (development licenses) to motivate the industry to develop new technological solutions to these challenges. As result of this, a wide variety of structural concepts have been presented over the past years. The concepts follow two main development trends: structures for closed containment aquaculture and structures for aquaculture in exposed areas. These development trends can contribute to more sustainable growth of aquaculture, by enabling new areas for farming, as well as more controlled production environments. The concepts range from closed and semi-closed structures to rigid net-based offshore structures, such as semi-submersibles (Fig. 4), turret moored ship-like structures, and TLPs and explore a wide range of materials (steel, concrete, polyethylene, fibre-reinforced plastic). Several concepts are currently being realized, while others are still at earlier stages of development. A thorough review of aquaculture structures is given in [16].

FIGURE 4: ARCTIC OFFSHORE FARMING IN ELEVATED POSITION. CREDIT: AKER SOLUTIONS.

2.4 Coastal infrastructure and floating urban areas

Floating structures have been suggested for various coastal and nearshore industrial and residential applications as alternatives to land reclamation. Floating bridges and submerged tunnels are of particularly high interest in Norway, due to the development of the coastal highway. In this public development project, several bridges and submerged tunnels may be constructed as alternatives to ferries and thereby keep the highway open for traffic around the clock all the year round. Some of the fjord crossings are so wide and deep that the only technically and economically feasible solutions will be floating bridges or submerged floating tunnels. Modern floating bridges have existed since the 1940s, but there is limited experience with long bridges in exposed environments [17]. There are four long floating bridges in the state of Washington and two in Norway, the latter two are about 1 km long and both were built in the early 1990s. Current development headed by The Norwegian Public Road Administration focuses on the following floating concepts for crossings of up to 5 km in relatively exposed environments:

- curved end-anchored bridges, see Fig. 5 for an example (the Norwegian bridges are of this type),
- straight side-anchored bridges (the bridges in Washington are of this type)
- suspension bridges with towers on floating support structures (TLP-type or spar structures), and
- submerged floating tube bridges (SFTB) supported by either tension legs or by pontoons, which represent an alternative to floating bridges.

No SFTB has yet been built, but such concepts have been evaluated for Høgsfjorden in Norway, as well as the straits of Gibraltar and Messina.

FIGURE 5: ILLUSTRATION OF CURVED FLOATING BRIDGE FOR BJØRNAFJORDEN, NORWAY. CREDIT: NORWEGIAN PUBLIC ROADS ADMINISTRATION.

Floating harbours, urban, industrial, and recreational areas are receiving increasing interest among city planners and developers. The coasts are being influenced by climate change and a very large portion of the world's population lives close to the sea. Floating coastal structures represent attractive alternatives to area usage on land and to land reclamation at sea, with low environmental impact. In Singapore, concepts for large, modular, multi-purpose floating structures to utilise sea space for urban functions and make scarce land resources available for other usage have been developed [18] (see Fig. 6 for an example). Similar concepts have also been developed in the European research project Space@Sea [19]. Possible applications for floating multi-purpose structures range from residential areas to ports and refuelling stations for ships.

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Floating airports were extensively studied in relation to the Megafloat project in Tokyo in the 1990s. Floating cruise terminals have been suggested in for instance Korea and The Netherlands. Temporary and permanent floating harbours exist several places in the world, and floating docks are being considered for assembly of floating wind turbines. For a more in depth review of very large floating structures, see [20]. Floating urban development and floating architecture is becoming more and more common and involves both permanently floating buildings and amphibious buildings [21].

FIGURE 6: MODEL TESTING OF A FLOATING STORAGE FACILITY FOR USE IN SINGAPORE. CREDIT: SINTEF OCEAN

3. BRIEF OVERVIEW OF RESEARCH NEEDS PER APPLICATION

3.1 Floating wind turbines

Although aero-hydro-servo-elastic numerical models have enabled significant industrial developments within floating wind, there remain gaps. For example, existing concepts generally have a large displaced volume to payload mass ratio. There are attempts to reduce the mass (and cost) of the steel/concrete floaters. Combining lighter and more efficient substructures with increasing wind turbine size will result in flexible structures with dynamic responses over a wide range of frequencies. The rotor (1P) and blade passing (3P) frequencies have typically dictated the design of the tower. Placing the tower frequency in between these ranges, is known as soft-stiff design. For 10 MW floating turbines, there are already proposals for stiff-stiff tower designs – that is, the tower natural frequency is above the 3P range. For such designs, elasticity in the floater (not just in the tower and rotor) and aerodynamic loads at 6P emerge as important considerations. Furthermore, accurate estimates of structural and hydrodynamic damping, as well as load mitigation through passive or active mechanisms, become critical for design.

For hydrodynamics, engineering models based on first and second order potential flow theory, which are widely used, are known to underestimate low-frequency wave-induced responses of semi-submersible floaters based on model scale experiments [22]. Better estimates of hydrodynamic excitation and damping, require further investigation of local flow details, especially around components such as heave plates, in the complex stochastic marine environment [23]. Finally, established mooring systems from offshore technology are being challenged in water depths shallower than 80-100 m [24]. Novel mooring system configurations and/or alternative materials such as synthetic fibre ropes, can be remedies in shallow water. The durability of synthetic fibre ropes is uncertain and qualification for long-term application is needed. Novel anchors, shared anchors or even array mooring systems can enable novel mooring configurations and reduce installation costs of the turbine system [8,25]. Integrated design tools (aero-hydro-servo-structure-soil) are necessary for evaluating the complex load scenarios shared anchors will experience. A multidisciplinary approach to design optimization can lead to innovative designs and subsequent cost reductions [26].

3.2 Floating solar

Although present FPV technology can be adapted to nearshore areas with low sea states, it is likely that FPV structures for more exposed areas will have to adapt other technology. Ocean Sun's FPV structure (illustrated in Fig. 2) is inspired by aquaculture structures and exploits the benefit of an elastic floating collar following the waves. A membrane supports the solar panels. Similar concepts have been investigated by using air-cushion as support for the solar panels [27], or several concentric elastic tori supporting an elastic porous membrane deck [28]. Modular concepts are based on rigid decks supported by pontoons, connected to form large arrays. There are several hydrodynamic challenges related to FPV concepts for more exposed wave conditions, such as hydrodynamic interaction between (elastic) bodies, membrane structures in waves and nonlinear response of floating elastic collars. Analytical, numerical, and experimental work are needed. The lack of knowledge on very compliant and modular structures implies that current design tools are inadequate and need to be improved. Another feature of floating solar structures is their large surface area and spatial variation and correlation of wind, waves and current may be important for calculation of loads and responses. Design and material choice for reliable connections between modules is a major challenge. Durability of materials may be challenging, corrosion and fatigue for steels and aluminium, and marine ageing for polymers and composites. Mass production or module production is another important aspect, and the manufacturing process will be important for the product, cost, and sustainability.

3.3 Ocean-based aquaculture

The hydrodynamic behaviour of open net-based cages is reasonably well understood [29]. Common for the newly developed concepts is the lack of background experience, and a need for adequate design tools and design methods to achieve safe and reliable structures. As an example, several new concepts are combinations of large volume structures and nets. For traditional large-volume structures, viscous damping is highly important for extreme mooring loads, but for these new concepts, the viscous loads on nets may be important for the wave

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excitation and may not only be regarded as (beneficial) damping. Another example is closed containment solutions, where sloshing and hydroelasticity often will be significant physical effects. Experimental, theoretical, and numerical work is necessary to develop physical understanding. Rational models and their implementation in simulation tools are necessary to ensure safe design. Reliability of connection points between membranes and other structural members, and failure mechanisms of membrane structures submitted to high loads are material-related challenges for closed containment systems. New concepts are developed for both true offshore locations and for coastal or sheltered areas. Improved metocean hindcast archives for coastal areas will improve the quality of metocean design basis, and thereby reduce uncertainty in the design of new aquaculture structures. Like floating PV structures, many aquaculture structures cover large surface areas and the spatial inhomogeneity and correlation of waves, wind and current can be of importance. There are several recent occurrences of anchor dragging, caused by a combination of limited or lacking geotechnical surveys, limited bollard pull of installation vessels and steep lines due to restrictions in the horizontal extent of the farms. Low-cost geotechnical surveys and efficient use of survey data can reduce the uncertainty in site characterization. Anchor models for use in design tools can reduce the number of such events, and potentially reduce the need for model- and full-scale testing of new anchor concepts.

3.4 Coastal infrastructure and floating urban areas

Although floating structures for coastal applications will be diverse, some common challenges can be identified. Most coastal structures will cover a significant water surface area and their deformations must be accounted for in global analysis. This is the case for both modular structures and for structures which will respond elastically to waves. For connected modular structures with gaps, gap resonances will occur. Potential flow theory largely overpredicts the loads and responses, since damping due to flow separation from the bilges often will dominate. General challenges concerning nonlinear wave loads on large volume structures will be highly relevant. This includes wave drift forces, wave-current interaction, and viscous effects. Shallow water and uneven bathymetry will influence wave actions and be challenging for mooring design, and anchors must be designed to sustain near shore geohazard. Safe design of coastal structures requires adequate description of wind, waves, and current, and spatial variation of metocean conditions can be important due to the size of the structures.

Current design tools for global analysis are good starting points but need to be improved. Design practice is limited due to large variations in types of structures. The service life of these structures will in many cases be very long and the safety level must be high due to public use. Durability is an issue, with corrosion and fatigue as a concern for steels (including mooring lines), as well as deterioration and corrosion of reinforcement in concrete. The bathymetry and soil properties can change over time due to environmental or mechanical erosion and influence the holding capacity of anchors. Development of smart monitoring and digital twin systems will ensure that anchor, mooring lines, and structures remain safe throughout their lifetime.

4. DISCUSSION

4.1 Societal and environmental impact

Large scale exploitation of the ocean for energy production, food production and infrastructure will require a lot of space, not only at the ocean surface, but also in the water column and at the seabed. To obtain license to operate, it is crucial to understand how various technological solutions impact the society (such as other concerned parties), as well as the nature and the environment, both in positive and adverse ways. Even if there are vast areas in the ocean, several parties will be interested in the same areas, for instance due to natural resources or due to proximity to infrastructure. Future large-scale developments of floating structures should therefore plan for coexistence and co-use. This may include sharing of infrastructure, such as power supply, service vessels, and supply bases, as well as design of structures which allow for other use of the same area (for instance mooring systems which allow for wild fish capture nearby).

There are global ambitions of protecting 30% of the oceans to reduce the loss of biodiversity. However, the impact of marine structures on habitats must also be understood. Such impacts be from the operations associated with the structure (such as waste from aquaculture), but also from the structures themselves. Some examples of the latter are:

- Reduced access to sun light below large structures.
- Wear and tear of materials and discharge of particles to water.
- Choice of mooring configurations and consequences for marine life in the water column and at the seabed.
- Some marine structures may potentially contribute to increased biodiversity by acting as artificial reefs.

It will be important to develop methods to assess both societal and environmental impacts of new developments at an early stage, to be able to minimize adverse effects and maximize potential positive effects.

4.2 Marine environment

Accurate descriptions of marine environment, especially wind, waves and current are necessary for safe and rational design and operation of novel floating structures. Novel coastal structures will have a horizontal extent and a lifetime that makes it necessary to take spatial variations as well as possible future changes into account. To reduce the threshold for designing new large structures in a reliable manner and at an appropriate safety level, knowledge of this variability should be available at an early stage of the design process. There is a need to calculate design actions for new structures and in new locations in a safe, optimal and efficient manner based on hindcast data sets considering wave conditions based on frequency-directional wave spectra, and with as few location-specific measurement

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campaigns as possible. There is also a need for cost-effective methods for seabed characterization.

Not only is it necessary to be able to describe the marine environment in complex environments, efficient and accurate numerical and experimental reconstruction is also essential. This calls for numerical wave tanks of varying fidelity, as well as experimental methods for wave generation and absorption in wave basins/tanks.

4.3 Loads and responses

With the developing demand for clean energy one challenge is up-scaling and cost efficiency. For floating wind this may require more efficient mooring and anchor configurations. This in turn implies that load and response analyses grow in complexity as one turbine may be interconnected with other structures. A consequence of this is that analysis tools also must adapt in order to provide a more efficient analysis of the global system effects. Sufficient fidelity at acceptable computational costs are key elements in this respect.

In addition to upscaling of offshore floating wind, we observe an increasing interest for other energy sources harvested at sea. Floating PV is one such example. The PV floaters varies wildly in concept, spanning from modular structures to membrane structures. This implies highly flexible, compliant, and interconnected structures, which complicates the response analysis. This implies that the load-response may be both hydroelastic, as for membranes, and driven by hydro-structure interaction, as between two connected modules. For most of these structures, the full physics of the hydro structure interaction is not fully understood, and analysis tools have not caught up with the concept, and the need for development is pressing.

Another element with regards to modular structures is that they are expected to be large. This implies a potential complex systems response. Yet more, being spatially large, the environmental loads may also be inhomogeneous, implying that sea states, wind and current may vary spatially. This especially applies to coastal structures such where effects from shore and bathymetry become important, e.g. as investigated for long floating bridges [30]. The importance of nonhomogeneous environmental loads is expected to be even more important for large systems of modular structures (floating PV, floating and modular terminals etc).

4.4 Mooring and anchors

The mooring and anchor solutions available today have to a large extent been developed for floating oil and gas structures. The novel floating structures discussed above will bring new challenges to the mooring and anchor system, driven by the operating requirements of the structures, the load regimes generated by the novel structures itself, the new environmental conditions for example near shore and in shallow water, and the need for cost optimization of the structures. To meet these challenges, there is a need to improve fundamental physical understanding of the mechanism involved and to develop numerical tools for the industry to innovate and optimize both the complete structural system, as well as the individual components of mooring and anchor systems.

The need for improved understanding of the physics is mainly linked to new operating conditions and more complex load regimes. Mooring line erosion around the anchors and multi-directional loading applied to shared anchors represent problems yet to be fully understood. Available integrated tools for global analysis of floating structures are continuously improved but lack reliable models of anchors. Other more dedicated numerical tools for analysing anchor installation and failure, has the potential of supporting concept development of anchors, and partly substitute costly physical testing. Coastal infrastructure in the nearshore environment such as floating bridges, will be exposed to risk of near shore geohazards such as submarine slides and tsunamis. For these structures, reliable live monitoring of the anchoring system will improve the robustness throughout the lifetime. Firm strategies for anchor monitoring and remote evaluation of anchor integrity are currently missing.

The large number of floating structures, mooring lines and anchors will require cost efficient solutions, such as mooring systems which reduce the material usage for mooring lines and anchors, and methods for geotechnical surveys over large areas with varying seabed conditions.

4.5 Materials and connections

Evaluation of mechanical properties of materials and components to provide designers with the most reliable data is crucial. How to obtain such properties is well known for metallic materials and concrete, but more challenging for polymers and composites. The constitutive models used in finite element analysis have also increased complexity, and subsequent, experimental calibration is fundamental to get the right parameters. Modularity and mass production are two important features of next generation marine structures. It is thus important to consider manufacturing technology during the design phase along with the choice of materials to optimise production costs. It is crucial to have a good overview of manufacturing techniques to suggest adapted material solutions. Next generation structures will have new requirements in terms of functionalities, thus requiring multi-material expertise. Numerical tools and adapted constitutive models have a key role in multi-material design. Low carbon footprint of materials must be ensured through sustainability and recyclability.

Another key enabler to allow multi-material solutions is to provide robust joining methodologies to the designers. Three multi-material combinations categories are found to be relevant to investigate, each associated with different research challenges:

Aluminium to steel (steel-steel) connections: A major problem when connecting stainless steel to aluminium, particularly when using mechanical connections, is the degradation of the aluminium components and their loss of mechanical properties due to galvanic corrosion. Throughout decades, standards, guidelines, and methods have been defined to avoid the problem, like e.g., electrical isolation of the steel and the aluminium. However, experience has shown that such expensive solutions are not especially reliable and do often fail.

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Robust multi-material joint solutions to connect rigid modules. It is a challenge to design such joints which couple modules in a modular floating construction. They are made of different material combinations (metallic and polymers) and are often the weak points of the modular concepts. The connection must transfer motions in certain degrees of freedom to allow flexibility between modules and must remain robust and durable.

Connections between soft materials (such as membrane and nets) and stiff ones (typically metallic components). This is another important combination that brings a lot of challenges in understanding the stress distribution in the softer material during dynamic loads. It is critical to understand what the failure modes of such connections are and define simplified but accurate methodologies to take them into account in global analyses.

4.6 Design and optimization

Improved analysis tools – based on filling the previously identified knowledge gaps – need to be linked to design. An important step in designing novel floating structures for new application areas is to identify performance criteria which specify what would be considered the “best” design. A quantifiable definition of “best” can be used as the objective function in a multidisciplinary design optimization (MDO). While the objectives for traditional design may have focused on economic costs (CAPEX and OPEX), function, performance and safety, there is a need to expand the optimization problem formulation to account for environmental costs and sustainability considerations. Installation and sustainability considerations have traditionally been ignored in design optimization studies within marine technology.

Having mathematically defined objectives, design variables, and constraints, existing MDO techniques can allow us to examine the trade-offs between different objectives and identify more optimal designs. The numerical tools for different disciplines such as structures, hydrodynamics, aerodynamics, mooring systems and control need to be implemented in MDO frameworks – including the computation of derivatives if gradient-based optimization techniques are to be used. The stochastic, dynamic nature of the responses of marine structures requires particular consideration in the optimization, and the realm of applicability of applied numerical models must be checked. Furthermore, there are unanswered questions regarding the level of fidelity required for accurate optimization.

MDO remains under-utilized within marine technology, although optimization of individual FWTs is gaining traction. The real strength of optimization is expected to relate to the cases where there is tight coupling between discipline, for example when hydroelasticity becomes important, there are potential gains by increasing stiffness or mass in certain components or regions and modifying the resulting hydrodynamic loads. For connected modular structures, reliability is expected to be a key issue, and optimizing the reliability of the system as a whole may differ significantly from the problem of a single component.

4.7 Digitalization

Digitalization is a very broad topic, here we focus on simulation tools in combination with measurements and their role in design of novel floating structures. Numerical models are extensively being used in design of floating structures, often in combination with model tests, where the numerical models are calibrated towards experimental data to compensate for physical effects (such as nonlinear or viscous hydrodynamic effects) which are inadequately modelled in engineering tools. However, the numerical models are often abandoned after the design process. The same numerical models can be brought into the operational phase of the structure, where they can be used as digital twins, and provide support for integrity assessments and operational decisions. Moreover, the numerical models should be designed to learn from operational measurements, both for improved performance of digital twins, but also as feedback to new designs.

Multidisciplinary challenges require collaboration, also between numerical tools and various sources of data. Open interfaces, standards and common data descriptions are needed to enable various numerical tools and sources of data to connect and interact. Initiatives such as Open Simulation Platform [31] and READI [32] are examples of frameworks for digital collaboration which may be pursued for floating support structures.

5. CONCLUDING REMARKS

Common research needs for novel floating support structures have been discussed. Applications include floating offshore wind, floating solar, ocean-based aquaculture and coastal infrastructure and we have highlighted research topics where progress may benefit all or several of these applications. The paper forms the background and motivation for the research centre SFI BLUES and several of the challenges discussed here will be addressed in the research plans of the centre.

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