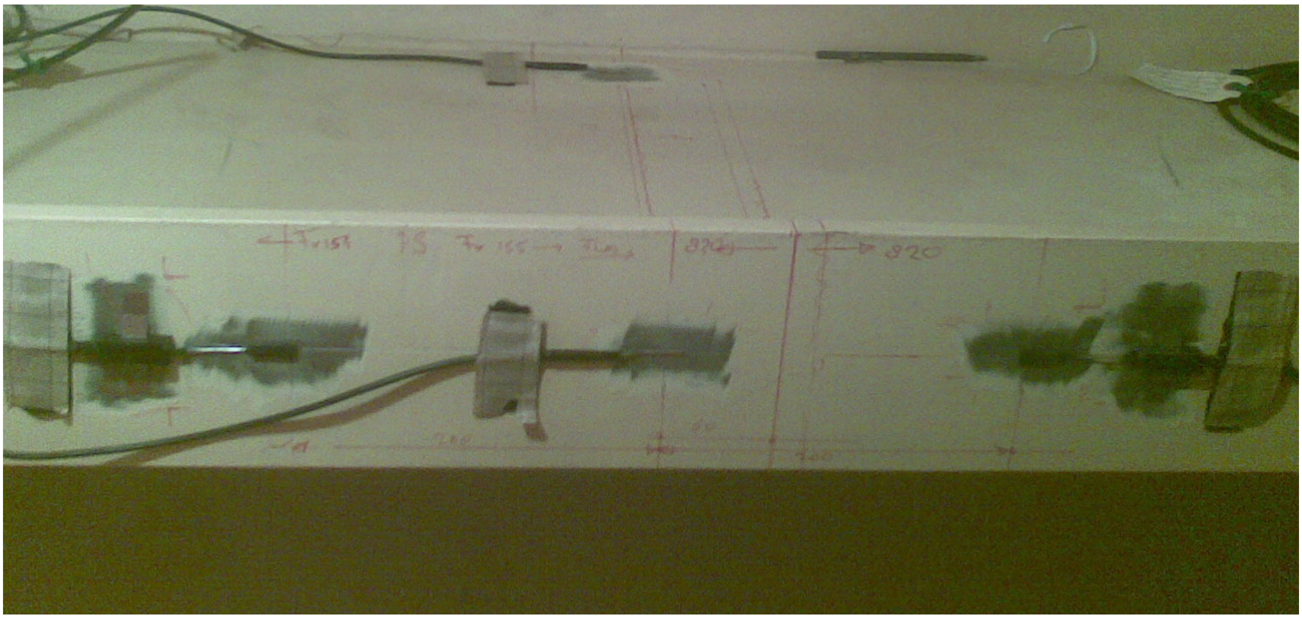


Figure 28 Spotweldable, prewired, sealed straingauges, still requiring protection for corrosion

Figure 29 Cold spot strain over 2 metres using 4-20 mA sealed displacement sensor. No explicit protection needed

Deflection measurements from camera observations, and possible in combination with digital image and machine learning data fusion provide extreme versatile options to capture complex shaped deflections as shown in Figure 30.

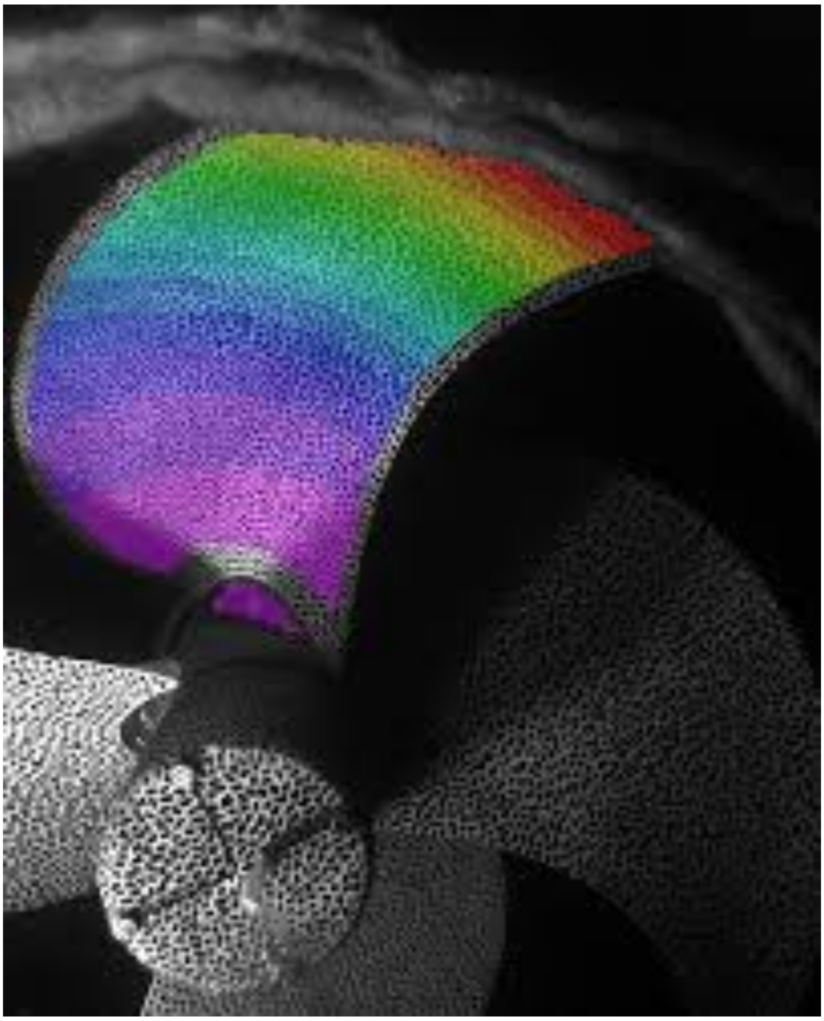


Figure 30 Structure (propeller) deformations from digital image correlation (MARIN)

The behaviour of in particular concrete structures in marine environment and exposed to complex loads from the mooring and the interconnectors may justify (local) application of image processing for derivation of complex deflecting shape.

Specific load monitoring with respect to mooring lines is nowadays often required for floating offshore facilities, however there are no rules and regulations for mooring systems of floating (permanently inhabited islands yet. The main difference with offshore units such as but not limited to offshore floating wind farms is that the Space@Sea island will have much more mooring lines and hence the impact when one single line breaks is much less significant on the remaining intact lines. Figure 31 shows an example of the chain stopper applied on the *Space@Sea* floating modules.

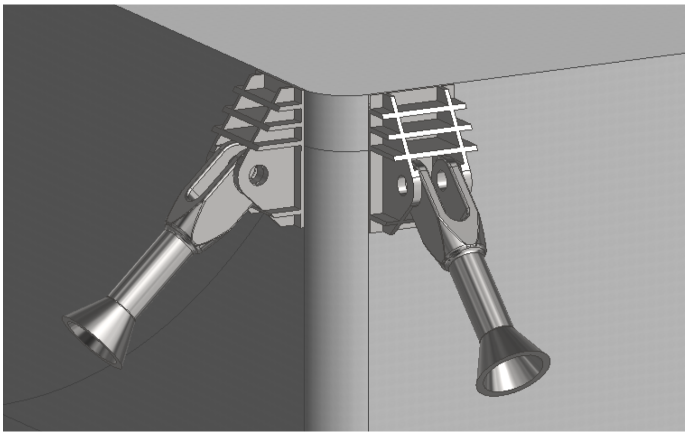


Figure 31 Underwater Chain stopper design

An example of an installed mooring line tension system by means of strain gauges on a chain stopper is shown in Figure 32.

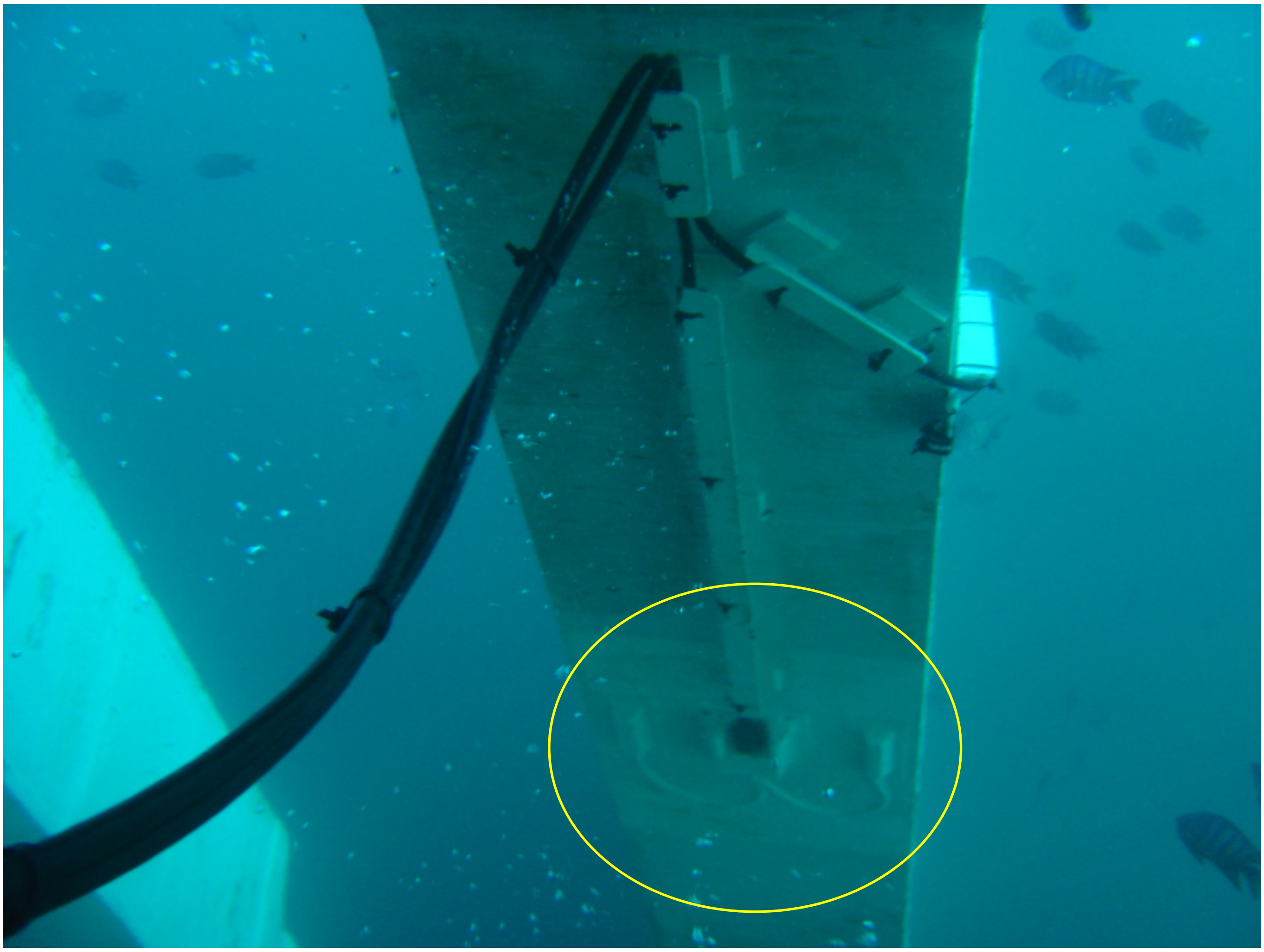


Figure 32 Strain measurements for RCA load monitoring (MARIN)

The sensors are in the encircled area. The strains are measured by spot weldable prewired strain gauges. A combination of mechanical and sealing protection is achieved by a fibre reinforced cover glued to the based material that is filled with flexible elastomer. The picture also illustrates the required efforts to wire and securing the cabling.

A difference between offshore units and the Space@Sea island is that the latter will have much more mooring lines and hence the impact when a single line breaks can be less significant on the remaining intact lines.

4.2.6 Underwater condition monitoring – Visual – ROV – Camera - Sonar

During the design phase of mooring lines, a wide range of factors are considered, including the location and environmental conditions. Although they are designed to withstand 100-year storms, only a very few have much reserve capacity above what is required to withstand them. It is important to consider that even if a mooring line has been in location without major incident in 20 or 25 years, it still needs to be able to withstand 100 year storm conditions to maintain class and insurance. Therefore, the longer a mooring line is in the field, the higher the probability that it will encounter extreme weather and the more likely the mooring line will fail.

The deterioration of mooring lines over time can lead to an increase in the failure of single or multiple lines. If the deterioration or failure of a single mooring line is not detected, multiple line failure can occur in the next instance of severe weather as a result of increased load on the remaining lines exceeding the design limits. While most offshore floating structures are designed to cope with the failure of a single line, in the event of subsequent line failures, the increasing loads tend to result in even more lines failing. Multiple line failure may result in a floating structure breaking away from the moorings and drifting off-station into the middle of the open area or against another floating structure. The amount of hardware required to install on the mooring lines is further discussed in section 4.2.5.

The cost of a single mooring line failure is significant when the expense of anchor handling tugs, ROV and/or dive support vessels, replacement parts and lost production are taken into account. For the reference, these costs have been estimated at a minimum of £2 million for a 50,000-barrel-per-day (bpd) FPSO (Floating production, storage and off-loading) in the North Sea and many times that for a larger production FPSO operating in a more remote and less serviced area of the world. It is clear that the potential cost of not detecting such a failure is far greater than the cost of implementing a real-time monitoring system.

Regular visual inspection can reduce the risk through early detection of issues, and real-time monitoring provides ability to detect the failure of a single line and, in some cases, provides an early-warning system of a change of angle, tension or position, which could be precursors to line failure. Despite the criticality of the mooring systems, with regulations varying across class societies and codes of practice, integrity management approaches seem to consist only of subsea ROV inspections or diver inspections, with very few FPSOs fitted with any form of mooring line monitoring systems. Where an FPSO is fitted with a monitoring system, these tend to be overcomplicated, poorly understood or unused, and do not provide any real-time capability or allow the operator access to historical data that would aid in assessing asset performance and integrity. Access to the area beneath the structure at the interface between the floating structure and mooring line is often limited to ROV inspection due to the risk of diving beneath. ROV inspection is itself limited by weather windows and access.

If an ROV can access the area beneath the structure, it can be used to verify the presence of the mooring chains in addition to inspecting the risers and moorings for typical damage and loss of integrity. However, this only represents a snapshot that can be compared against data from the last inspection. There are documented occurrences during ROV inspection when mooring chains have failed sometime after the previous inspection, unbeknownst to the operator. In some cases, multiple lines have been found to have failed, increasing the risk of more failures and the possibility of a major incident. Operators are learning that if they do not inspect on a regular basis or monitor in real time then they will not know for certain if the mooring lines are still in place.

Condition monitoring technologies for mooring lines include inclinometers, in-line strain gauges, tension measurement devices and sonars. Thought must be given to system functionality, reliability, maintenance requirements and ease of deployment, in addition to how to power the sensors and transfer data back to the floating structure. If the data rate is sufficiently low bandwidth, acoustic transmission is possible, removing the need for the sensor to be hardwired back to the FPSO. In either case, the sensors need to be powered, usually by battery, which needs to be changed out by diver or ROV to maintain functionality. To extend the battery life of these sensors, data are normally collected in short bursts and transmitted to the surface on a scheduled basis; therefore, they are not real time. Common issues with this type of setup include interference with acoustic transmissions due to the in-water noise beneath the turret and loss of sensors and questionable reliability due to harsh subsea conditions. If a single sensor fails, it is impossible to know without inspection if the mooring has failed or if it is the sensor itself that has failed.

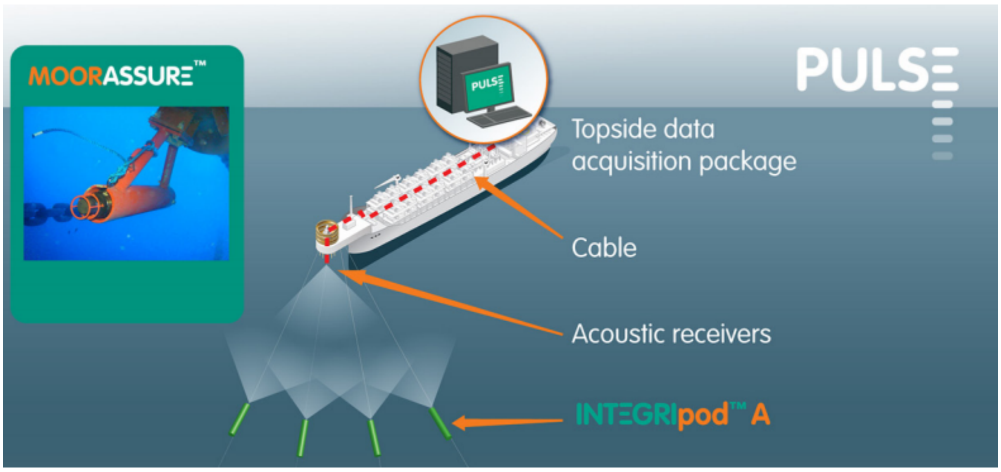
The *Space@Sea* floating island concept for the Mediterranean Sea is making use of 750m long catenary lines whereas a large part of the lines is laying on the seabed. Remote monitoring of the mooring lines consists of monitoring the loads induced by the movements of the floating modules, the presence of marine growth and potential damage caused by failures or corrosion effects.

Real-time monitoring of mooring lines is not commonly done due to its large amount of data. Typically, mooring lines are being inspected with ROV or divers after very severe storms (occurring once in very 5 to 10 years) and/or frequently per year (reference is made to D5.2 O&M). When an anomaly has been inspected, the O&M contractor will replace the mooring line.

Because of the fact that the *Space@Sea* floating island accommodates people, the criteria for mooring line failures are most likely more strict than current existing on floating windfarms. This means that the mooring lines should be monitored in real time and especially when the weather predictions are not good. There are many types of monitoring system available on the market and some of them based on different technologies were already mentioned in this paper (4.2.5).

One type of monitoring system used to confirm the integrity and performance of a catenary mooring system is the "moorassure" system which monitors the mooring line angles to deduce the mean tensions. On each mooring line, an inclinometer is attached to measure its mean angle. Using acoustic data linkers, the measure is angle is periodically transmitted to the acoustic received mounted onto and/or inside the floating modules. Using the measured mooring line angles together with the draught of the floating modules, the mean tension of each mooring line is deduced using a mooring line mathematical model. The acoustic inclinometer is placed in a holder to allow its retrieval and installation by an ROV and the logger holders can be attached to the chain links or on the chain stopper.

This type of measuring system provides data on the mean tensions on the mooring lines but also on changes in the draught of the floating module.



Another SONAR based system is the RAMS system.

https://www.seascapesubsea.com/downloads/Integrity-monitoring-system-for-FPSOs-RAMS.pdf

It is based on multibeam sonar technology which detects mooring lines, risers etc. under the structure and detects line failures in real time by comparison against the expected design configuration. In order to make positional measurements, assess curvature and measure strain, multiple acoustic transponders need to be fitted to each mooring line. These may be fitted either during deployment or subsea using an ROV, or divers. Measurements are transmitted to the surface transceiver using acoustic telemetry. This technique requires multiple sensors to be fitted to each of the target lines, some or all of which are battery powered. Sensors are often subject to adverse subsea conditions that may cause damage or loss, making the maintenance of such a complex deployment very expensive.

4.2.7 Connection pile anchor and mooring line monitoring

The lower end of the mooring line is attached to the anchor point. It has been decided in WP3 to opt for a 'fixed anchor pile' based on both the hydrodynamical loads induced by the offshore weather conditions of the floating modules and the most viable soil conditions at Mediterranean Sea location which is either clay or sand. The transport and offshore installation of this fixed anchor pile is described in WP5 and shows that the pile is approx. 45m embedded in the seabed whereas the pad eye, connector between the anchor pile and mooring line, is approx. 15m embedded in the seabed. This is shown in Figure 33.

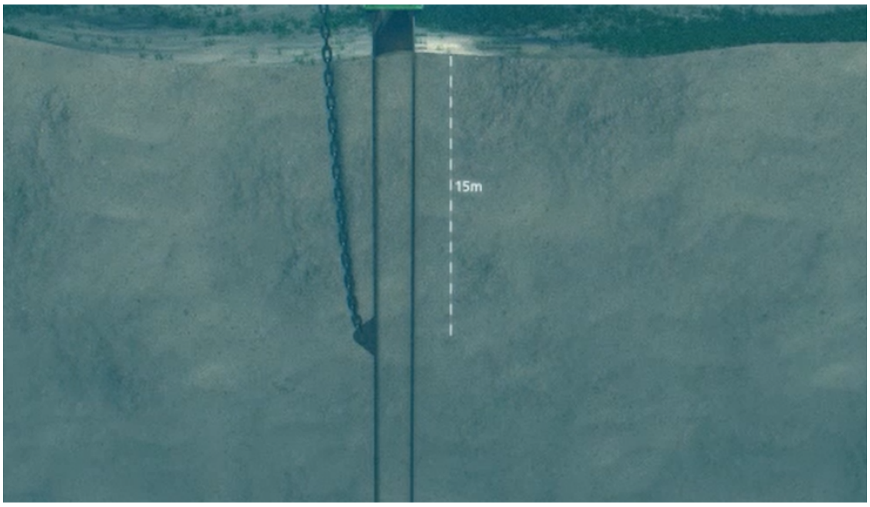


Figure 33 Pile anchor and mooring line

This type of specific functional requirement comes from the offshore wind, where bottom fixed foundations, embedded in the seabed, are being monitored to track its structural health and inclination during its operational lifetime of 25 years. Embedded strain gauges are used to monitor the vertical movements of the bottom fixed foundation inside the seabed.

Anchor piles are typical anchor types for floating systems with high design loads. The resistance mobilised by the mooring line in and on the seabed contributes to the anchor holding capacity. Heavy pulling forces, induced by the floating modules through the mooring lines, might create uplift forces resulting in a vertical movement of the pile and could create stresses and loads in the primary steel and also the connection point between the foundation and mooring line. The latter is further described in section 4.2.7.

Figure 34 Monopile instrumentation for bending and axial loads (left), zoom-in on fibre optic sensors (right)

The Space@Sea floating island is making use of fixed anchor piles embedded in the seabed. This means that visual inspection of the pile anchor by means of an ROV is not possible and only sensors attached to the pile are able to provide data on the structural integrity. Measuring the loads and movements of the pile anchor is not commonly done and from a mooring integrity point of view it is not required, according to *Bluewater*.

Due to the fact that the *Space@Sea* floating island is using catenary line with a length of approx. 750m, and the majority of the line is laying on the seabed, it will not generate any strong loads on the anchor pile causing vertical lift off forces. Based on that, it has been concluded that monitoring this type of pile anchors is not required.

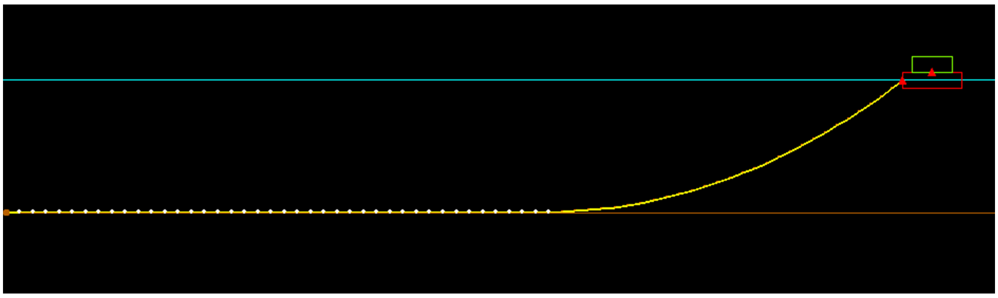


Figure 35 Catenary line for Mediterranean mooring concept

The connection between the anchor chain/wire and the anchor pile typically consists of pad eye(s) and is shown in Figure 36.

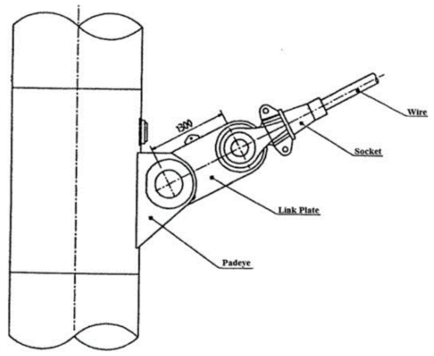


Figure 36 Connection pile - mooring line

A pin with horseshoe locking device connects the link plate to the pad eyes. To centralise the link plate between the two, typically a bulb at each side at the inner end is designed. The link plate is connected at the outer and to a socket that is the termination of the anchor segment of the anchor line.

Figure 37 shows an example of stress distribution for a local pile and pad eye connection due to the maximum mooring load under intact condition at the pad eyes.

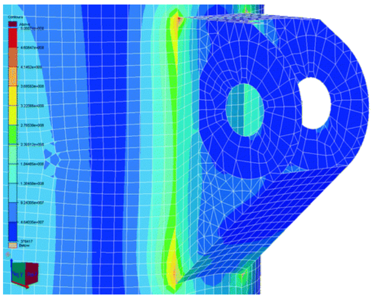


Figure 37 Stress concentrations pad eye connection

As stated above, this the pile/chain connection is approx. 15m embedded in the seabed which means that it is not possible to inspect the structural health of the connection visually. This means that the anchor pad eye should be monitored with the use of decent strain gauges in order to notify any load displacements during operation of the *Space@Sea* island. Subjected to cyclic/repeated loading, a component can reach premature failure or damage well below the yielding stress of the component material, known as fatigue. This is because small crack-like defects exist and when they are subject to a sufficiently large cyclic tension stress, they will grow in size and eventually cause the member to reach fatigue failure. The cracks are developed in four stages;

- Crack initiation (usually starts from the surface and can be detected by common technical means
- Stable crack growth
- Unstable crack growth
- Ultimate ductile failure

The connection (pad eye) between the catenary line and anchor pile can sometimes be critical in terms of fatigue damage. Different methods can be used for performing fatigue assessment of those connections, such as the stress-based approach, fracture mechanics; or strain-based approach for low cycle fatigue assessment associated with the development of plastic strain. It is often the case that, before a fatigue assessment of anchor piles, a fatigue analysis of the associated mooring line above the seabed is already performed.

The Space@Sea floating island is making use of pad eyes to connect the mooring lines with the anchor piles. Reference is made to D5.1 which shows that the anchor piles are being vibrated into the seabed while the mooring line is already connected to the anchor pile. As stated above, the pad eye is located approx. 1/3 of the pile length into the seabed. Measuring the structural integrity of the pad eye is not commonly done and from a mooring integrity point of view it is not required and impossible as the strain gauges will get damaged during the driving operation, according to *Bluewater.*

It has been decided that remote monitoring of the pad eyes is not necessary required as this can be monitored at another monitoring infrastructure asset.

4.2.8 Scour monitoring

Scour around the anchor piles in steady currents has been investigated extensively in the last decades. The fluid mechanics of the scour process are relatively well understood. The key element in the scour process is the horseshoe vortex, formed around the pile just above the seabed. This vortex, which is formed due to the presence of rotation in the incoming velocity profile, is able to erode a significant amount of sediment away from the area around the pile. Scour around piles in waves and in combed waves plus current has attracted much attention in recent years considering its application in the offshore wind.

Scour around the anchor pile can cause several engineering problems such as the reduction of the bearing capacity or increasing tensions of relevant mooring lines attached to the structure. Prediction of scour focuses on either final equilibrium state, or time-evolving feature. For instance, the scour starts to develop when the structure is constructed until reached equilibrium. Scour could keep on changing if the surrounding flows change continuously like tidal flow.

When multiple piles are constructed close to each other, scour hole depths are affected by the number of piles as well as the dimensions of the pile due to enhanced turbulence generated by the many piles around.

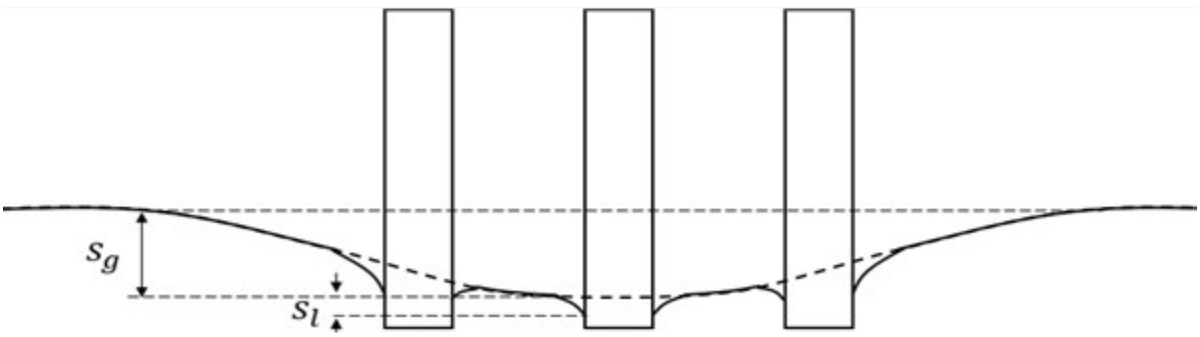


Figure 38 Scour around three (3) piles

The anchor pile can either be protected against scour by using scour protection solutions or be designed such that scour development can be allowed. Designing the anchor pile such that the development of scour has limited to zero impact on the structural integrity results in a potential larger cost due to its larger pile diameter and/or wall thickness requirements. On the other hand, using scour protection solutions such as but not limited to rock dumping requires extra investment for installing the rocks, monitoring the behaviour and attendance of the rocks and if required, installing extra rocks after a certain period of time. Scour protection and its installation in shown in Figure 39.

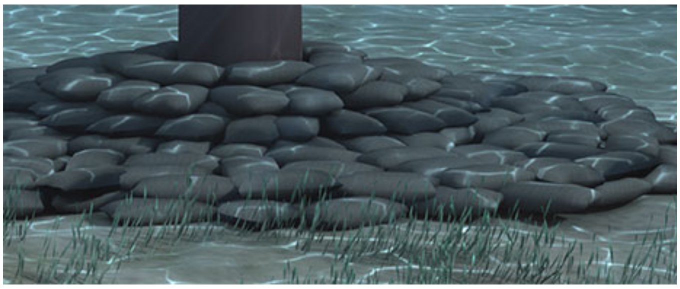



Figure 39 Scour protection installation vessel (left) and scour protection (right)

As mentioned above, scour does not always occur and is highly dependent on the weather conditions at the specific offshore area. Monitoring the effects of scour can be either executed by using a multibeam survey vessel which performs physical bathymetry inspections. Another solution is the use of an acoustic scour monitoring system attached on the pile which allows continuous data collection during scour event. The system uses 4 narrow acoustic beams to detect the along beam distance from the sensor to the seabed at 4 points away from the structure. By monitoring scour events, operators can determine the requirement for protective measures such as rock dumping, as stated above. Figure 40, the picture on the left shows indicatively a typical multibeam sensor applied on a wind turbine foundation, and the picture on the right the same sensor on the legs of a jack up vessel.

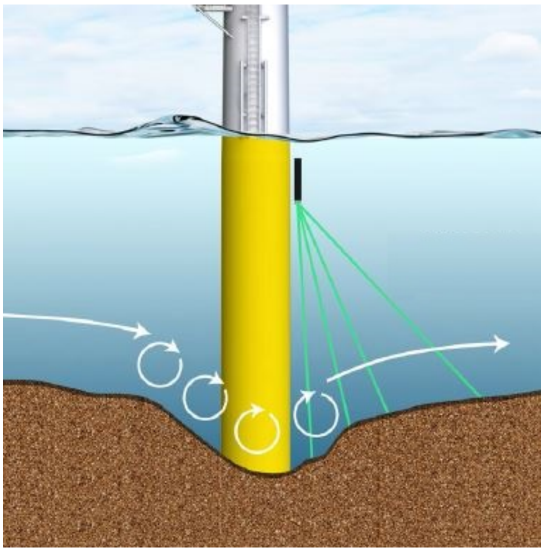
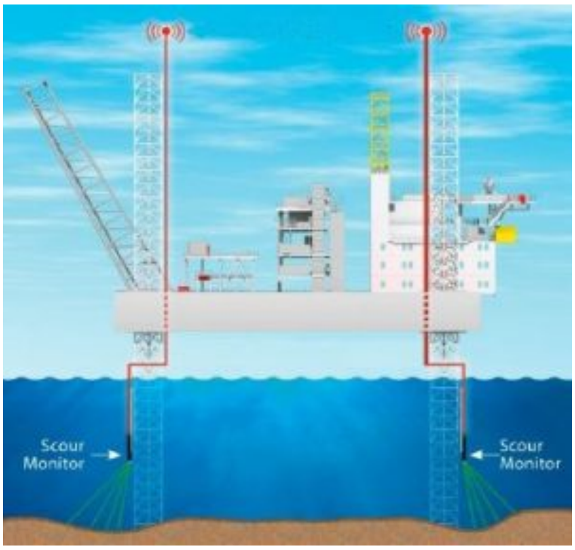



Figure 40 Multibeam scour sensor on a foundation (left) and jack up vessel (right)

It has been decided by WP3 to opt for a fixed pile anchor which is completely embedded in the seabed as shown in Figure 33. Due to the fact that there is a limited pile stick up above the seabed, it means that scour is limited or even not take place. This paper concludes that monitoring of scour by applying sensors as proposed above is not required and that scour easily can be inspected by means of an ROV during O&M inspections. Subsequently, any occurrence of scour would be visible in the retrieved data of the embedded sensors alongside the pile. Monitoring the scour around the pile is a nice to have but definitely not a need to have as the occurrence is very low and any effects of scour can be monitored by other monitoring infrastructure.

4.2.9 Marine growth monitoring

Any hard structure submerged in the sea will eventually host a community of marine organisms growing on and associated with its surface. This marine growth, or biofouling, is comprised of a variety of species depending on the location, depth and configuration of the structure. Marine growth on offshore structures can have consequences for structural integrity, hydrodynamic efficiency, and survivability, and may also encourage the establishment and growth of non-native or invasive species.

The industry consultation indicated that key concerns associated with the development of marine growth were: biofouling mass, thickness, surface roughness, heat transfer properties, corrosion, and impacts on wet connectors. In exposed locations occupied by wave and tidal energy devices, the growth of biofouling may be more rapid than in other, less exposed locations. Marine growth can alter the weight of structures considerably. The weight of biofouling acting on a structure is dependent on the volume of biofouling and the relative proportions of hard, dense species and soft, less dense species. While effect thresholds for biofouling mass on devices are presently hard to define, understanding the weight, weight in water, and density of biofouling associated with biofouling mass are highlighted as important knowledge gaps to be filled to support engineering decision making. Marine growth serves to increase the effective diameter of structural components, with potential to alter structural drag and added mass coefficients.

The thickness of marine growth is strongly related to the effective diameter of components, and will be influenced by species composition and growth rates, which are in turn influenced by location-specific environmental characteristics. As marine organisms begin to colonise the surface of a newly deployed device, surface roughness will increase, with implications for device efficiency, drag coefficients, and added mass coefficients. Surface roughness will also be influenced by species composition and growth rates in a location-specific manner

Approaches to dealing with marine growth vary within the marine renewable energy industry and across the wider marine engineering and operations field. The consideration of marine growth is an important step when designing marine structures to ensure appropriate design tolerances. Structural elements designed to account for additional structural loading due to marine growth can be incorporated at the early stages of the development process. These design considerations will require an understanding of biofouling growth characteristics (e.g. accumulation rate, weight, thickness, surface roughness).

Operational maintenance plans often incorporate activities to scrape, clean, or remove biofouling from specific structural elements or from entire submerged structures across the life of a development. Location-specific understanding of biofouling characteristics may reduce the occurrence of additional, costly, unscheduled maintenance activities resulting from biofouling. A range of marine protective and antifouling coatings are used on submerged components to reduce marine growth. The Reliable Data Acquisition Platform for Tidal (ReDAPT) project tested the efficacy of a suite of coatings in extreme conditions at the Fall of Warness in Orkney over a period of 24 months. Results indicated that both biofouling and corrosion rates were rapid at this site, and highlighted that selection of appropriate coatings could be a key consideration for ensuring the long term operation of tidal energy devices. Cathodic protection is a further method used to control corrosion of structural components, but has also been demonstrated to enhance marine growth under certain conditions. For long term deployments, both cathodic protection and antifouling coatings will need to be carefully considered in the context of likely fouling species and the potential long term build-up of marine growth.

There is no “direct” monitoring system that can capture and monitor the amount of marine growth on the floating structures. Monitoring relies on visual underwater observations, by divers or ROV.

Machine learning technologies are being developed to recognise various types or class of biofouling and quantify scale using training picture data sets. (Ref : Intelligent Image Recognition System for Marine Fouling Using Softmax Transfer Learning and Deep Convolutional Neural Networks, C. S. Chin et al., 2017).

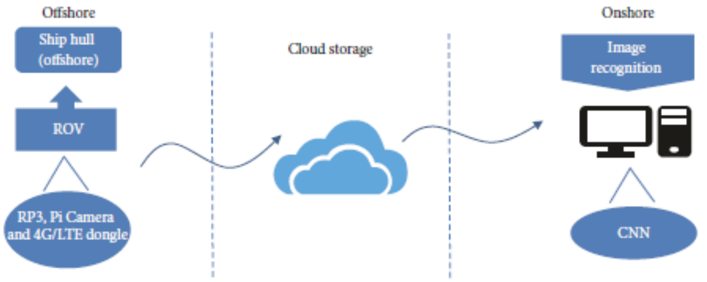


FIGURE 1: Proposed fouling recognition system design in this study.

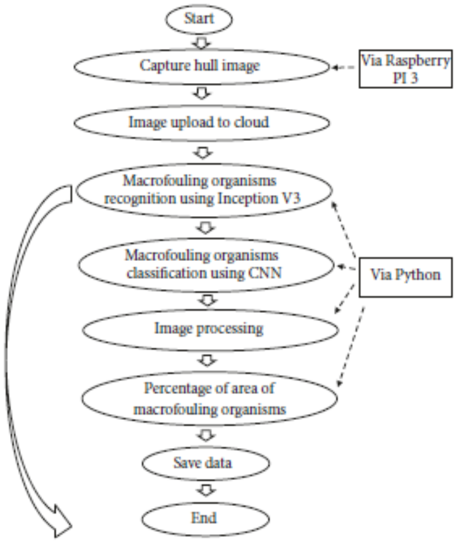


FIGURE 2: Software program flowchart.

Figure 41 Marine growth from image processing - Chin et al., 2017

Figure 42 Training set for marine growth image processing - Chin et al. 2017

The paper reference concludes that recognizing and quantifying surface density of the described approach was considered sufficient. Important aspects as mass estimates, roughness and thickness were not listed.

4.2.10 Water quality monitoring

An ecologically important aspect of floating islands will be their impact on the surrounding marine environment. Inputs that may be tracked over longer time should include abundance of fish in water column around and about the floating island. Several approaches are listed to track that input:

- Water temperature and salinity along the water column.
- Phytoplankton and algae concentrations from direct and Chlorophyll measurements.

These observations will require measurements to be conducted at various depths. This can be done by lowering equipment through the water column. Measurements may also be conducted by ROV or UUV craft as piggy backed or even dedicated equipment.

Fishing vessels are using sonar based applications to recognise presence and type of fish under their vessels. These fish finders determine fish species based on characteristics of the returned SONAR chirp in relation to the fish itself, its size, swim bladder and on whether it is a single reflection or indicative of a large amount school of fish.

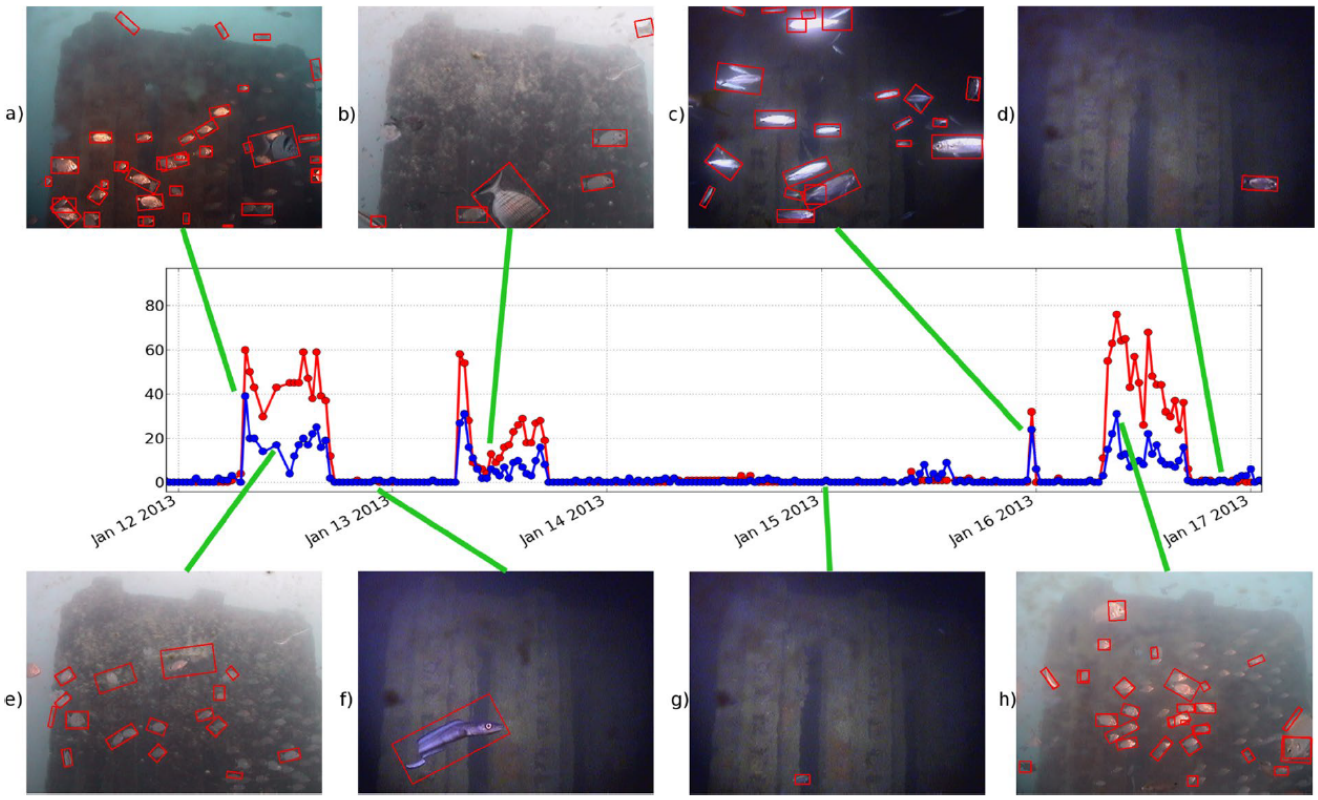


Figure 43 Automatic generated trend lines of fish abundancy based on camera image recognition

Since under water inspections are expected to be a common occurrence on floating islands also under water images may be used to determine or characterise fish abundance and water quality. Reference is made to “Tracking Fish Abundance by Underwater Image Recognition” by Simone Marini et al., 2018. Effects of bio fouling and water turbidity were included in the investigation as their effects showed clearly in the used image data set. The paper illustrates that camera observations in combination with image processing can provide information on and classify:

- Water turbidity
- Fish abundance

Both are proposed as indicators for water quality around and under the island. Example output is shown in Figure 43.

4.2.11 Noise / audio monitoring & PA

Noise or audio provides relevant operational information to oversee, be alerted to, or listen back to in case of unexpected or specific events. Both airborne and underwater noise may be considered. Above water noise measurements through industrial micro phones for audio, or through sound level meters or analysers for direct quantification into less high data density. Underwater noise may be collected using under water hydro phones suspended under the structure, deployed under a buoy, or mounted at the structure itself.

Several aggregation stages for audio can be considered:

- Direct audio as WAV time series, or compressed audio in MPP or MP3 formation for high resolution
- Weighted Sound pressure level in dB(a) to provide a condensed slowly varying quantity
- Analyser output in octave or 1/3 octave band spectra

4.2.12 Closed Camera observations

Closed camera observations produce a vast amount of data to be stored. In practice when phenomena are observed that were not originally anticipated, the camera information is one of the most intuitively interpretable inputs. Review of camera data however is very time consuming so image processing technology has been developed to recognise changes in images. Data streams are compressed by storing only the relevant changes to successive images. Image processing technology can be configured to recognise and quantify observed activity. Examples are object tracking and recognition etc. The options are plentitude. Dedicated examples were already referred in sections 4.2.9 and 4.2.10. The promise to future O&M related input is very strong and many developments are expected to take place over coming time. Further details of present options are not further discussed here.

4.2.13 Alarm triggers

Many alarm indicators can be considered as inputs into a floating island configuration. These vary from standard fire, gas, and smoke detectors, to bilge alarms, water tight door opening indicators, and output flags for mooring line integrity, relative motion alarms etc.

5 Digital twin, and data quality insurance

Measured sensor values often do not directly provide the information that is relevant for status or process control. Typically measured values have to be combined with static reference values to evaluate if particular process parameters are in acceptable range limits or they are combined with other dynamic inputs to estimate more global state indicators of a process that than in turn can be checked against target values and ranges.

The digital twin concept is a top down approach for this process. The digital twin is a virtual representation of selected properties of its real world counterpart. The twin is thus comprised of

- properties that represent selected aspects that are relevant to be tracked.
- Methods that keep the selected properties aligned with the real world using inputs from in situ inspections, sensor observations, data fusion models etc.

The benefit of a digital twin approach is that it enables to provide different specific views on the real world counterpart based on a shared set of inputs. Relevant questions for Space@Sea related to O&M are:

- what aspects need to be represented by the Digital Twin,
- How can these aspects be obtained from a practical data collection arrangement
- How to recognise extraordinary events and anomalies or sensor faults in the data streams.

5.1 "A" S&S digital twin concept

"Digital twin – the future of engineering" as cited by DNV-GL, is a model-based approach to anticipate the behaviour of a system or a machine through its virtual image. The digital twin concept involves acquiring, storing, and assessing all significant aspects of a physical object in a computer system. In essence a digital twin might represent "all" aspects of the real structure in the widest sense. But since the information to fully describe a real life structure is infinite so implementing a full offshore floating structure digital twin is thus unrealistic. Digital twins are aimed to provide a representation of specifically selected aspects of the structure with finite resolution.

The final design of a floating structure will determine the parameters that need to be represented by the digital twin. The Space@Sea design for the Mediterranean case calls for validation of all the O&M parameters as reported in WP5.3 task O&M and life cycle scenarios. The digital twin should allow to:

- Provide a view onto the true "now" state of the island and individual modules. This to have a global island part, and an individual floater part. The now state is needed to assess the instant the motion and loading state of the island, including the mooring loads and forces in joints, and also the quasi-static aspects as ballast arrangements and alarm systems.
- Validation of short-term design assumptions of island motion and load state as function of wind, waves and current. This implies that the digital twin should be aware of the environment and how it relates to that environment. An intuitive representation of that behaviour is required to assess if behaviour is "in line" with design expectations, or if unexpected behaviour is occurring that requires attention in short or longer term.
- Tracking of long-term condition of individual parts as floaters, joints, fenders and moorings. The digital twin model should provide an estimate of the condition of these parts indicating the need for preventive or reactive maintenance.

A digital twin should collect data from the physical system and assess it to allow more informed decisions to be made. Along with data collection, management, and transmission, a digital twin may have models and corresponding physics-based simulation tools and data analytics capabilities. References to digital twins that include structural degradation commonly refer to capturing large amounts of sensor data. There are a number of challenges to implementing a digital twin that includes motion status and structural fatigue of a floating structure. This section discusses a proposed approach and the necessary developments. The gaps in knowledge and associated required research are presented and discussed. The software and hardware requirements for a digital twin are covered in previous sections (Chapter 3). This document examines the current state of the art for components of the proposed framework and identifies the necessary research to realise the proposed solution. Figure 44 gives an overview design of the digital twin for this project. It consists of: a) analytical models for hydrodynamics and structures; b) operational models of components and structures, that operators can update the associated inputs; c) 3D visualisation models of components and structures; d) time-domain models of components and systems; e) real-time measurements from various sensors; f) fault detection and prediction system for alarming.

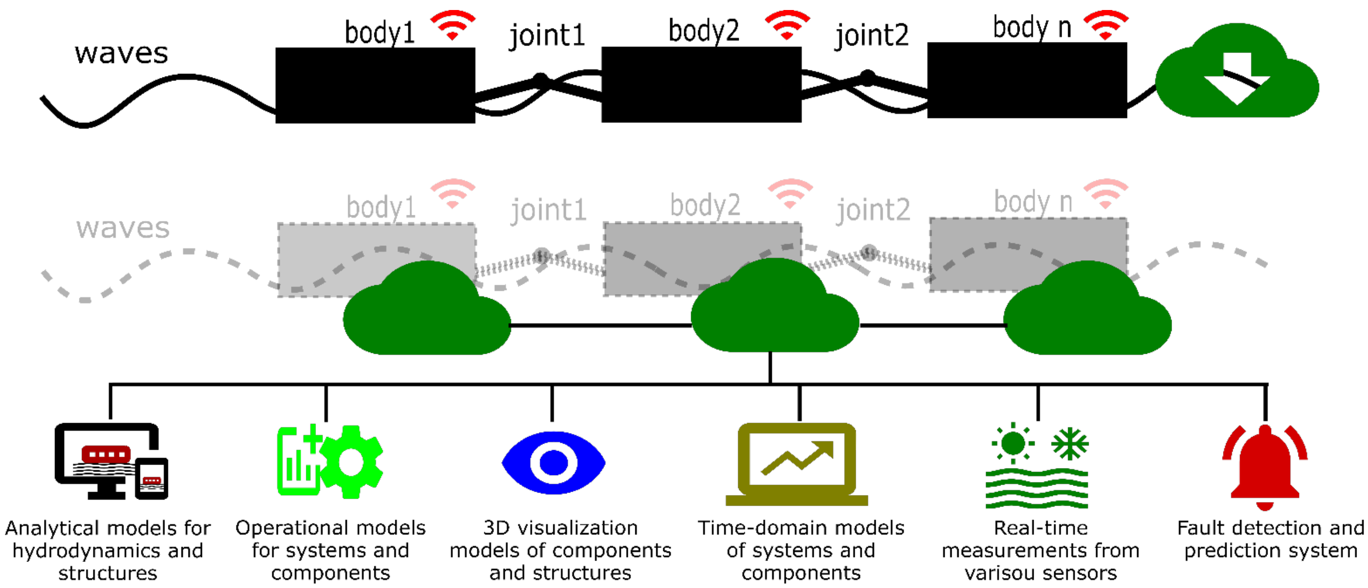


Figure 44 An overview of the design of a digital twin for a floating island

5.1.1 Identifying floating modules and fatigue areas of interest

Monitoring the overall motion status and structural degradation of each floating module that make up an entire floating island is possible within digital twin, but it may not be necessary. Instead, by identifying modules likely to crack, we could focus modelling efforts where they are most need. The most interesting floating module can be identified through the setup analysis of the targeted island configuration. For a module crack to initiate, there must be high cyclic stresses (due to wave loads, mooring tensions or hinged joints), and either a stress concentration or high residual stressed due to a weld. Meanwhile, their identities can also be updated by post-processing the measured real-time sensor signals (forces on hinge joints and moorings, velocities and accelerations). In general, the floater located in the first row in heading waves suffers the largest wave induced loads and moments, consequentially, having the largest motions, velocities, as well as accelerations. For example, for a floating island consists four modules in a column arrangement, and the wave comes from the right-hand side. We can identify that the module encountering waves suffers the largest motions and loads, as shown in Figure 45.

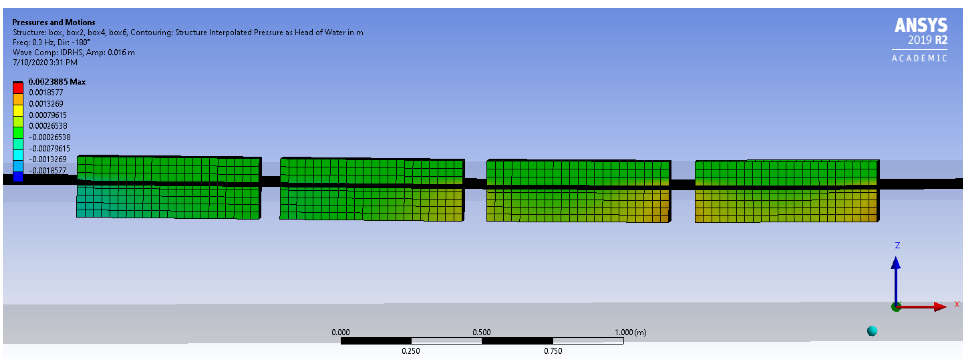


Figure 45 An example of a floating island consisting of four modules

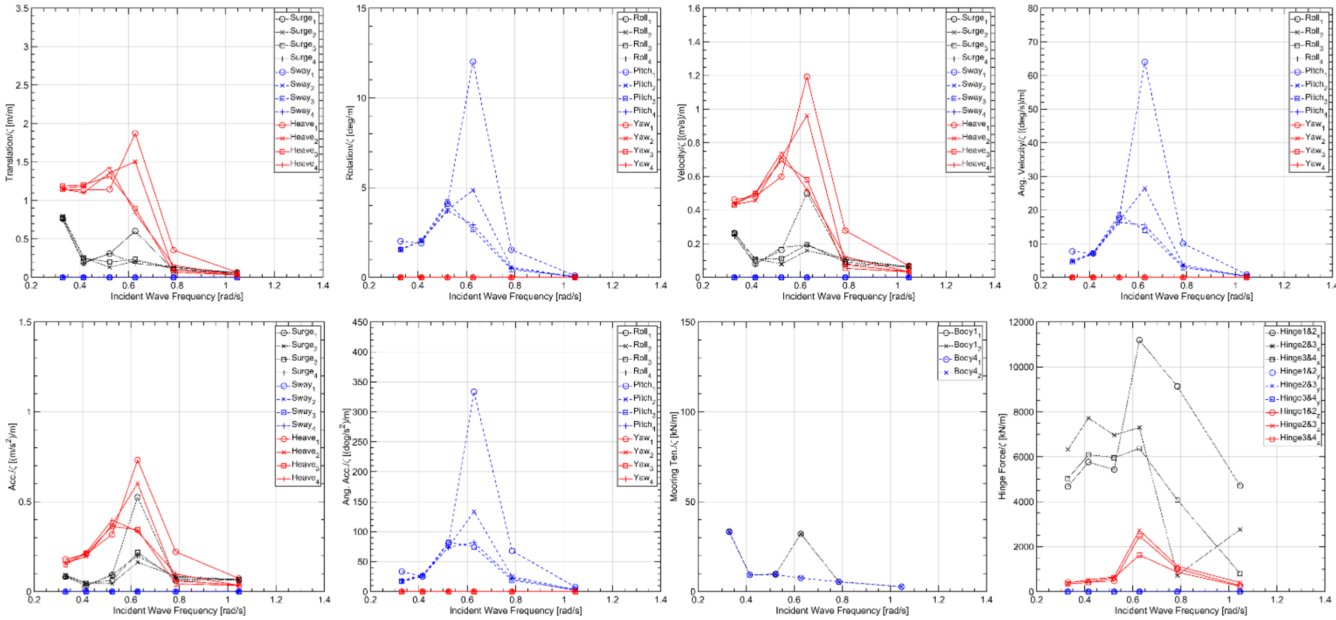


Figure 46 Motion characteristics of a floating island, and top left to bottom right are a) translational motions; b) rotational motions; c) translational velocities; d) rotational velocities; e) translational accelerations; f) rotational accelerations; g) mooring t

The fatigue areas of interest for each floater can be identified based on a structural analysis. There are several approaches to perform a structural analysis. They require the transfer of the predicted hydrodynamic loads to the computational structural dynamics (CSD) solver. Two approaches, namely, the one-way coupling and two-way coupling techniques, were evaluated herein to incorporate predicted hydrodynamic loads from a BEM solver or a CFD solver. One-way coupling required computing wave-induced loads based on rigid-body motion using a fluid dynamics solver and then applying these forces on a wet elastic model to predict structural responses, whereby the structural deformations computed by the CSD solver are not fed back to the fluid dynamic solver. Two-way coupling allows the elastic de-formations of the structure to be fed back to the fluid domain, which can be important for the computation of pressures when the structure deforms during a slamming event or when large deformations influence the flow field. The following figures show the identified areas of interest for a single floater in waves.

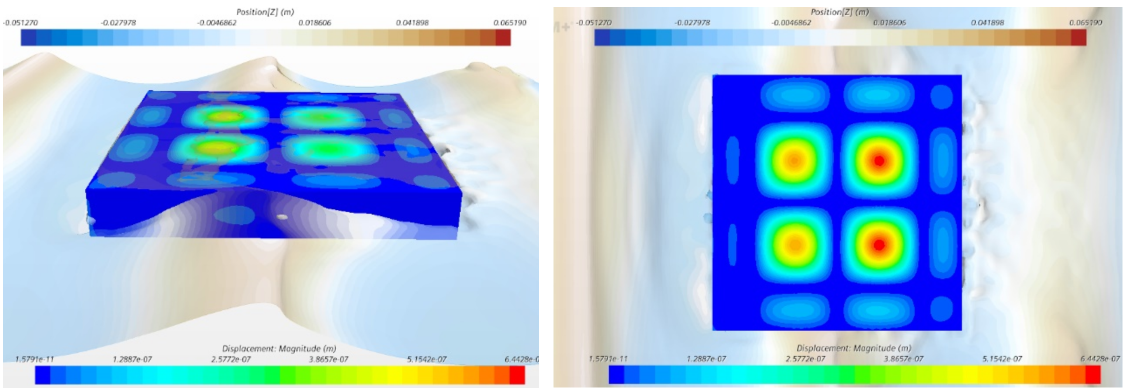


Figure 47 Distribution of hydrodynamic pressures (left) of a rigid module, and the structural deformation (right) of a flexible module at the same time instance

5.1.2 Motions Status and its Structure Health Monitoring

The generation of a digital twin for the floating island requires properly simulating the rigid body dynamics, as well as its structural dynamics. Modelling the rigid body dynamics of the floating island involves the interaction between the incident waves, floater motions, hinged joints, and mooring system. The potential-flow theory based radiation and diffraction approach can be used to predict the dynamic performance. The radiation and diffraction approach generally obtains the hydrodynamic forces from a frequency-domain boundary element method (BEM) solver using linear coefficients to solve the system dynamics in time domain. The hydrodynamics coefficients can be calculated from general BEM tools, like WAMIT, AQWA, and et al. The equation of motion for articulated bodies from Roy Featherstone (2014) [Ref. 1], then can be implemented into this model to predict the rigid body dynamics. It is based on the field of robotics, and has been developed to solve wave energy problems. A simple case is shown in Figure 48, as an illustration.

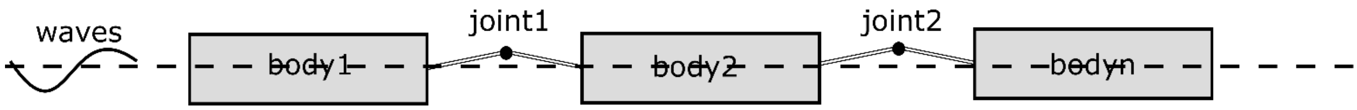


Figure 48 Simple case for a 3 body articulated motion floating structure

The equation of motion of the rigid body system can be written as

$$H(q)\ddot{q} + C(q, \dot{q}) = \tau \tag{4.1}$$

Here, q, $\dot{q}$, and $\ddot{q}$ are the position, velocity and acceleration of the joints. H is the inertia matrix. C is the force which will produce zero acceleration. C accounts for forces like gravity, Coriolis and centrifugal forces. τ is the total force acting on the bodies. C can also be said to be the value of τ that will produce zero accelerations. In this equation multiple values can be calculated depending on what has been provided. It can be divided into forward dynamics and inverse dynamics.

For forward dynamics we have:

$$\ddot{q} = FD(model, q, \dot{q}, \tau) \tag{4.2}$$

It means that the initial position, velocities and forces have been provided which will be used to calculated the acceleration.

For inverse dynamics we have:

$$\tau = ID(model, q, \dot{q}, \ddot{q}) \tag{4.3}$$

It is the inverse of forward dynamics, which means that acceleration has been provided and it will be used to calculate the required force to have that acceleration. We will work with forward dynamics as the forces will be known to us which will be used to calculate the acceleration. This acceleration will be integrated for the first time step to get the new position and velocity which will be used as an input for the next time step. And this will continue during the whole period of the simulation. The Propagation method works by calculating the coefficients of the rigid body dynamics equations for one link and then propagating it to neighbouring bodies until the end of the chain is reached. It can be understood as

$$f = I^A * a + C \tag{4.4}$$

Here I^A is the articulated body inertia which is starting from the inboard joint of this link to the end of the chain, *a* is the link acceleration and C is the bias force. *f* is the force applied by the inboard joint of this link. All the values are unknown over here. These values are calculated starting from the tip and ending at the base of the system. It is done inductively. It means that none of the equations can be solved individually. All the equations have to be formed which will then be solved simultaneously because there is interdependence between them. To make it more clear an equation for acceleration of link *i* has been shown as:

$$\ddot{q}_i = \frac{Q_i - \hat{s}_i{}'\hat{I}_i^A \hat{X}_{i-1}\hat{a}_{i-1} - \hat{s}_i{}'(\hat{Z}_i^A + \hat{I}_i^A \hat{c}_i)}{\hat{s}_i{}'\hat{I}_i^A \hat{s}_i} \tag{4.5}$$

Here subscript i denotes the link number varying between 1 to n. $\ddot{q}$ is link acceleration. All the values seen in the above formula need to be calculated for every value of i. Similar equation exists for articulated body inertia, bias forces. This means that all the equations have to be formed from1 to n which will then be solved together to give the acceleration of all the links. This is why it is called propagation method. To conclude there are three basic steps in this algorithm:

- Computing the absolute velocities of all links starting from the tip to the base;
- Computing the articulated inertia and zero acceleration force (bias force) for each link starting from tip to the base;
- Computing the acceleration of each joint starting from the tip to the base.

Then the hydrodynamic analysis, as well as the modelling of the mooring system can be implemented to couple with the equation of rigid body motion, like general hydrodynamic analysis tool at the state of the-art.

Structural Monitoring:

The floater hull monitoring involves taking measurements to understand the floater's response to operating and environmental conditions. Current challenges involve managing and analysing large amount of data, since gaining useful insight requires long monitoring periods. Interpreting the large datasets, and challenges using the results to calculate local structural degradation are the main barriers to building the digital twin. Identifying effective ways to use the data may facilitate its inclusion in a digital twin. Within a digital twin, data analytics may enable effective assessment of the data. Combining physical measurements and numerical assessments will make better use of data and help identify the requirements of a monitoring system that provides the necessary data with a minimal number of sensors.

The structural health can be monitored using short-term operating parameters as inputs to numerical models to determine the stress state. Its procedure is explained as follows: 1) wave loads must be calculated for each condition the floating module may experience; 2) stress transfer functions resulting from the wave loads must be determined. Stress transfer functions describe a structure's stress response to operation in each combination of incident wave angels and wave spectrum; 3) operational data and measured or modelled wave data must be collected and merged to know the amount of time the floater has spent in each of these combinations; 4) stress spectra are calculated for each of these combinations using the wave spectra and stress transfer functions. The wave-induced loads can be calculated using hydrodynamic analysis, as discussed in the monitoring of the floater motions status. Once the full set of wave loads have been calculated, the resulting stresses are determined. As discussed in Section 4.1.1, stress calculations use FE analysis. Transfer functions are created for the stress in an element of interest or, for coarser analysis, hill girder primary stresses due to global bending. When calculating stress transfer functions in the area of interest or a separate refined local model can be used with top-down analysis. The former method results in undesirably large FE models when there are numerous local areas of interest. Top-down analysis applies boundary conditions to the local model from the global model solution. Displacements and rotations at global FE model nodal locations are applied to coincident local nodes (master nodes). Displacements of remaining local model boundary nodes (slave nodes) are calculated using linear interpolation between the master nodes. After prescribing the boundary conditions, FE analysis is used to calculate the stress distribution. Figure 49 shows an example of global FE model used for this project.

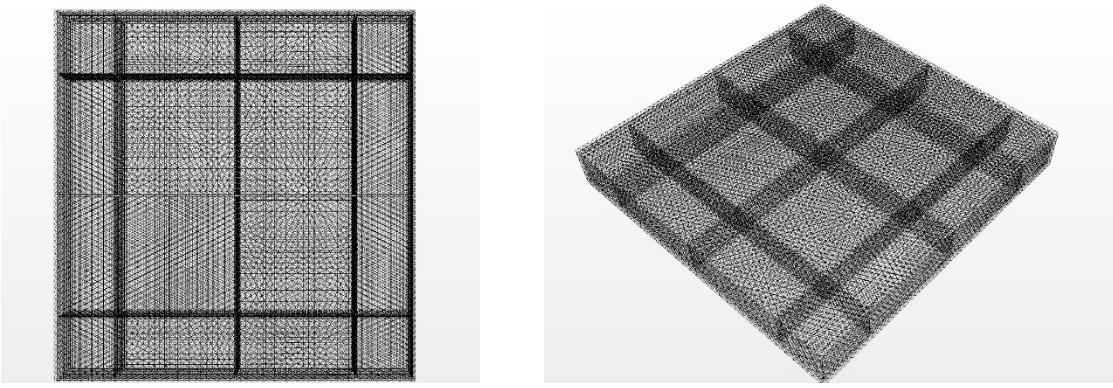


Figure 49 An example of global FE model for a standard floating module

The full set of calculated stress is used to create stress transfer functions. These functions provide the stresses (based on the wave loads) calculated at a given location for each combination of considered incident wave angels over all the wave frequencies. Although this dataset of functions is necessary for virtual hull monitoring, a clear image of the encountered stress conditions requires combination with operational data, which can be directly measured by the approach/equipment described in Chapter 3. Figure 50 shows the data flow for this technique where grey blocks are development areas, and green blocks represent aspects where data will be collected as inputs or simulation methods will be used. For instance, work is required to access wave data and determine the appropriate resolution, but wave loads can be determined using existing methods.

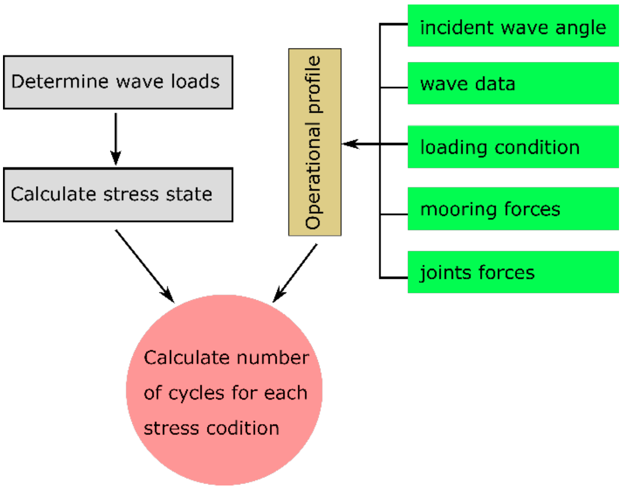


Figure 50 Flowchart describing the floater structural health monitoring

5.1.3 Model Parameters updating – True Digital Twin

The good performance of the digital twin is not solely related to its ability to accurately represent the motions status and structural characteristics, but also the real-time operational conditions and environmental profiles. A floater's dynamics is very sensitive to changes in the loading conditions, and the standard floater will be used for different functionalities, during which it's mass and centre of gravity (CG) may vary much. In order to prevent it from capsizing under bad loading conditions and heavy weathers, the real-time loading conditions and its CG have to be updated into the digital twin in real-time. Actually, the mass, or inertia, is one of the most influential parameters in most mechanical systems. During this parameter updating process, the mass of the floater is derived by the directly measured water draught. Its CG can be derived using the approach proposed by Linder et al. (2014) [Ref. 2], as shown in Figure 51.

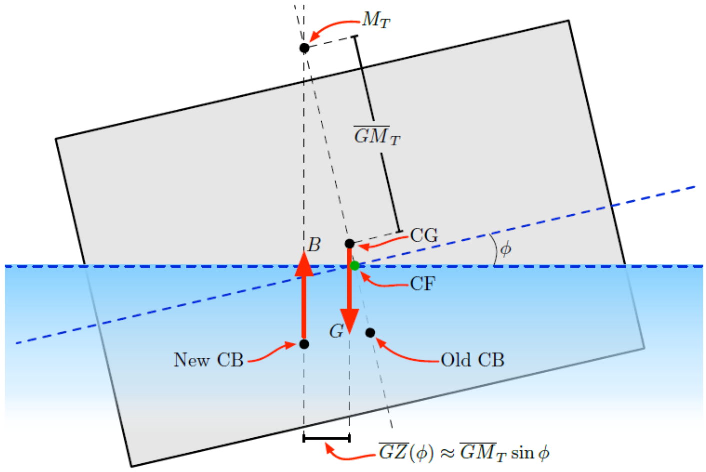


Figure 51 Example of deriving the CG of a floater using the sensor data

Another critical aspect is to make sure the wave load modelling in the digital twin is accurately representing the real conditions. Typically, adopting wave load modelling parameters from codes and standards relevant for the specific structure will yield conservative fatigue predictions. Evaluating and optimizing the wave load model used in the digital twin can be achieved using the real-time measurements. An example of wave load calibration for an 8-legged jacket is shown below. Four strain gauges are installed to provide valuable information both for local member response in the splash zone, and for the global platform response. In addition to this the structure is equipped with 3 wave radars, providing measurement of the sea surface elevation and thus sampling information about the sea state conditions. The digital twin is, as mentioned, established to provide real time information about the fatigue damage accumulation in all elements and nodes of the structure based on measurements from only a limited amount of sensors. In the current case this is achieved by employing the measured sea surface elevation and the associated measured wave direction as direct input to the wave load modelling for the real-time simulation.

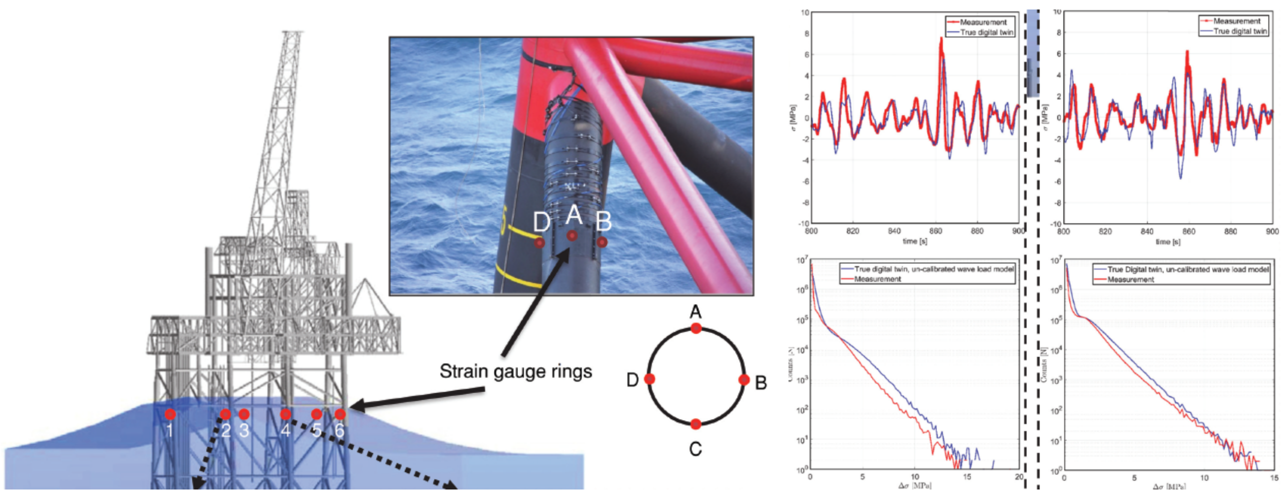


Figure 52 Example of wave load calibration for the digital twin

Assuming that the true digital twin provides the best possible representation of the structural response, it is only possible to improve the fatigue prediction of the true digital twin by calibrating the wave load model against measured sea state conditions. In general terms, the idea of calibrating a load model to measured sea state conditions is defined as an optimisation problem, where relevant load parameters are selected as the governing variable in the optimisation of the load model. The objective of the calibration is to minimise the discrepancy between the measured and the predicted response by calibrating the wave load modelling part of the FE analysis. For the current case the wave load calibration was performed by the SIMA software, which has an integrated wave load calibration toolbox. In this case, it was chosen to use the global hydrodynamic parameters in terms of Cd and Cm, representing the drag and inertia term of the Morison equation. The target of the wave load calibration therefore is to identify the set of hydrodynamic parameters, which provide a minimum discrepancy between the measured and predicted stress history curves. The reference model of the true digital twin, which includes the real-time measurements, the inputs of real-time operational profiles, and risk reduction in process plants, in shown in Figure 53.

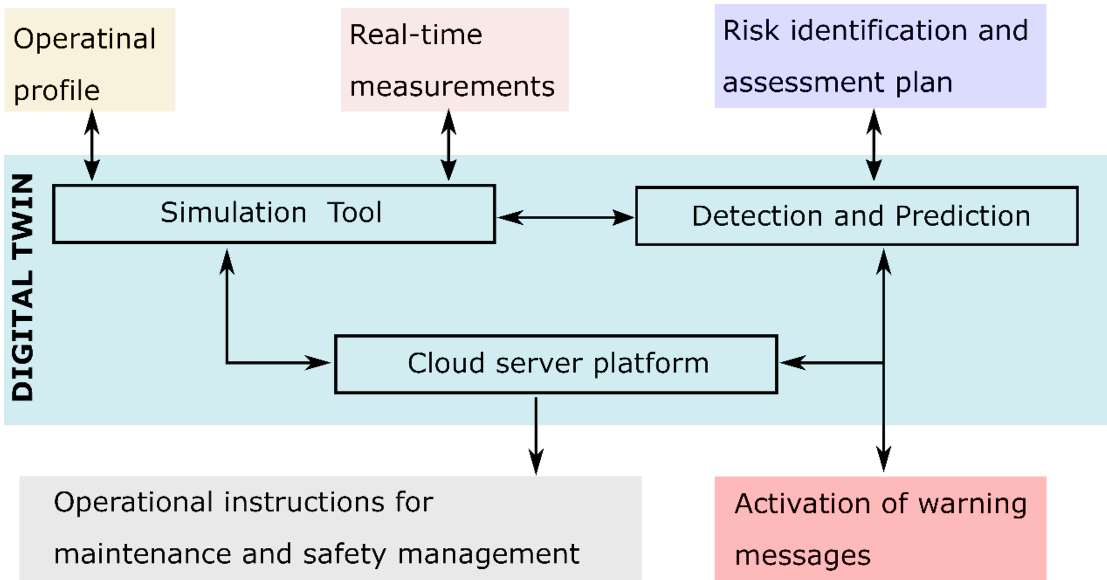


Figure 53 The achievement of a true Digital twin model

Assessing typical structural health monitoring data is challenging; however, the results are direct measurements of the structural response to wave loads. Conversely, calculated stress and fatigue damage estimates from techniques (various simulation tool) may be easier to manage, but the results and influenced by model errors and omissions. By combining physical measurements with simulation tool (as shown in Figure 53), the resulting digital twin benefits from the positive aspects of each method. Also, this fusion may allow measurements taken by one instrumented floating module in an island to be used by models of all other floating modules. As shown by Zhu and Collette (2017) [Ref. 3], the calculated vertical bending moment distributions using limited hull monitoring data with Bayesian models was improved. Their approach changes the skewness and kurtosis (although other statistical parameters could be changed) based on comparisons between numerical predictions and those derived from measurements. Another approach by Mondoro et al. (2016) [Ref. 4] uses limited structural health monitoring data to estimate the monitored ship's structural response to conditions not experienced in the monitoring campaign. Their technique uses accepted forms for sea wave spectra to fit the observed power spectral density of structural health monitoring measurements. Challenges in this research area are related to identifying methods to merge physical measurements with calculated values, performing the appropriate data analytics, and validating the results. Although significant work may be required before this area is sufficiently mature for use with a floating island, it has great promise for a digital twin. If sparse instrumentation is sufficient to correct modelling errors and omissions, the structural fatigue component of a digital twin described herein could be accurate and applicable for a floating island.

5.1.4 Digital Twin State

This section provides a brief overview of some of the benefits that could be realised by incorporating rigid body dynamics and structural fatigue into a digital twin. Figure 54 shows the potential benefits using the digital twin.