PSA STUDY STRUCTURAL HEALTH MONITORING OF OFFSHORE STRUCTURE BY USE OF SENSOR DATA

Structural health monitoring by use of sensor data

Petroleumstilsynet

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Customer: Petroleumstilsynet
Professor Olav Hanssens vei 10
4021 STAVANGER
Norway
Customer contact: Bjørnar Owren
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DNV AS Energy Systems
Technology Centre Oslo Advisory-4100-NO
Veritasveien 1
1363 Høvik
Norway
Tel: +47 67 57 99 00
VAT ID: 945 748 931

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Objective: This report explores structural health monitoring (SHM) as a decision support tool to assess the structural health of offshore structures. The main objective of this report is to evaluate how SHM may be used to improve safety and inspection and maintenance planning with use of sensor data and structural failure history. The report evaluates different SHM approaches, including strengths and weaknesses, and contains some examples of use of SHM for both maintenance planning and to capture safety critical behavior of offshore structures.

Prepared by:

Horn, Agnes Marie Digitally signed by Horn, Agnes Marie Date: 2024.02.21 09:01:52 +01'00'

Agnes Marie Horn
Senior Principal Specialist

Storhaug, Gaute Digitally signed by Storhaug, Gaute Date: 2024.02.21 11:09:45 +01'00'

Gaute Storhaug
Senior Principal Specialist

Håland, Joar Digitally signed by Håland, Joar Date: 2024.02.21 15:50:38 +01'00'

Joar Håland
Principal Specialist

Jagite, George Digitally signed by Jagite, George Date: 2024.02.21 10:46:33 +01'00'

George Jagite
Senior Engineer

Verified by:

Ole Gabrielsen Digitally signed by Ole Gabrielsen Date: 2024.02.21 10:22:07 +01'00'

Ole Gabrielsen
Team Leader
Floating Structures

Approved by:

Sigurdsson, Gudfinnur Digitally signed by Sigurdsson, Gudfinnur Date: 2024.02.21 13:00:24 +01'00'

Gudfinnur Sigurdsson
Head of Section – Environmental Loading & Response

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1 EXECUTIVE SUMMARY

To prevent unwanted incidents with possible loss of structural capacity of offshore installations, this report explores structural health monitoring (SHM) as a decision support tool to assess the health of an asset. The main objective of SHM is to detect a structural failure and may further be used to provide warning on potential future structural failures, to localize a structural failure and finally to evaluate the consequence of a detected structural failure. The report covers state-of-the art SHM methodologies which is input to maintenance and inspection planning.

The use of SHM as a diagnostic tool is crucial for more accurate prediction of an asset's condition and integrity and to reduce risks of structural failures, especially having in mind that the life span of several offshore structures will exceed their initial design life and new assets may be designed for up to 50 years life. It is also envisaged that with a SHM system in place, the information from such a system may replace and or limit inspections. The SHM may vary in extent depending on purpose and may consist of sensors, source data, data storage, monitoring systems, models/algorithms, and applications.

Design according to rules and regulations may be associated with large uncertainties when it comes to accurately predicting the limit state of offshore units, however, the magnitude of the uncertainty is difficult to quantify. Sensor data in combination with numerical models (digital twin) representing the unit's capacity may reduce the uncertainties related to loading and structural response. However, sensor data of an offshore unit may not alone capture safety-critical behavior not yet experienced /51/.

Digital technologies offer great opportunities for structural integrity management (SIM) where the different real-time SHM approaches may contribute and link various information together (see Figure 1-1). Important parameters influencing the structural integrity may be checked and measured in real time like environmental parameters, structural responses (stress and fatigue loading), deflections, vibration, and material degradation (corrosion) or coating break down. Digitalization is currently boosting this technology for structural diagnosis and prognosis based on model-based, data-driven, or hybrid solutions. Hybrid twin solutions combining numerical predictions with sensor information of a given structure to evaluate its integrity, is believed to be the most accurate solution to reduce uncertainties in loading and response of complex structures subjected to fatigue and extreme loading events. Sensors are also more likely to detect anomalies like excessive vibrations or sudden failure. With sufficient and reliable data, the data driven twin offers great opportunities for SHM when considering many units and not necessarily only sister units.

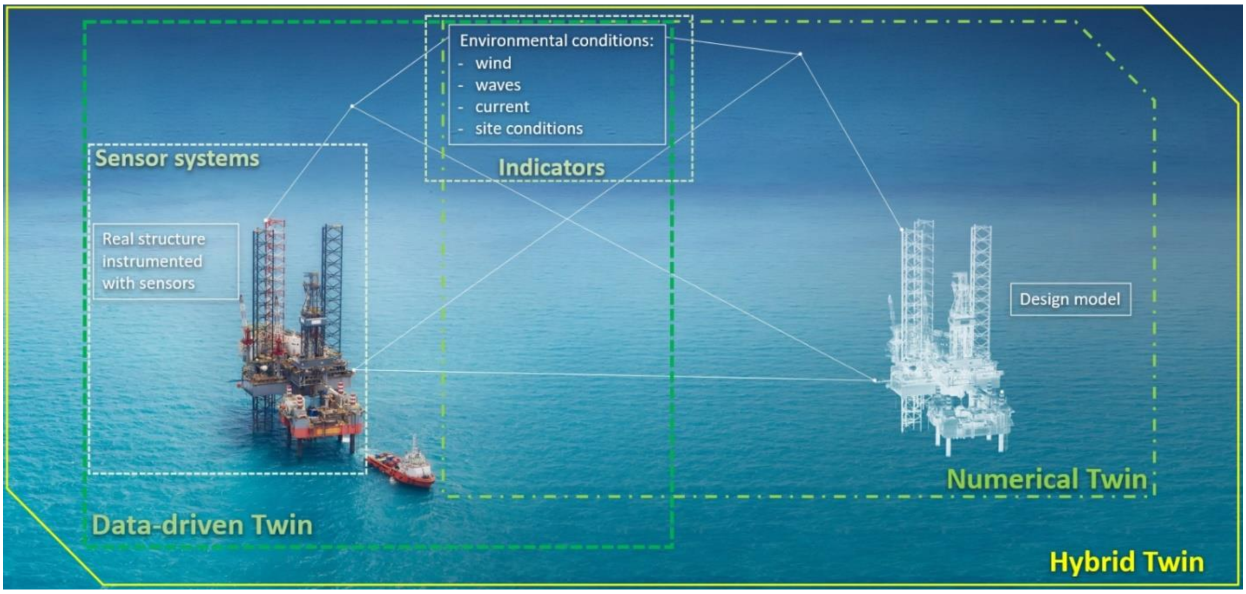


Figure 1-1 Various SHM approaches linking environmental loading, structural responses, and structural capacity.

Fixed or floating offshore structures, including mooring lines, may need a different sensor setup and different SHM approaches, where the most common once are discussed in this report.

For fatigue cracking, representing by far the most frequent reported failure mechanism of oil and gas facilities on NCS /2/, there are several SHM approaches available, e.g., the numerical and hybrid twin concepts. For major hazards, which cover many different types of possible failures mechanisms, several different SHM approaches are regarded necessary, some being addressed below:

- For excessive vibrations these are relatively easily covered by sensors like strain gauges, accelerometers, velocimeters or alternatively camera-based solutions like digital image converters (DIC). Significant and unexpected change in the natural frequency is a frequently used approach to detect significant structural failures on many fixed jacket structures although not used so much on the NCS.
- Broken mooring lines can be caught by the surveillance by use of AIS or GPS based SHM solutions of the floater, but also based on tension measurements of the mooring lines itself. This may potentially result in a high-risk failure since significant offset introduces high bending moment in the riser system which can cause structural failure to the wellhead and release of hydrocarbons. Hence, early detection is important.
- Tendon failure on Tension Leg Platforms can be monitored by use of sensors (most often strain sensors) attached to tendons. Due to challenges of cabling of more traditional sensors, piezoelectric patches are currently explored as the sensors do not require any battery /53/.
- For leakage caused by pitting and grooving, rupture from impact, leakage detectors, moisture detectors, gas detectors and ullage monitoring of tanks filled with liquid are viable solutions (gas detectors are common for LNG membrane tanks).
- For ship impact from supply vessels, camera and/or radar-based solutions are necessary tools to be installed onboard as part of a collision avoidance monitoring system and to be able to detect and report undesirable manoeuvring close to the facility. Commercial systems exist. Proposals for improvements to online decision support for safer FPSO and Shuttle tank tandem off-loading operations have also been made by several researchers. However, other vessels than supply vessels and shuttle tankers may be relevant and even icebergs also covered by commercial systems. Marine traffic data based on AIS, see NAIS | NAIS - BarentsWatch (kystverket.no), in combination with radars may also support to identify vessels which are on collision course. In principle such anti-collision risk system may be supported from shore on a national level (but understood not to have been formalised) but has been already demonstrated to assess collision risk along the Norwegian coast also to plan for location of rescue vessels. In addition, the rescue coordination centre and DNV ERS (emergency response service) have drift models to predict time to collision for ships that have lost propulsion, and this is a subscription service which has already been used in relation to a possible platform impact.

The focus of SHM in research and literature is high and increasing. Many solutions exist today, but most have not fully reached commercial application or as part of SIM but are more ad hoc activities or part of research pilots. Population-based SHM is related to the offshore wind industry representing identical or very similar units, but has a potential for mooring lines, risers, flare towers or even sister units within a certain geographical area where conditions are similar.

A framework for SHM within the SIM is proposed and supported by international standards and recommended practises, but to a limited extent defined and required in rules and regulations. A main issue is also that the terminology “SHM” is not properly defined, which is the case in NORSOK and DNV rules for offshore units or other marine structures. The relation between sensors, sensor systems, monitoring systems, SHM and SIM is illustrated in this report and a definition of SHM is proposed.

It is again emphasised that thorough planning of SHM needs to be done in the context of SIM. It should also be considered how SHM with more well documented data may be used for further improvements to design, inspection regime, rules and regulations.

This report addresses use of SHM of offshore structures, while for topside processes systems a PSA report on SHM for topside piping systems and equipment is already available, see /46/.

1.1 Abbreviation and definitions

Abbreviations used in this report is listed in Table 1-1.

Table 1-1 Abbreviations

Term	*Description*
CBI	condition based inspection
CFD	computational fluid dynamics
CVI	close visual inspection
DFF	design fatigue factor
DFU’s	defined hazard and accident conditions
GVI	general visual inspection
HISC	Hydrogen Induced Stress Cracking
ISSC	International Ship and Offshore Congress
NCS	Norwegian Continental Shelf
NDT	non-destructive testing
POD	Probability of detection
PSA	Petroleum Safety Authority Norway (in Norwegian “PTIL” www.ptil.no)
RAO	response amplitude operators
SIM	structural integrity management
SHM	Structural health monitoring
SMYS	Specified minimum yield strength
SNR	Signal to noise ratio
TBI	time-based inspection
TLP	Tension Leg Platform
Unit	the asset under consideration being a fixed or floating offshore unit

Term	*Description*
UTM	ultrasonic thickness measurements
RIT	remote inspection technique
ROV	remote operated vehicle
RUL	remaining useful life
VIV	vortex induced vibrations
WOAD	worldwide offshore accident databank

Definitions used in this report is presented in Table 1-2.

Table 1-2 Definitions

Term	*Definition*
SHM	SHM is a diagnostic tool that has the objective to detect a structural failure, and may in addition warn, localize and evaluate the consequence of a structural failure.
hazards	something that is dangerous and likely to cause structural failure.
DFU's	«Definerte fare- og ulykkeshendelser» in Norwegian is the same as "defined situations of hazards and accidents" (DSHA) PSA def (PSA homepage) defines DFU's to be: • Leaks of flammable gas or liquids • Well control incidents • Fire/explosion in other areas • Collisions and other structural failure to a facility • Leaks from subsea production facilities with pipelines and associated equipment
digital twin	A digital twin is a virtual representation of a system or asset that calculates system states and makes system information available, through integrated models and data, with the purpose of providing decision support over its life cycle. (From DNV-RP-A204)
examination	combination of those activities used to verify and evaluate the condition of a component or assembly of components in order to determine its ability to perform as required
Inspection	process of examination, measurement and/or testing to determine a condition or state of an item
data-driven model	data-driven models are a computational model that primarily rely on historical data collected throughout a system's or process' lifetime to establish relationships between input, internal, and output variables
sensor system	number of sensors including virtual sensors which reacts to certain physical condition

Term	*Definition*
sensor	a sensor is a device that detects and responds to some type of input from the physical environment
virtual sensors	virtual sensors are numerical sensors or derived based on physical sensors
monitoring system	a monitoring system receives information about the system through measuring devices (sensors), and makes it available to the operator
monitoring	regular recording of operational data and other relevant data to establish the current condition of a piece of equipment and analyses its rate of degradation
mooring system	term used to describe the assembly of components intended to ensure the connection/fixation between the unit to the seafloor. Consists of a number of components such as chain, wire rope, synthetic rope, connecting hardware, clump weight, buoy, winch, fairlead, and anchor
operational barrier element	the actions or activities which personnel must perform to realise a: barrier function. (PSA)
organisational barrier element	personnel with defined roles or functions and specific competence involved in the element: realisation of a barrier function. (PSA)
barrier function	the task or role of a barrier. (PSA)
parameter	variable representing some significant measurable system characteristic (ISO 13372)
failure mechanism	physical, chemical or other processes which may lead or have led to failure (EN 13306)
influence factors	conditions which are significant for the ability of barrier functions and elements to perform as intended (PSA)
predetermined inspection	inspection task carried out in accordance with established intervals of time or number of units of use but without previous condition investigation
risk-based inspection	risk-based inspection (RBI) is a process that identifies, assesses and maps industrial risks (due to corrosion and stress cracking), which could compromise equipment integrity in both pressurized equipment and structural elements. RBI addresses risks that can be controlled through proper inspections and analysis. During the RBI process, engineers design inspection strategies (what, when, how to inspect) that most efficiently match forecasted or observed degradation mechanisms.

2 INTRODUCTION

2.1 Strategy and Vision

History has revealed that structural failures in the oil and gas sector do occur, ranging from minor to major structural failures. The latter may be unacceptable events that can lead to hazards and must be mitigated. The vision for the oil and gas industry is that:

- The oil and gas industry shall not experience any major hazards leading to severe accidents.

The strategy to reduce the risk of structural failures is handled through requirements to design and workmanship during construction phase to ensure a robust structure. During the operational phase, the strategy is related to the individual inspection programs and maintenance scheme of the structure. All information available of a structure's health should be used to facilitate cost effective and justified maintenance and inspection strategies to ensure safety as well as useful decision support when unexpected events do occur. Inspection and maintenance may, however, not be enough, as there may be additional unexpected events taking place during the lifetime of an asset. In the context of SHM the strategy is to:

- Reduce risk of structural failures that can lead to hazards through SHM.

PSA defines hazards in the content of DFU's where the following are listed:

- Leaks of flammable gas or liquids
- Well control incidents
- Fire/explosion in other areas
- Collisions and other structural failure to a facility
- Leaks from subsea production facilities with pipelines and associated equipment

Some of these are related to special events. In the content of this report the well control incidents and collisions and other structural failures to a facility is discussed in the context of SHM.

2.2 Limit state design

Several limit states are relevant to the oil and gas sector. Those are typically identified from the description of specific conditions for which the entire structure, or some components, would fail to maintain the designated functionalities. From the SHM point of view, the main ones are regarded as:

- SLS – Serviceability Limit State where the objective is that the unit is designed to handle the functional conditions it is exposed to during operation.
- FLS – Fatigue Limit State where the objective is that the unit is designed to avoid fatigue cracking of the structure during the operational lifetime in the intended operational area.
- ULS – Ultimate Limit State are those associated with collapse, or with other forms of structural failures which may endanger the safety of people. Limit states prior to structural collapse which, for simplicity, are considered in place of the collapse itself are also classified and treated as ULSs. For structures designed according to NS-EN 1993-1-1, structural failures which imply significant pollution or major financial consequences should also be considered in addition to human safety (Norsok N-004).
- ALS – Accidental Limit State where the objective is that the risk should be limited in case unexpected and unintentional events do occur during the lifetime of the unit. These may be related to structural failures and progressive

development in case of structural failures due to rare events (abnormal environmental conditions, fire, collision, dropped objects) which should be separately reported.

There could potentially be changes to the original design assumptions during operation which may require detailed assessment, some of them being:

- The lifetime may be extended
- The operational condition may change
- The functional or operational conditions may change
- Structural failures may already have developed due to degradations, bad workmanship during construction, increased environmental exposure.

SHM is relevant for all the limit states listed above and is a viable approach to capture uncertainty of change in design assumptions during operations.

2.3 Structural failure scenarios

There are many structural failure scenarios relevant for the oil and gas sector, and these need to be controlled to ensure the asset's structural integrity. The most likely structural failure scenarios will be further studied in Section 3.5 and Section 5, but a list of scenarios is provided in Table 2-1 and where SHM may be a relevant technology to assess the risk and consequence which can be used as input to inspection and maintenance program

Table 2-1 Overview of different failure scenarios

Scenario no.	*Scenario description*
1	Fatigue cracking from low and high cycle fatigue
2	HISC related cracking
3	Pitting and corrosion
4	Dropped object on deck
6	Overloading in yield from extreme loading
7	Local and global buckling from extreme loading
8	Global collapse from extreme loading
9	Dents from local wave impacts
10	Broken mooring line or tendons
11	Water ingress from leakage
12	Impact abnormal environmental conditions (wave in deck)
13	Explosion

2.4 Sensors or sensor systems

Since SHM implies data collection which in most cases involves measurements from a sensor or a sensor system, a clarification is needed on what is characterized as sensors. A sensor is a device that detects and responds to some type of input from the physical environment. It is emphasized that sensors do not only include physical sensors but also virtual sensors either being numerical sensors or derived based on physical sensors. A sensor may also imply a collection of various sensor data to produce a measured or a determined quantity. A list of the most common sensors used for SHM is given in Table 2-2. There may also be other data available which are not regarded as sensors, but as sensor systems. See also DNV-RP-0317 "*Assurance of data collection and transmission in sensor systems"* for further guidance.

Table 2-2 Common sensors relevant for SHM

Sensor no.	*Sensor description*
1	Strain sensors: Uniaxial or multiaxial strain sensors to measure uniaxial stress or shear stress
2	Accelerometers: To measure acceleration
3	Velocimeters: To measure velocity
4	Acoustic emission sensors: to record dislocations, cracks or deformations in materials
5	Vision based sensors, cameras, digital image converter (DIC)
6	Ultrasonic guided-wave sensors
7	Deflection sensors and lasers
8	Wave buoys, wave radars and Doppler wave radars
9	Anemometer and wind sensors
10	Current meters
11	Temperature sensors
12	Position sensors (GPS, AIS) including course and speed over ground
13	Gyro log (heading)
14	Speed logs for speed through water, current radars
15	Motion reference units (MRU) (motion, velocity, acceleration in 6 degrees of freedom)
16	Virtual sensors for any of the quantities above either purely numerical or hybrid sensors based on other sensors
17	Load sensors
18	Echo sounder for water depth
19	Radar
20	Leakage detectors
21	Gas detectors

Sensor no.	*Sensor description*
22	Humidity sensors

Many of the sensors listed in Table 2-2 relates to the environment, but others are more directly related to structural response or even local structural failure detection. One of the possible features with use of SHM for structural failure detection is the possibility to capture the level of vibration and natural frequencies, which may not be addressed during the design. A large change in the natural frequency may imply a structural structural failure whereas leakage detection is useful for assessing the integrity of compartments.

For more details on sensors, this is complemented by Table 5-3 in /3/.

2.5 Monitoring system vs. SHM system

A monitoring system may vary in complexity and may be represented by a single sensor, a sensor system and/or source system where the measured quantities or parameters are collected and processed and provided as output. An illustration is provided in Figure 2-1. The monitoring system should be regarded as part of an SHM system which also includes data collection, models and applications that produce a useful outcome. The outcome may be detection, warning, prognosis or fit for purpose evaluation. In certain cases, the monitoring system could be the SHM system, but usually the monitoring system shows the status of parameters which may be input to a more global SHM system.

To take a common example, the monitoring system may be a hull monitoring system according to the ship rules DNV-RU-SHIP Pt.6 Ch.9 Sec.3, which provides sensor data and fatigue structural failure accumulation at the measured locations, but not at the critical areas or inspection points. However, for a ship-like structure it could potentially measure the still water bending moment and wave induced bending moment including wave induced vibrations which may be compared with the collapse strength of the cross section thereby transparently and directly showing the hull girder utilization on a display onboard. In this case it provides a warning if the utilization is high. Such a system may also be relevant for an FPSO. The hull monitoring system is then an SHM for the extreme loading for hull girder collapse, but not for fatigue cracking where it is only a monitoring system.

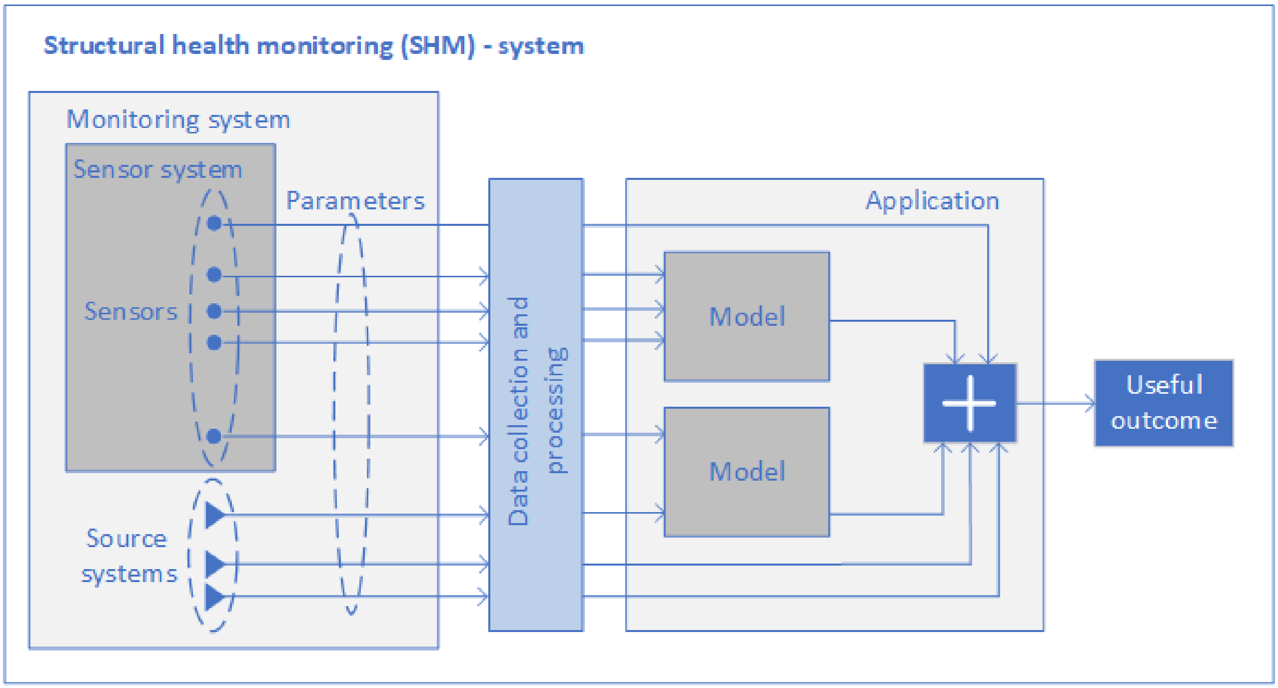


Figure 2-1 Illustration of possible components within a SHM system.

2.6 Definition of SHM

Based on the vision, limit states, regulations, examples, and structural failure scenarios it is relevant to define different levels of SHM. Ryther's /6/ defines four categorizations of structural failure detection which is regarded essential for SHM systems:

- Level 1: The method gives a qualitative indication that structural failure might be present in the structure (Detection).
- Level 2: Level 1 + the method gives information about the probable location of the structural failure (Localization).
- Level 3: Level 2 + the method gives information about the size of the structural failure (Assessment).
- Level 4: Level 3 + the method gives information about the actual safety of the structure given a certain structural failure state (Consequence).

Two additional stages are added here in the case a structural failure has not yet occurred, but may occur in the near future or to simply confirm that the asset is fit for purpose accounting for uncertainties present at the design stage:

- Prognostic: the method may give information if there is a likelihood of structural failure to occur in the near future (Warning/prognosis).
- Fit for purpose: the method may be used to validate or verify that the strength of the structure is sufficient.

The SHM may also be related diagnostics looking back at what has happened but also for prognosis considering what may happen in the future.

Based on this SHM is defined in the context of this report as:

> ***SHM is a diagnostic tool that has the objective to detect a structural failure, and may in addition warn, localize, and evaluate the consequence of a structural failure.***

It is evident from the study that many regulations, rules, standards, and publications addressing SHM or the intended objective of SHM scheme do not really define it, e.g., NORSOK N-005:2017. A common definition of SHM should be defined and agreed within the energy and maritime sectors.

2.7 Practical examples of use of SHM

To understand the wide range of possible structural failures and situations that may occur some examples are given in Table 2-3. The examples are taken from real life experience mostly from DNV classed units in operation, although considering anonymity to a specific asset. In appendix D, example of structures and sensor system providers are provided.

Table 2-3 Example of structural failures with decision support from SHM system

Example no.	*Case*
1	Flare tower: SHM used to determine if fatigue structural failure could be repaired during normal operation and determine the operational window for the repair.
2	Bottom fixed mobile offshore unit: Fatigue structural failure detected in the leg close to bottom. Was the fatigue crack caused by poor workmanship or high wave loading? SHM confirmed it was high wave loading, so the offshore unit was found unsuitable for the current location.
3	Ship shaped unit: Claimed fatigue structural failure found in several locations on a relative new unit operating in harsh environment. SHM confirmed that the high cycle and low cycle fatigue loading had

Example no.	*Case*
	been low, so the apparent fatigue crack was poor coating quality which cracked at hot spots without real fatigue structural failure of the structure.
4	Ship shaped unit: Fatigue cracking occurred after 15 years. Should the detail be repaired to original standard? SHM confirmed that unit was relocated, and fatigue structural failure occurred 1 year after relocation. The first 14 years the fatigue loading was insignificant, so in practice the fatigue life was 1 year, and the repair needed significant design improvement.
5	Ship shaped unit: DNV class required extensive strengthening of a new design beyond normal rule requirements. 800 tons of steel added. SHM confirmed few years later that the strengthening was necessary and saved the structure from potential collapse.
6	Floating offshore unit: Broken mooring line structural failure. SHM system confirmed that unit was moved 70 m to a new position (in such case potential progressive structural failure to riser system)
7	Jackets: Severe structural failures to struts, bracings, columns. SHM system uses sensors to reveal changes in natural frequencies before and after storms to reveal structural failures which has occurred on many platforms in the Gulf of Mexico.

2.8 Application of SHM

The application and focus of this report are towards use of SHM for fixed and floating structures, including mooring and tendons /52/, with a secondary focus on structures for renewable energy like fixed and floating offshore wind farms. Guidance related to the topside equipment is addressed in /46/.

The focus related to structural failures are on:

- major incidents (hazards) which have high consequence, but with low probability of occurrence
- minor incidents which have low and intermediate consequence, but with higher probability of occurrence

On the NCS fatigue failure was categorized as the failure type occurring most frequently /2/. Together with dents and corrosion it is the main failure types addressed by the survey regime and relevant for inspection and maintenance planning /2/.

For major incidents, a different type of SHM may be necessary and the use may be more event-based as input to maintenance planning, see section 8 which presents how SHM can be used to capture safety critical behavior of offshore structures. SHM may in both cases be defended by a cost-benefit analysis, and where the SHM is intended for continuous use and should be designed for the life of the assets.

3 SCOPE AND RELATION TO PREVIOUS PSA STUDIES

3.1 Background

The use of sensor data for safety and maintenance purposes has been used by many industries for decades and the aerospace, health and civil engineering industries have been pioneering industries. Relevant sensors are also installed on several offshore units, but often only used to monitor unwanted behavior caused by dynamic environmental or process loads and not actively used as decision support for SHM. NORSOK N-006:2015 A.8 also provide some guidance related to measurements made to calibrate wave loads and the calculation models.

However, the use of sensor data is not considered a mature technology in all areas, such as assessing the structural integrity and use in inspection planning of an assets. There are, however, many reasons for the limited use of sensor data for offshore structures, where the major challenge has been more practical and related to battery and cabling limitations, and to retrieve relevant sensor data ashore for evaluation and decision support. The latter is no longer considered a major challenge, as it is becoming more common to process data locally at the oil and gas facilities. In addition, lack of rules and regulations, cost related to planning, operation of sensor systems, data acquisition, analysis and development of decision support tools and approval and management are not in place.

Norsok N-005 provide guidance to Risk-based inspection (RBI), this is a tool/framework that can benefit from increasing the accuracy by use of sensor data. However, today limited platforms actively use sensor systems for decision support related to structural integrity. One of the reasons why so few platforms are instrumented is that we engineer so far have failed to show a positive cost-benefit using real-time measurements for decision support. The potential and value of real time sensor data both for SHM and input to risk-based inspection (RBI) is therefore considered large.

The value depends on the type of structure, functionality and consequence of a possible structural failure or downtime. For sister units at similar location (e.g. wind farms), it may be relevant to monitor some structures and use experience from these to evaluate remaining structures, alternatively to monitor a few in detail and the rest with marginal instrumentation. These are variations of new methods that fall under the term «population-based structural health monitoring (PBSHM)» which may be relevant to mooring lines, tendons, similar units, or the renewable industry like wind farms.

The oil and gas assets that are approaching its design life, have generally been designed for a life of 20-25 years, however, several new assets have today a design life of up to 50 years. The increased operational life will put even higher demand on the documentation of SHM as of today because the industry has limited field experience with such long operational time frame. In addition, it is of high importance to have consistent track records of degradation mechanics and fatigue crack growth for such long lives.

The field of SHM is developing quickly in line with digitalisation and a framework is appearing. For fixed structures like jackets, where the industry has large operational experience, and where several jackets have been retrieved and inspected, the information gained should be reflected in a common industry practice for use of sensor set-ups. Also, for floating assets like TLPs, FPSOs and Spars, a common industry standard should be established to easier adopt an SHM system based on active use of sensor data.

A possible process for establishing SHM systems is illustrated in Figure 3-1. The illustration should not be confused with the integrity management loop - as described in e.g. NORSOK N-005, DNV-RP-0002, API RP 2SIM and ISO 19901-9. The planning phase is important prior to new installation of a SHM system both for new built assets but also for assets in operation. For retrofit of new SHM on existing structures, there may be other considerations that are necessary compared to new built, and the need may differ depending on age and accessibility. Considerations and values may therefore be different for new and existing offshore units.

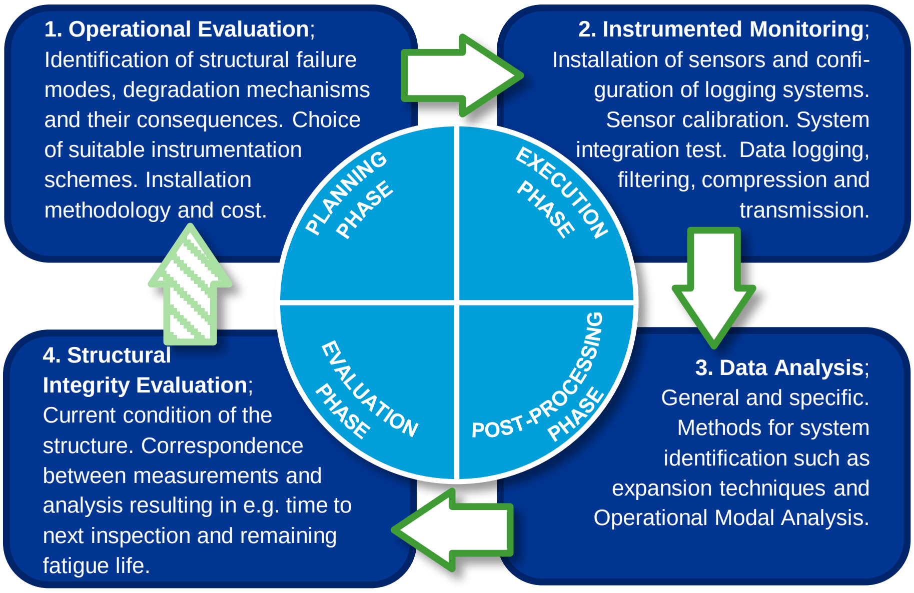


Figure 3-1 Illustration of SHM process.

DNV’s energy transition report for Norway published in 2023 /19/ suggests that the oil and gas sector will continue at a high production rate, but with roughly halved energy production by 2050 compared to today’s levels. Many of the existing structures are expected to remain operational which imply continuous aging of the units and for many beyond their design lives. This increase in life must not compromise the safety of the asset. SHM may here have an additional benefit to reduce the risk of a critical event by reducing its probability, which is illustrated in in Figure 3-2.

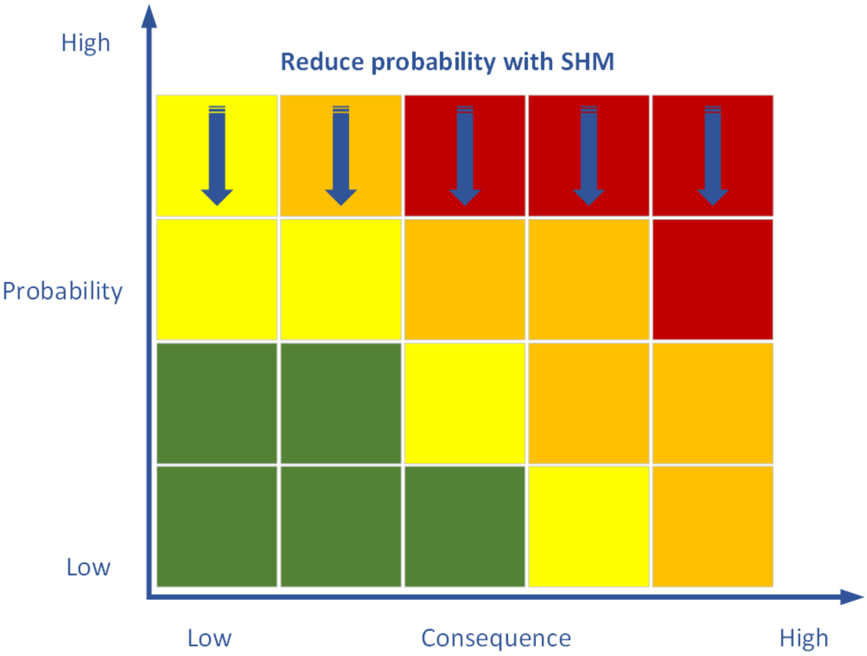


Figure 3-2 Desired outcome of SHM systems.

3.2 SHM practice for oil and gas sector at NCS

To make more rational decisions, the offshore industry early recognized that design, fabrication, and inspection were subjected to uncertainty and adopted risk and reliability methods. The integrity management framework used in Norsok N-005 /13/ is shown in Figure 3-3 where the “control of as is condition” is relaying on data, evaluation, inspection and execution of monitoring programs. In this context, the use of sensor data may increase the accuracy of the structural integrity management decision tool as more reliable data linked to the structural response can be collected and assessed more accurately, and further knowledge may be used as input to the monitoring program.

Reliability methods are crucial to support decisions about safety and economy of degrading structures and this is well documented in Norsok N-005 with reference to RBI in DNV-RP-C210 “Probabilistic methods for planning of inspection for fatigue cracks in offshore structures” /28/. Limited guidance is provided on how in-service integrity management of structures and marine systems can be improved by use of sensor data. The standard includes the following advice:

- Installation of sensors or other measuring devices may be needed or desired to monitor critical areas, such as fatigue sensitive areas, grouted pile-sleeve connections, bridge movements relative to bridge landings etc.
- Monitoring may also be used to identify the natural period and survey possible change in the natural period over time, and to calibrate/validate analysis methods for extreme storms and fatigue.

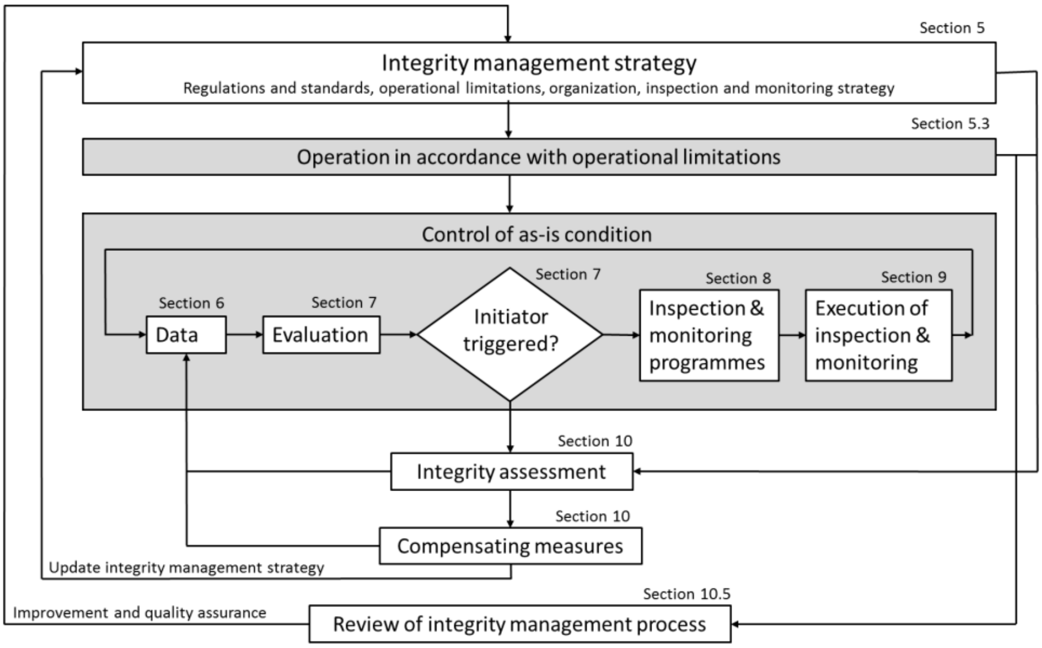


Figure 3-3 Integrity management process /13/.

3.3 PSA Regulations

The main principle of PSA’s requirements is that the companies involved shall know the condition of their equipment both individually and collectively and work continuously to reduce risk. There is further a requirement that conditions that are important for a sound and safety-wise execution of the activities are monitored and kept under control at any time (management regulations § 10 /18//). In addition, one must work continuously to identify the processes, activities, etc. where improvements are needed and implement necessary improvement measures. The full set of PSA regulations can be downloaded at PSA - Home (www.ptil.no). In the following, regulations where use of sensors technology will be an important technology to support the decision management making are listed from the Management Regulations, the Facilities Regulations and the Activities Regulations **/**18/**:**

§ 5 ‘Barriers’

Barriers shall be established that always can:

a) identify conditions that can lead to failures, hazard and accident situations,

b) reduce the possibility of failures, hazard and accident situations occurring and developing

c) limit possible harm and inconveniences.

Personnel shall be aware of what barriers have been established and which function they are intended to fulfil, as well as what performance requirements that have been defined in terms of the concrete technical, operational or organisational barrier elements necessary for the individual functional barrier to be effective, see Figure 3-4.

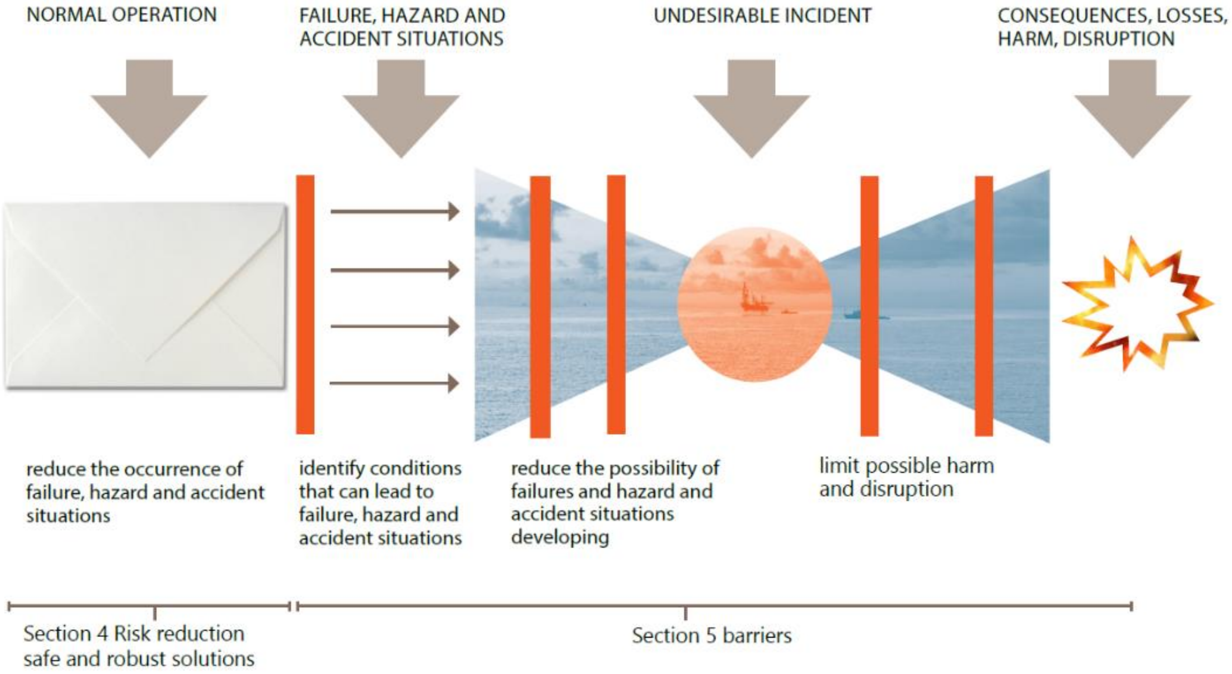


Figure 3-4 Bow tie with barrier functions in accordance with PSA Management Regulation /20/.

§ 19 ‘Collection, processing and use of data’ (the Management Regulations)

The responsible party shall ensure that data of significance to health, safety and the environment are collected, processed and used for:

1. monitoring and checking technical, operational and organisational factors,

2. preparing measurement parameters, indicators and statistics,

3. carrying out and following up analyses during various phases of the activities,

4. building generic databases,

5. implementing remedial and preventive measures, including improvement of systems and equipment.

§ 17 ‘Instrumentation for monitoring and recording’ ("The Facilities Regulations)

Facilities shall be outfitted with instrumentation for monitoring and recording conditions and parameters that can be significant in verifying the results from analyses, as well as parameters of significance to the facility's further use. The instrumentation should be designed so that it can monitor and record:

1. structural integrity for load-bearing structures and pipeline systems: Monitoring of structural integrity includes recording parameters that result in significant tension or compression stress, or large movements as a result of waves and currents.
2. critical degradation of materials: Critical degradation may include corrosion and erosion. In order to monitor corrosion, multiple independent corrosion monitoring systems may be relevant if maintenance, including inspection, is difficult to perform.
3. critical operational parameters: Critical operational parameters can include the drilling fluid's properties, pressure and particle content in the production stream, pressure in seal oils in swivels and gas composition and pressure in facilities for manned underwater operations.

§ 47 ‘Maintenance programme’ (The Activities Regulations)

Failure modes that may constitute a health, safety or environment risk shall be systematically prevented through a maintenance programme. This programme shall include activities for monitoring performance and technical condition, which ensure identification and correction of failure modes that are under development or have occurred. The programme shall also contain activities for monitoring and control of failure mechanisms that can lead to such failure modes.

§ 50 Special requirements for technical condition monitoring of structures, maritime systems and pipeline systems (The Activities Regulations)

Technical monitoring of new structures and maritime systems shall be carried out during their first year of service.

For new types of load-bearing structures, data shall be collected during two winter seasons to compare them with the design calculations.

When using facilities beyond their original design life, instrumentation of relevant structure sections shall be considered so as to measure any ageing effects.

When facilities are disposed of, the operator shall carry out studies of the structure's condition. The results shall be used to assess the safety of similar facilities.

3.4 Purpose of this PSA study

The purpose with this study is to continue the work carried out in 2021 and 2022 regarding use of digital solutions and SHM to ensure structural safety. The previous studies are covered by the two PSA reports from Rambøll, /2/ and /3/.

The current study should consider the strength and weaknesses of SHM methods with specific focus on worldwide accidents and how SHM could have been used to reveal structural failures earlier and provide information on the course of the events. This should especially represent a continuation of the work from 2022 regarding which type of structural failure and defects that can be revealed by use of SHM.

Further it was desirable to continue to evaluate the data which was produced regarding structural failures and defects in /2/. In addition, it is desirable with a simple walk-through on how population based SHM may be used for offshore structures.

3.5 Review of previous PSA work

In 2022 two reports were issued on behalf of PSA related to SHM of offshore units. In the following, the main findings of the are provided below. It is recommended to read these two reports in conjunction to this report as it is a continuation of the published work by Rambøll:

- “The use of digital solutions and structural health monitoring for integrity management of offshore structures” February 2022 /3/
- “The evaluation of structural failure detection and structural health monitoring for integrity management of offshore structures” December 2022 /2/

The first report /3/ provides an overview of relevant parts of ISO, API /52/ and NORSOK standards that cover specific requirements for offshore structures with focus on design, fabrication, transportation, installation and in-service conditions. In general, the guidance addresses structural integrity management (SIM) and not SHM. One key standard is NORSOK N-005 “in-service integrity management of structures and marine systems” which is widely used by the operators at NCS. Rambøll concludes that “*a framework that includes requirements of structural monitoring systems and the application of SHM on offshore structures is lacking*” (this framework is what this report will try to highlight) and that there is limited information (guidance or frameworks) in the existing codes and standards regarding these topics. The report also presents sensor technologies like accelerometers, stain gauges to more advanced sensor techniques like acoustic emission for measuring crack growth and electrical resistance (ER) probe for corrosion measurements. Further it emphasises the challenges of data management and the importance of the planning phase for successful use of SHM. Rambøll points out that success by use of sensors is depending on correctly mapping of critical elements related to the structural safety and identification of failure modes are important to consider when designing a structural monitoring system. This mapping is especially useful, see Table 5-1 in /3/. The framework it presents is focused on the use of measurements into the digital twin approach with uncertainty assessment included in an RBI context and focused on fatigue. This is understood as a straightforward RBI approach, but by replacing design assumptions with measurement data. This resembles the DNV FMS(Sens) class notation but without the corrosion part and inspection plan and it defines the framework in a narrow sense around the digital twin design model, see Figure 3-5 related to analysis and “structural failure detection” in terms of fatigue loading. However, the report /3/ gives an additional aspect of the value creation of SHM in Table 7-1 in /3/ related to CAPEX and OPEX which are important considerations. A guideline is also established and presented in the appendix of /3/ related to the framework and related to purchase and use of SHM.

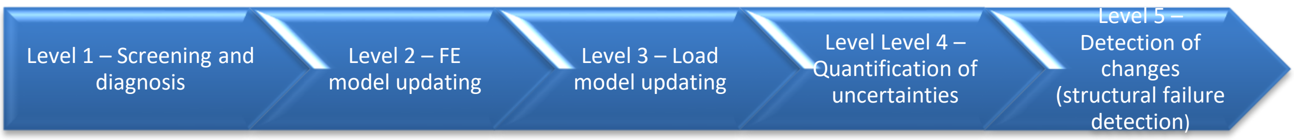


Figure 3-5 Framework for digital solutions and SHM for integrity management /3/.

The second report /2/ starts with a list of offshore structures and an overview of when the 180 units were installed on the NCS with about 95 still in operation, where roughly half are on lifetime extension with most being about 30 years old. The state-of-the-art SHM are presented and categorized into model-based, data-based and hybrid, and includes population based SHM with a decision-making process. This description is relatively limited. An overview of significant structural failure modes on the NCS are presented in Table 1 in /2/ for different offshore structures as well as causes related to storms, earthquakes and vessel impacts. The incidents have decayed after 1990. The last 20 years it is roughly constant without any clear indication of improvement. Few incidents are major, but the major incidents are present. The structural failure database makes up a major part of the report with about 10 significant failure modes. These are listed in Table 3-1.

The final part of the report covers the overview of SHM standards, but related mainly to other industries covering wind turbines, transportation, bridges, buildings and viaducts. These may, however, be useful in establishing standards for offshore units even though half of them is old, see Table 4 in /2/. However, it points out that the number of standards is rising the last decade but lacking for the offshore energy sector except the renewable sector, which is newer than the offshore sector, but still has at least two guidelines.

Table 3-1 Significant failure modes from /2/

Failure mode no.	*Description*
1	Cracking (through thickness) due to fatigue and corrosion
2	Member separation due to fatigue or corrosion
3	Missing member due to fatigue or corrosion
4	Dents and bows due to vessel impact or dropped objects
5	Grouted connections (slippage and failure) on fixed installations
6	Overloading (settlement and subsidence) on fixed installations
7	Scour on fixed installation
8	Excessive/unexpected vibrations for multiple reasons
9	Bridge bearing issues (interconnecting bridges) for multiple reasons
10	VIV issues due to wind, wave or current actions

From Table 3-1 from Table 3 in /2/ it is evident that fatigue, corrosion, overloading and vibration accounts for much of the significant structural failures on the floating units while the fixed installations also have failure modes related to the seabed interaction and bridges between platforms. It should be noted that dropped objects and ship impacts are included in the failure statistics /2/.

In Section 5.1 two figures from /2/ is included highlighting fatigue as the number one incident in terms of frequency, but that for major incidents the different failure modes are as illustrated in Table 3-1.

4 FRAMEWORK FOR SIM

4.1 Structural integrity management (SIM)

Structural integrity management (SIM) is a continuous process used for demonstrating the “fit-for-purpose” of an offshore structure from installation to decommissioning. SIM provides a framework for inspection planning, maintenance, and repair, see Figure 4-2. The process consists of four fundamental elements:

- data and information collection,
- evaluation and assessment,
- evaluating and selecting a strategy,
- and establishing an inspection program.

When implemented, the process should be continuously improved based on changes and experience.

Introducing SHM as part of structural integrity management (SIM) should be planned and implemented considering the impacts it will have related to systematics, work process, resources, and new support functions. It should also be considered how it may be used as part of barrier management with a clear understanding of its capabilities as well as limitations.

4.2 Barrier management

The introduction of SHM should be considered from a barrier management perspective and how it may be incorporated into barrier management thinking, but that requires precision and careful thinking.- Barrier management involves ensuring, through a systematic and continuous process, that necessary barriers are identified and in place, to provide protection in failure, hazard, and accident situations.

Following definitions in /20/ from PSA:

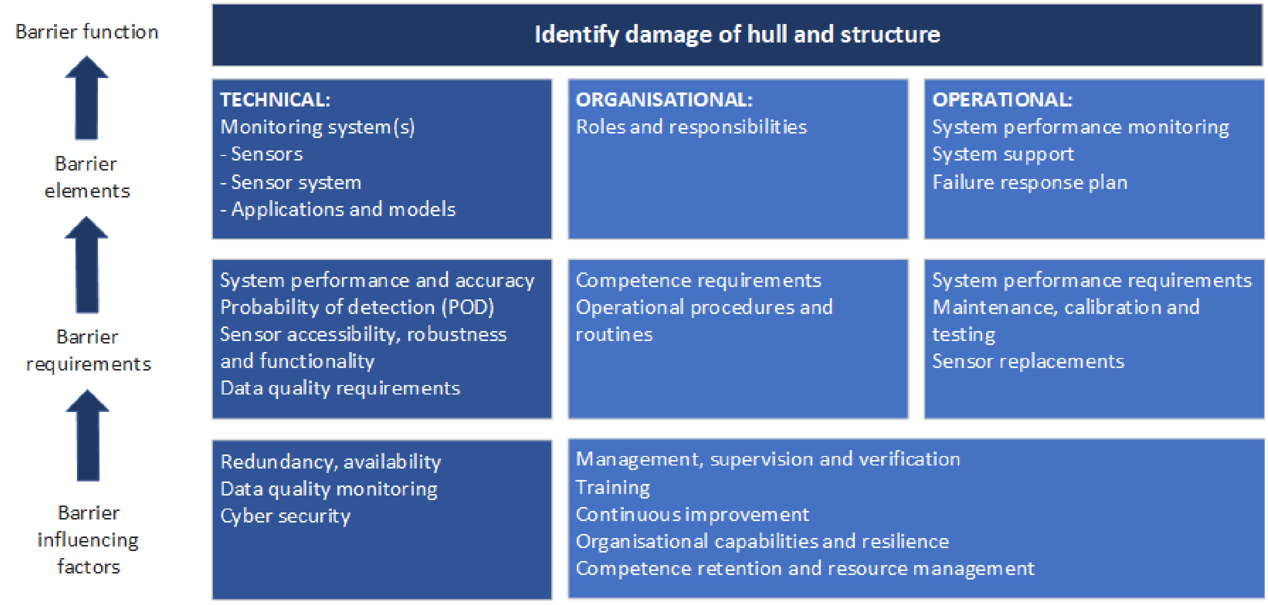
- **Barrier:** Technical, operational, and organizational elements which are intended individually or collectively to reduce possibility for a specific error, hazard, or accident to occur, or which limit its harm/disadvantages.
- **Barrier element:** Technical, operational, or organizational measures or solutions which play a part in realizing a barrier function.
- **Barrier function:** The task or role of a barrier in the chain of events leading from a failure, hazard or accidental situation to the accident.
- **Performance-influencing factors:** Conditions significant for barrier functions and elements to function as intended.

Degradation and failure mechanisms should not be regarded as hazards but more threats to the technical barriers, defined as influencing factors for the barrier function. Inspection and maintenance then become important to limit the effects.

SHM could be defined as barrier element where it is used for detection of hazardous situations for incidents related to structures and marine systems.

SHM is also used to capture usage and condition data to confirm an intact condition, determine when to inspect based on accumulated structural failure, and to establish predictions for remaining useful life. This application is sorted under the general risk management established to avoid failure, hazard,/20/ for more details.

Applying the SHM system as an active preventive technical barrier element and a breakdown according to associated operational and organizational elements by defining barrier requirements and influencing factors is illustrated in the example in Figure 4-1.



Barrier function	Identify damage of hull and structure		
Barrier elements	**TECHNICAL:** Monitoring system(s) - Sensors - Sensor system - Applications and models	**ORGANISATIONAL:** Roles and responsibilities	**OPERATIONAL:** System performance monitoring System support Failure response plan
Barrier requirements	System performance and accuracy Probability of detection (POD) Sensor accessibility, robustness and functionality Data quality requirements	Competence requirements Operational procedures and routines	System performance requirements Maintenance, calibration and testing Sensor replacements
Barrier influencing factors	Redundancy, availability Data quality monitoring Cyber security	Management, supervision and verification Training Continuous improvement Organisational capabilities and resilience Competence retention and resource management	

Figure 4-1 Foundation of barrier management based on PSA /20/ .

The required performance of the SHM system should be ensured by defined requirements for the system, its sensors/sensor system, and the collected data. If the system is unavailable, not able to deliver performance according to requirements and if collected data is compromised, this will render an unsuitable output.

The organizational and operational barrier elements that need to be in place to ensure required performance includes a quality assurance function, see ISO 9001 and ISO 9004, performed by an organization with sufficient recourses, competence, and robustness to deliver a continuous service and support.

As well as the importance of providing (procuring) a robust SHM system that can deliver according to performance requirements, it should be of equal importance to ensure that the organizational and operational elements are implemented and can deliver the support and ensure measurable efficiency upon introduction of SHM.

4.3 SHM based SIM

When integrating the SHM with the SIM systematics as described by /13/ and illustrated in Figure 4-2 the systematics now describes how SHM is introduced both for structural failure identification and for monitoring usage and condition. The figure also resembles/is based on the “Maintenance loop” described in NORSOK Z008 that is widely adopted in the oil and gas and other industries. SHM becomes an additional source of information that provides important input and more accurate understanding of the performance. The systematics (framework) describe 3 essential pillars:

1. **Design** which includes the design basis, design data, industry developments (rules and standards), fabrication and installation data, and operational history (existing installation). This includes the technical barrier element, as described in Figure 4-1.
2. **Operation** representing what should be established to effectively manage the SHM in a SIM systematics. This includes the organizational barrier element, as described in Figure 4-1.This includes SHM as a technical barrier element, see Figure 4-1.
3. **Resources** needed to provide the support and process to ensure a functional operation. This includes the operational barrier element, as described in Figure 4-1.

When introducing monitoring in the operational phase this becomes an additional source of information that provides important input and more accurate understanding of the performance, see Figure 4-2.

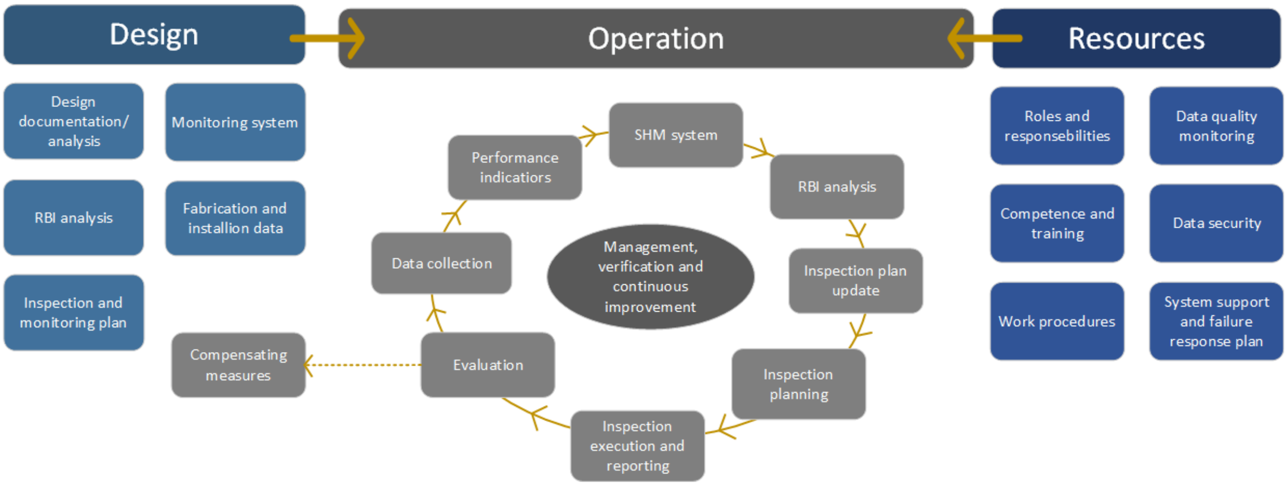


Figure 4-2 SHM within the SIM framework.

Risk-based inspection planning can be done using qualitative, quantitative or by using aspects of both (i.e., semi-quantitative). The methods range from a strictly relative ranking to rigorous calculations. Each approach provides a systematic way to screen for risk, identify areas of potential concern, and develop a prioritized list for more in-depth inspection or analysis.

The inspection and /or monitoring to get information of an asset's condition shall be determined, where the following degradation mechanics and failures should be documented:

- Degradation due to fatigue, corrosion, or other time dependent structural failures
- Fabrication or installation structural failures
- Structural failures due to overloading
- Structural failures due to human errors (workmanship)

4.4 Data driven inspection planning

An inspection plan should be based on the results from a risk-based inspection (RBI) analysis according to Norsok N-005 /13/. The RBI analysis may be performed:

- **based on generic design basis** and assumed operation using historical inspection data and experience from same or similar structures with an inspection scope that is based on a conservative assumption for operational usage/utilization.
- **qualitatively**, combining history and experience from same or similar structures with the specific design/fabrication details. The inspection scope will be more targeted on known special areas subject to higher utilization.
- **quantitively**, based on probabilistic analysis on specific design.

The inspection plan will include predetermined (scheduled) intervals between inspections that should be adjusted according to inspection results when implemented.

The main purpose of introducing SHM is to reduce uncertainties and the possible second benefit is to provide additional information which can be utilized to optimize the inspection plan. By collecting usage and condition data as input for analysis and decision support, the predetermined inspection can be more targeted on items with failure mechanisms and degradations representing high consequence. Targeted inspection using inspection techniques with better accuracy and high performance may be relevant to fit to the specific failure mode and SHM approach.

In addition, condition-based inspection (CBI) planning may be introduced where the item's conditions indicate a need for inspection (when to inspect). SHM also represents monitoring of structural response which may be used as input to predict structural failure events that need attention.

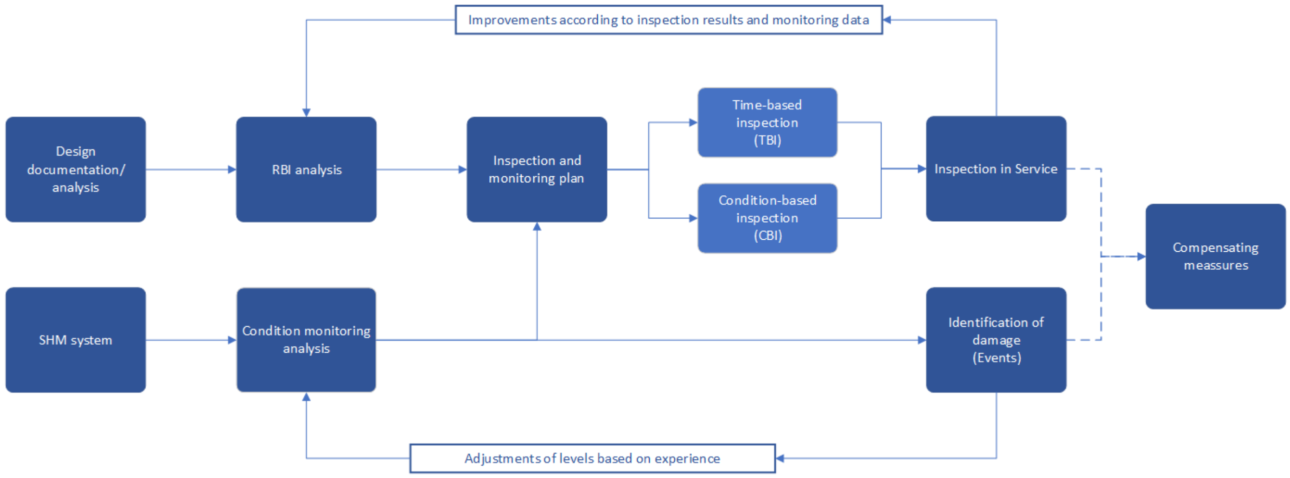


Figure 4-3 RBI analysis as basis for selecting TBI and/or CBI for the inspection and monitoring plan

The SHM system may provide condition monitoring data, represented by fatigue structural failure accumulation, which may result in updated prediction of the accumulated fatigue structural failure which may lead to reduced inspection frequency. An SHM system can also be used to monitor the development of structural failure that has already been detected, but where repair cannot be done promptly. A typical shift from the calendar based to more performance and condition-based inspection is illustrated in Figure 4-5, where the figure to left is illustrating calendar-based inspections, while the figure to the right is illustrating a more flexible inspection regime based on structural condition, opportunities, and events. In between the physical inspections onboard, remote inspections may be carried out as well as data driven or condition-based evaluation as an additional activity prior to potential physical inspection.

Opportunities?

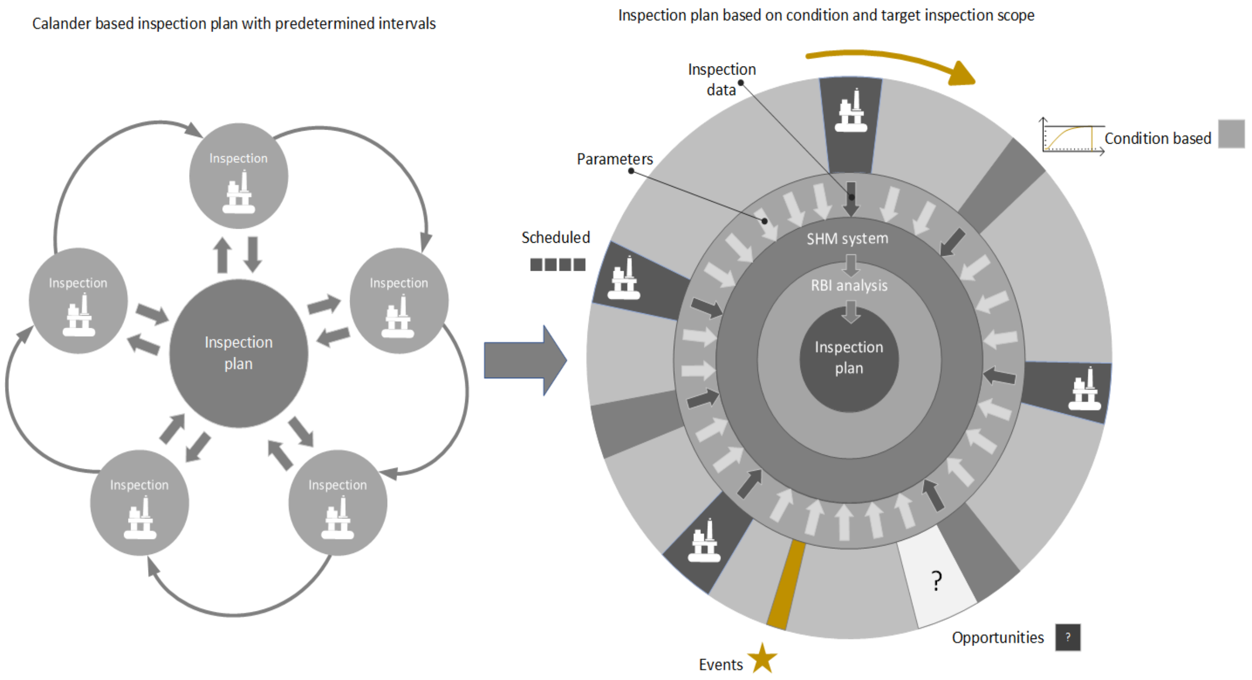


Figure 4-4 From calendar-based survey regime to performance-based data driven inspection.

The structural integrity lifecycle is illustrated in Figure 4-5. The operational experience may provide useful insight which can benefit future design and material selection solutions. The know-how gained should be reflected by development of new and improved design rules.

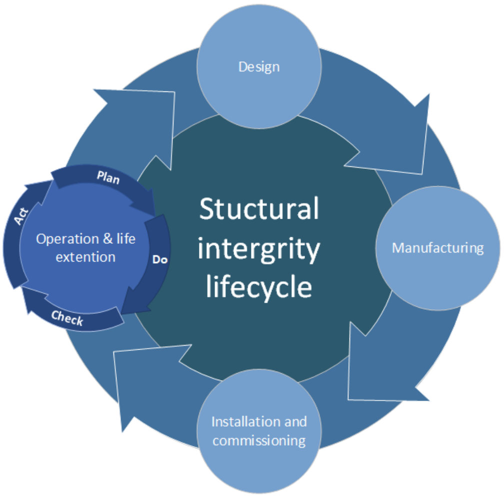


Figure 4-5 Structural integrity lifecycle.

The value and benefit of SHM may then go beyond the cost benefit of the specific unit where SHM in implemented. Dividing the costs through the structural integrity for a specific unit into the following SIM elements:

- Design models
- RBI approach
- Instrumentation with of sensors, establishing and maintaining SHM system
- Developing and maintaining an inspection program
- Executing inspection

These elements are basically fixed costs also without the SHM system, except for the sensor part. The cost of sensor systems may be limited and with the cost may easily be exceeded by the savings in the improved and optimized inspection program, including the inspection. In the case of similar units, the benefit may also be increased considerably. For many of the new built structures, there are already sensors in place to e.g., monitor installation operations which most likely can be used in a SHM context during operation. Still, it has been challenging for so far for engineers to show a positive cost-benefit of using real-time measurements and SHM as a diagnostic tool implemented in SIM.

For rule development and design, it is desirable to instrument the unit early as the costs of the instrumentation are regarded lower at the construction phase than as a retrofit on an existing structure. However, retrofit may also be suitable in case of lifetime extension of the unit to handle uncertainties to degradation of the structure or to monitor a specific structural failure location. Early instrumentation also in case of retrofit is desirable to reduce the uncertainties in prognosis and diagnosis by having more valid data as incorrect data may cause confusion and decision may be taken on wrong assumptions.

4.5 Data quality and security management

Data quality and security management are central both onboard the installation, but also onshore when safety related data is being used onshore and retrieved from offshore units. This is a key element in order to have untampered data which can be trusted and used as decision support. This will not be described in detail, but reference is made to DNV-CG-0564 *Data collection infrastructure*, section 8 /29/ and in Appendix C where a detailed overview of DNV recommended practices is provided.

5 STRUCTURAL FAILURE MODES FOR FIXED AND FLOATING OFFSHORE STRUCTURES

A general statistical overview of common structural failure modes for facilities on the NCS is collected and evaluated in /2/. A total of 10 significant structural "failure modes” were identified and statistics of occurrence for NCS with respect to the structural failure detection possibilities using SHM is presented: crack, member separation, missing member, dents and bows, slippage and failure of grouted connection, overloading, scour, excessive/unexpected vibration, bridge bearing issues and vortex induced vibrations (VIV) issues /2/.

5.1 General failure modes

The general failure modes of steel structures are loss of structural capacity, and the failure mechanics consist of material degradation including embrittlement, material loss, fatigue, and excessive loading. The most common influencing factors causing these failure mechanisms are shown in Figure 5-1.

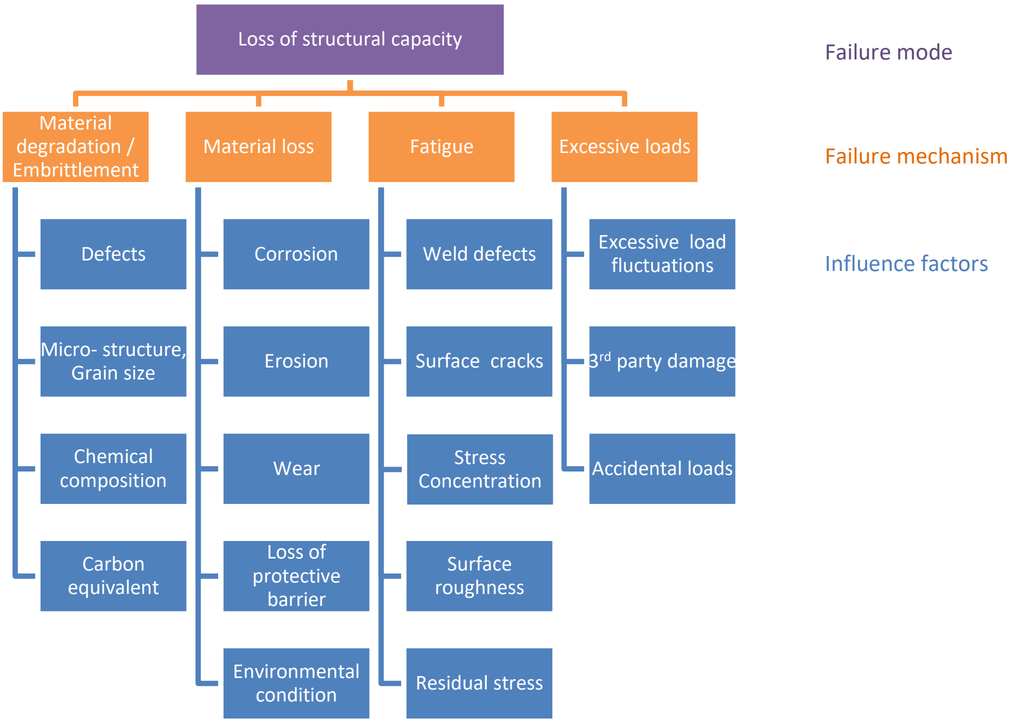


Figure 5-1 Illustration of failure mechanisms and influencing factors of steel structures.

The Rambøll report /2/ addresses reported failures at the NCS from 1974-2021 taken from the CODAM database, the incidents are categorized as insignificant, minor and major. It can be noted that the period with the most reported accidents from 1980-1995, where reported incidents decline significantly. Incidents categorised by anomaly and grouped by severity is plotted in Figure 5-1 and incident causes grouped by severity is plotted in Figure 5-3, further details and statistics are presented in /2/.

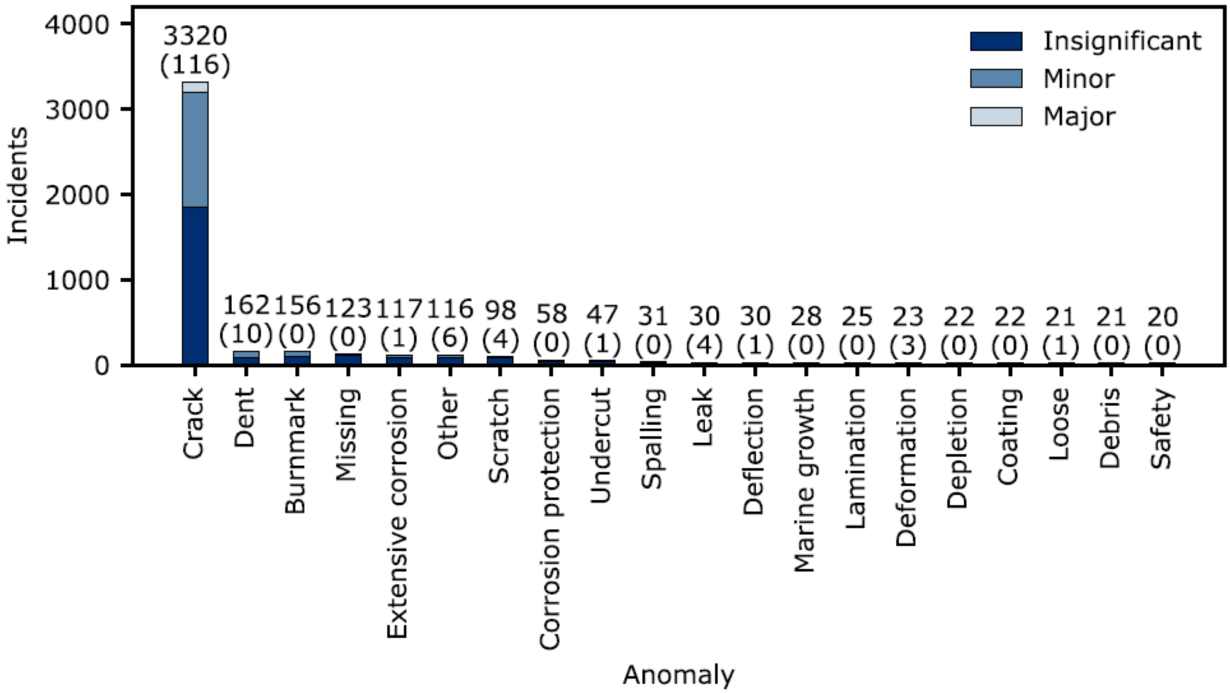


Figure 5-2 Incidents categorized by anomaly and grouped by severity from the CODAM database in the period 1974-2021. The numbers in parentheses indicate major accidents /2/.

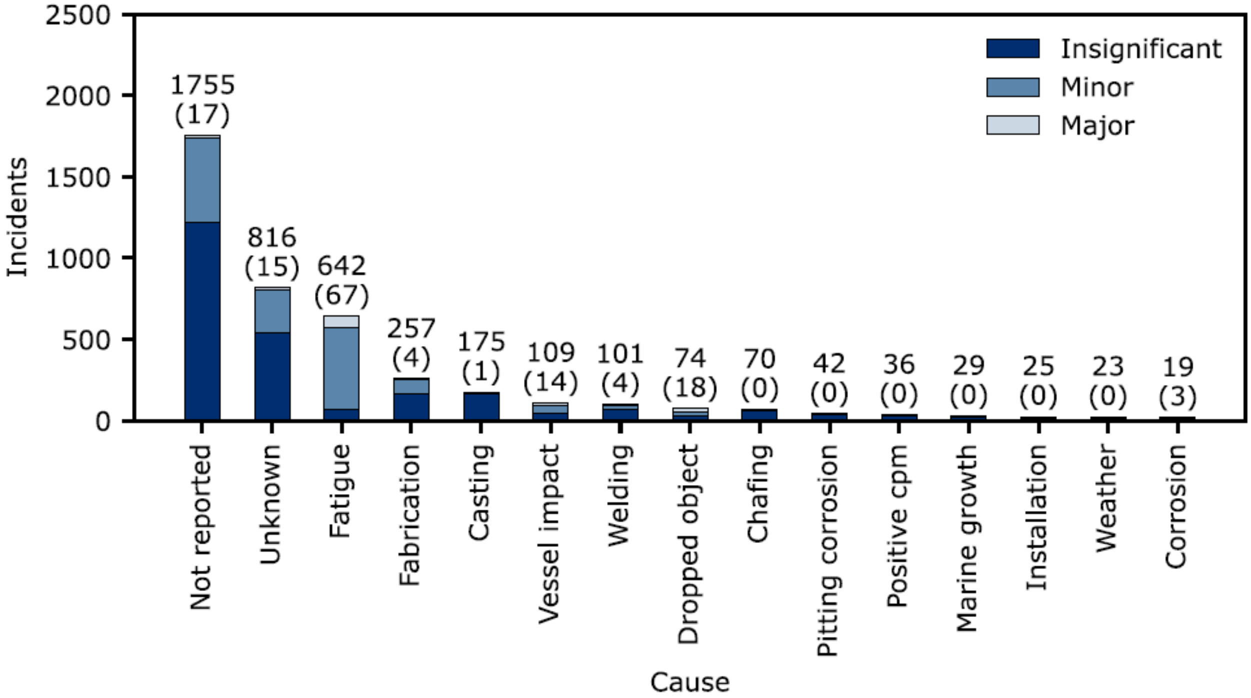


Figure 5-3 Incident causes grouped by severity from the CODAM dataset in the period of 1974-2021. The numbers in parentheses indicate major accidents /2/.

5.2 Failure databases for offshore structures worldwide

The worldwide offshore accident databank (WOAD) consists of a repository of information on accidents occurring in the offshore oil and gas industry from the mid-1970s to 2010. There are 2,288 fatalities currently recorded in WOAD among the recorded 6451 accidents, mostly from operations in North Sea and Gulf of Mexico, see Figure 5-4. Very few accidents from other locations of the world are included, hence, the reported numbers are believed to be underestimated.

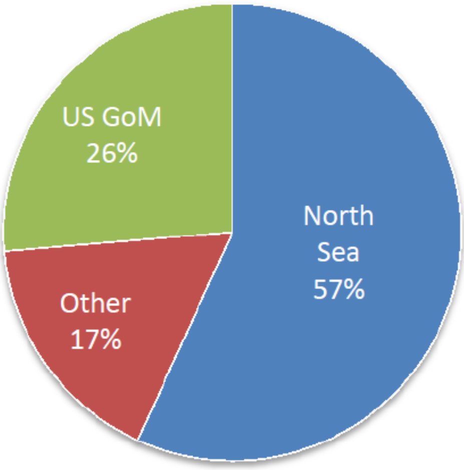


Figure 5-4 Geographical distribution of accident source data /47/.

In Table 5-1 a high-level summary of the most common offshore regulators and their reporting of major structural accidents are summarized for the past few years. As can be seen, only one major accident has been reported by EU which was the INA's missing platform.

Table 5-1 Reported incidents defined as major the past five years

Location	Reported incidents
EU: Safety of offshore oil and gas operations (europa.eu)	Report instances with loss of structural integrity. Data is 2016 (0), 2017 (0), 2018 (0), 2019 (2 – not possible to identify what these were), 2020 (1 – total loss of platform in Croatia - INA's missing gas platform found on seabed | Croatia Week), 20.21 (0).
UK: Mandatory with RIDDOR to report dangerous occurrences i	Operators shall report an accident related to: Collapses: "Any unintentional collapse or partial collapse of any offshore installation or of any plant on an offshore installation which jeopardises the overall structural integrity of the installation". Subsidence or collapse of seabed: "Any subsidence or collapse of the seabed likely to affect the foundations or the overall structural integrity of an offshore installation". In informal discussion with regulator, no records of any of the major failures above. Some failures have occurred, but not to the level to be reported, though very few known of.
IOGP	None reported, informal feedback that there are no instances of structural failure.

Location	Reported incidents
US: Offshore Incident Statistics | Bureau of Safety and Environmental Enforcement (bsee.gov), Regulator collects offshore incident data	Search for major incidents in 2018, 2019, 2020 and 2021, only reported various crane incidents, but no mentioned of jacket failure, though some boat impacts with leg damage are noted.
Australia: NOPSEMA	Zero regulatory actions relating to structural (and well) integrity in 2019-2020.

5.3 Specific failure modes for fixed structures including jack-ups

DNV's in-house failure database does not reveal any failure related to fixed structures. The database does, however, not cover structural degradations like fatigue cracks and severe corrosion where gross failure has occurred. Lately there have been reported HISC-related failures of structures made of high strength steel with SMYS of 690 MPa, however, none of these has led to any major hazard, but major repair work was needed. It is believed that the root cause of these flaws is cold cracking from welding and developed to larger cracks during operation due to fatigue loading and high tensile loading.

The most reported structural failure of offshore wind installation is failure in the fixed bottom structure in the transition in the grouted connection, scouring protection by use of rock dumping and weld defects in the transition pieces /48/.

5.4 Specific failure modes for floating structures

The DNV in-house failure database contains several reported failures of mooring chains made of low alloy steels the last years. The failure mechanism is fatigue, often influenced by severe corrosion and HISC in combination with unfavorable bending loading.

5.5 Inspection

Inspection (examination) is performed for verification and control of performance. The main objective with the individual inspection plan with input from SHM is to determine what to inspect, where to inspect, when to inspect and which method to use during inspection, see Figure 5-5.

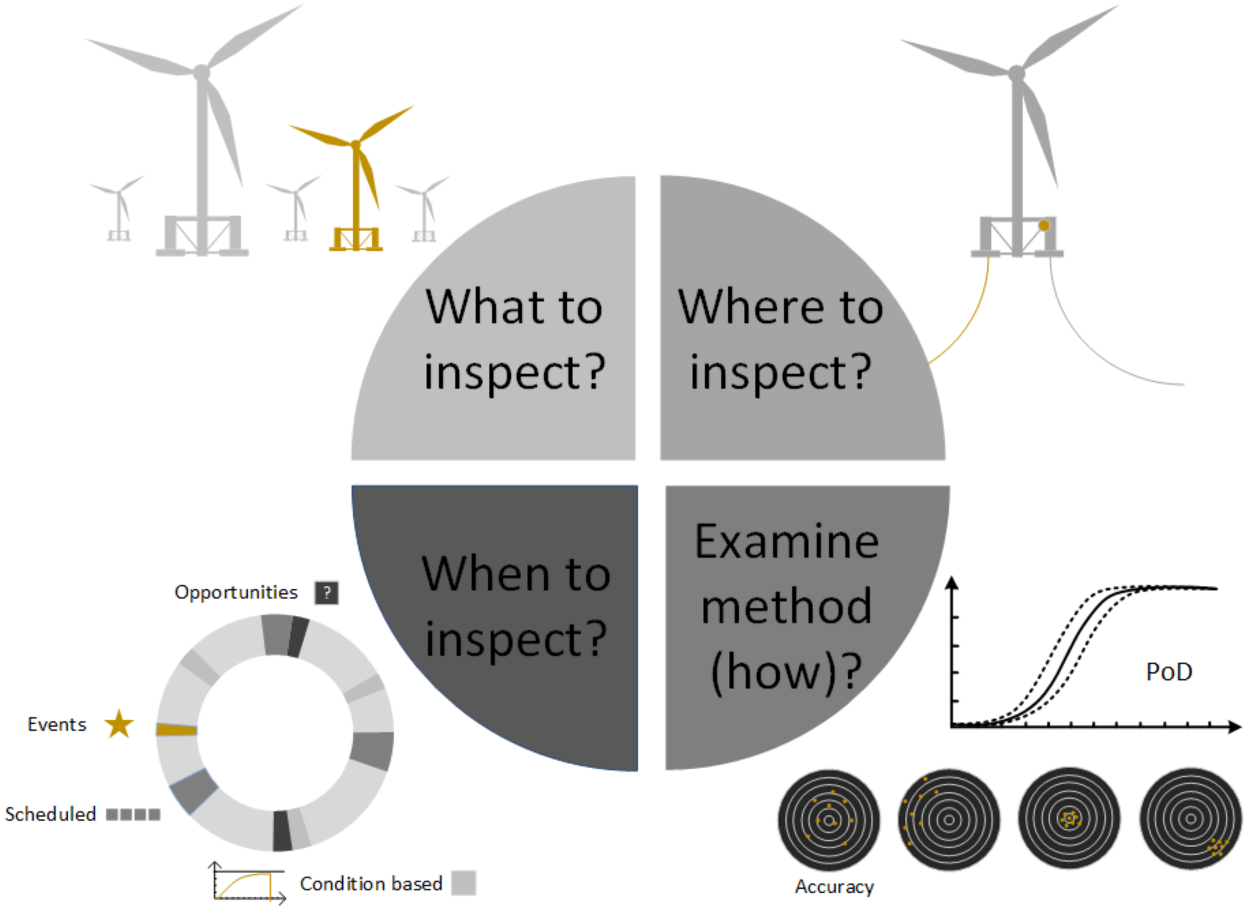


Figure 5-5 What, where, how and when to inspect.

Inspection methods usually include general visual inspection (GVI), close visual inspection (CVI), Non-destructive testing (NDT) also known as non-destructive examination/evaluation (NDE), ultrasonic testing (UT) and measurements. The methods can be performed manually by inspection personnel or by using a remote inspection technique (RIT) like remotely operated vehicles (ROVs) or other types of RIT-like crawlers, borescope, mini-ROVs, drones, etc. In addition, techniques using data driven verification can be applied. This is also an area where SHM by use of sensors may play a more pronounced role in future inspection regimes.

With the introduction of SHM to SIM, the inspection plan should be of a dynamic type adjusted based on structural health according to the actual loads experienced in operation. Figure 5-5 suggest how population based SHM may have been used, as part of SIM to select the most relevant asset (from a population of assets) to focus the inspection (yellow wind turbine). This asset will typically be the one that has seen the highest loads and have the highest utilisation or exposure among all the units. The results and verified condition for this asset should provide information that can be used to estimate the condition on adjacent assets or parts of the group of assets.

By having access to data and models representing the asset (digital twin) it is further possible to identify where to focus the inspection on the specific asset. This can be a specific structural member, special area (hotspot) or a specific mooring line or mooring line component. Same principles apply here, the inspection will be target to the item(s) that has the highest utilisation and where a verified condition can be used to further estimate the condition of same and similar items/components.

In this context, it is crucial to emphasize that while there is a high correlation in global loads between individual structures, the correlation between local stress concentration effects and fatigue capacity may not be equally high. It is important to exercise caution in drawing conclusions that all other structures are in the same condition as the one inspected. Nevertheless, it is reasonable to assume some degree of correlation in structural capacity among the structures, and this may reduce the total inspection scope.

An inspection method should be selected considering the probability of detection (POD) of the technique. POD can be used as a metrics to describe the accuracy of an inspection technique and how well it can detect abnormalities and defects.

The terms trueness and precision can be used to describe the accuracy of a measurement method and results, see Figure 5-6. Trueness refers to how close the measurements relate to a baseline or other known reference value. Precision refers to the closeness of agreement between independent results, collected with (under) the same conditions.

For applications using classification models, performance may be measured by one or more metrics including: confusion matrices, area under curve (AUC), classifier precision, recall, classifier accuracy, sensitivity, F1-score.

Accuracy and how well a method can detect a defect can also be used to describe the two different dimensions; how well it detects that there is an anomaly present and how accurate it then can measure the detected defect /54/.

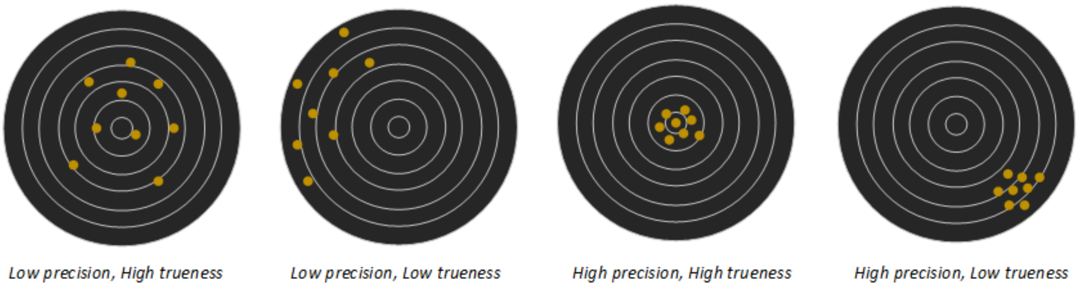


Figure 5-6 Illustration of accuracy as combination of trueness and precision (ISO 5725-1).

In the context of SHM it should be considered relevant to select a method with a POD and accuracy aligned with the basis for the model or application used to determine the condition. An example illustrating this can be an SHM system using a model based on fracture mechanics to estimate fatigue utilisation. By using fracture mechanics to calculate crack growth it is estimated when a structure based on experienced operational conditions can, with a defined probability, have a crack with a certain size. This should then indicate when inspection is needed to confirm the condition of the assets. The inspection technique should then be able to detect the maximum allowable crack size used by the method.

The inspection methods used today represent a large variety of capabilities and the rapid development now provides solutions with POD and accuracy that was not available just a few years ago. These new techniques may require more resources and have a higher cost compared using a more traditional technique with lower POD and accuracy. The value of using a more accurate technique may be proven when applied on specific items and areas providing inspection data and information representing an accurate representation of same or similar items in a population.

When to inspect should be based on a combination of time-based inspection (TBI) with fixed time or calendar-based intervals and condition-based inspection (CBI) performed according to a continuous analysis of the asset /component. TBI should make up the basis of the inspection plan and be established from the results from the RBI analysis. TBI may also be regarded as the initial basis that can be replaced by CBI based on experience and increased confidence in the SHM system.

CBI shall only be used for degradations that allow for condition monitoring (CM) by using data and information gathered from sensor systems and source systems. Data should be collected at intervals and acquisition rates being able to capture any significant change in parameters and with sufficient completeness in the data.

The inspection intervals and frequency should be determined based on an evaluation of the item or component degradation rate due to fatigue utilization, wear and corrosion. The inspection interval and frequency should ensure sufficient lead time between detecting a degraded state and performing mitigating actions (maintenance, repair, and replacement) before it may lead to failure.

This inspection plan should be adjusted based on inspection data and changes in operation and condition.

A well-structured and organized SIM should also include opportunity inspection as an option. This is typically an inspection task that is not yet planned but is performed when an opportunity arises and when the inspection team is already mobilized. In this way additional scheduled or condition-based inspection may be included for additional items representing next in line or items with condition requiring attention soon.

6 SHM APPROACHES

6.1 Introduction

Structural health monitoring (SHM) may vary in extent, methodology and objective, hence, SHM may be assigned different meaning depending on who is the stakeholder. The definition of SHM is given in Section 2.6 and with input from Appendix A.

6.2 Approaches

Based on different input a categorization of SHM approaches is outlined in Figure 6-1. The different approaches will be briefly explained in the subsequent subsections. These approaches may also be divided into reactive or active, where the passive looks at what has happened and the active may be used more online and even include forecast predictions (prognostic).

Another categorization from /5/ resembles the categorization from Ryther in Section 2.6:

- "Determining whether a structural failure exist in the structure" ("Detection")
- "Detect where the structural failure is located" ("Localization")
- "Quantify how severe the structural failure is" ("Assessment")
- "Estimating the remaining lifetime of a structure" ("Consequence")
- The method may give information if there is a likelihood of structural failure to occur in the near future (Warning/changed conditions/prognosis)
- The method may be used to validate or verify that the strength of the structure is sufficient (Fit for purpose)

The categorization comes from Ryther's hierarchy with four levels marked in parenthesis and defined in his PhD thesis in 1993 /6/. The two additional levels are added here and represents a variation of the fourth to represent that the past risk may not reflect the future risk in case conditions change and the risk of structural failure increases, due to e.g subsidence of a fixed structure or for instance when moving a unit from one site to a new harsher location for jack-ups. It may also be a warning system in case something may likely occur in the near future like a ship impact or an impact from an abnormal environmental condition. This may be relevant for marine structures similar to the civil engineering business where it comes from. In addition, a level of fit-for-purpose is relevant because a structure may have been designed under a set of uncertainties and through the SHM system the uncertainties may be quantified as low, and the design may be regarded as fit-for-purpose and a benefit may even be reduced extent of inspection or extended inspection intervals which will serve as a benefit of the SHM system. This is related to minor incidents. These are basically passive SHM methods and Figure 6-1 covers basically all of them.

Active SHM implies deliberate or automated changes to the operational conditions to reduce the risk of structural failures, which may be less likely for SHM systems relevant for hull structures. Active systems are more based on smart technology which is turned on to reduce the response in the system in case of high response.

What is common for all the approaches in Figure 6-1 is that they can provide visualization of findings as input to decision support which may be followed up by inspections either by use of physical inspection or sensor data, or a combination of both in case there is a likely risk of structural failure. The decision support may, however, also be used for other purposes than the maintenance and inspection regime depending on the stakeholder. A traditional physical survey without available information prior to inspection is a simplified version of SHM, but this is regarded as a conventional method which is the approach we want to improve. The SHM approach is generally not intended to replace physical surveys although remote inspection techniques and data driven verification are alternatives to today's practice.

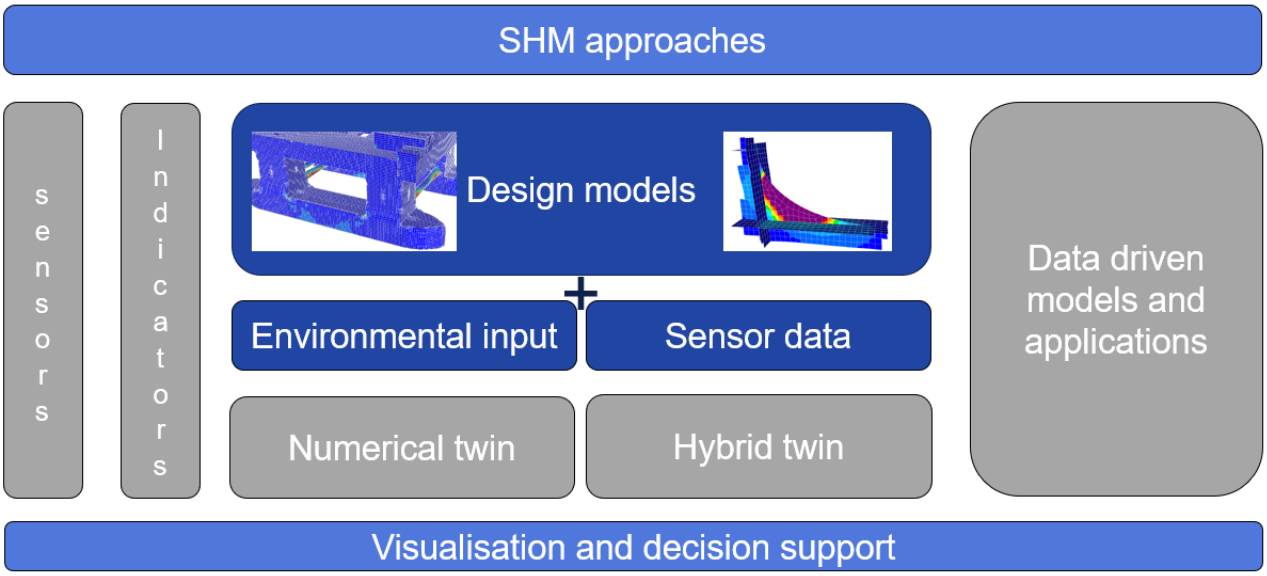


Figure 6-1 Various approaches of SHM systems.

6.2.1 Sensors

Sensors may be used directly to evaluate the structural condition. Various sensors may be used for different purposes like:

- Strain gauges for static and dynamic strain including overloading and fatigue structural failure, but generally requires a structural model for capacity verification (fatigue and or strength)
- Accelerometers or velocimeters for vibration levels
- Cameras/radar (digital image correlation, thermal or normal) for visual inspection of coating conditions, corrosion, cracks, deformations etc.
- Acoustic emission sensor

Further guidance related to types of sensors is provided in /2/.

6.2.2 Indicators

Indicators may be environmental based, or response based. For instance, indicators may be based on:

- wave data height to the power of 3 (slope of S-N curve) related to the design wave environment (FLS and ULS) to assess the fatigue utilization or simply maximum significant wave height encountered divided by design significant wave height to define the structural extreme utilization.
- wave data combined with the characteristic RAO to predict the response spectrum which can be used to calculate the fatigue structural failure or structural extreme utilization.

Information on the static loading condition may be provided to improve the structural extreme utilization value considering also static loads in addition to the dynamic loads.

The response based characteristic RAO are generally calculated specifically for an asset based on hydrodynamic calculations and represents site specific environmental data, where long term environmental statistics are presented for wave height with corresponding periods.

In principle also a sacrificial structural detail may be fitted to the structure and designed to fail earlier to indicate the fatigue utilization spent, however, this indicator assumes that there is a full environmental and structural correlation which may not always be the case. The sacrificial details should have a higher stress concentration than relevant for real critical details to fail before the main structure. While this has been tested out on offshore structures, it is rarely used within the offshore sector.

6.2.3 Numerical twin

A design model may be said to be a digital twin that die at birth. A numerical twin is a design model where the design assumptions related to the original design environment is replaced continuously with encountered environmental input from hindcast data like waves, current, wind, temperature, salinity etc. The design model may also be updated based on actual as-build design as well as thickness changes due to corrosion.

A generalization of the digital twins with overview of elements are described in DNV-RP-A204 /25/ including connection between design and operational digital twins. In short terms the digital twin may be perceived as a dynamic equation with time dependent input, engine and time dependent output which ends up in decision support. For the numerical twin for structures the input is the encountered wave data, and the output is the condition monitoring of fatigue structural failure and extreme response utilization relative to design response. The design response may be the stress level, yield or buckling capacity. Taking this information to decision support by use of fracture mechanics and risk-based methodology is turning the condition monitoring data into inspection intervals.

6.2.4 Hybrid twin

Hybrid twin is using sensor data to replace the design assumptions on environmental input like waves, current and wind. The generalized typical digital twin architecture may be taken from DNV-RP-A204 /25/ and is illustrated in Figure 6-2. For the hybrid twin structure, the predictive maintenance and the safety aspects are the main functional elements with source systems related to time series, 3D models and life cycle management. The data platform part may be related mainly to data quality profiling and API management while cyber security is regarded part of a larger system also providing other data to shore. To capture potential structural vibration, a sensor system with high sampling frequency in the range of 10Hz or more is needed,

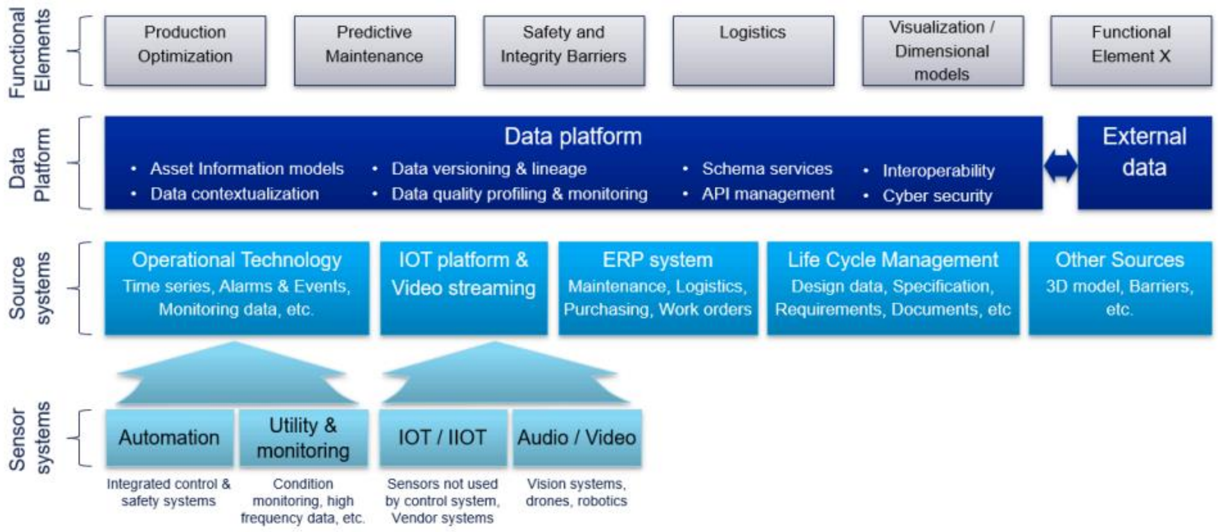


Figure 6-2 Typical hybrid twin architecture taken from DNV-RP-A204 Assurance of digital twins /25/.

6.2.5 Data driven models

The data driven models are deliberately placed to the right in Figure 6-1 since it may be based on any of the other approaches and potentially also additional data. It may take data from:

- Sensors
- Indicators
- Numerical twins
- Hybrid twins
- Inspection findings
- Characteristic data of the asset like main dimensions from as-built drawings or e.g. thickness measurements

Data driven models may thereby not represent the physical asset as it looks, but may use machine learning (ML), neural networks, artificial intelligence (AI) and other technologies to combine the data and assess the risk versus the 6 categorizations in Section 6.2.

6.2.6 Design models

As previously mentioned, both the numerical and hybrid twin models require the existence of a design model. In principle, a design model comprises a numerical model and calculation procedures to simulate the structural responses under a given environment, either assumed in the early design phase or the encountered environment when used within a digital twin approach. Within the maritime and offshore industry, the most common approach is to employ the finite element method within the evaluation of limits states in order to ensure that the structure can withstand the environmental conditions. It is further important to mention that given the complexity of the environmental conditions, the parameters describing the structure, as well as the desired lifetime of several decades, several assumptions and simplifications must be considered. The usual practice is to evaluate each of the considered limit states separately, together with appropriate assumptions. It is outside the objective of this report to deep dive into the limitations of design models; hence, a comprehensive review will not be presented herein. For an overview of the recent progress regarding the numerical simulations of different failure modes, the readers should check the ISSC reports, which are published every three years. However, as the majority of mechanical failures are caused by fatigue, it is worth noting some of the recent trends observed within the literature. Among others, the improvements within the calculation of remaining fatigue lifetime by shifting from a linear structural failure accumulation to non-linear structural failure accumulation methods, should be mentioned. A review of the recent progress can be found in /38/, /39/. Depending on the assumptions and the level of complexity desired, the non-linear fatigue calculations can be performed using iso structural failure curves (non-linear fatigue structural failure accumulation model) and S-N fatigue structural failure envelope /40/, /41/, stress interactions effects on the fatigue lifetime /42/, /43/, /44/ or fracture-mechanics based approach /45/. The main aim of the non-linear fatigue models is to account for ultra-low-cycle fatigue, where some of the loading cycles induce plastic deformations in the structure, as well as to account for the loading sequences. Thus, the general objective is to reduce the uncertainties within the design models by increasing the complexity of the physical models considered. Although significant fundamental research is reported on the evaluation of the accumulated fatigue structural failures, the next step required towards improving the accuracy of numerical and hybrid twin models is to implement more complex models for the evaluation of the remaining lifetime in order to allow for better predictive maintenance.

7 LITERATURE REVIEW - LATEST DEVELOPMENT WITHIN SHM

SHM has become an evolving area of research in the last few decades with the increasing need of online monitoring for the condition of large complex structures.

There are already a few journals on the topic of SHM, although it may not contain much for the marine industry which may be related to “other industries” in their context:

- Structural health monitoring – an international journal https://journals.sagepub.com/home/SHM or International journal of structural health monitoring. The three most cited papers (about 1000) from here are:
    - Wei Fan and Pizhong Qiao, 2010, Vibration-based Structural failure Identification Methods: A Review and Comparative Study, Volume 10, Issue 1, https://doi.org/10.1177/1475921710365419
    - E. Peter Carden and Paul Fanning, 2004, Vibration Based Condition Monitoring: A Review, Volume 3, Issue 4, https://doi.org/10.1177/1475921704047500
    - Peter C. Chang, Alison Flatau, 2003, Review Paper: Health Monitoring of Civil Infrastructure, Volume 2, Issue 3, https://doi.org/10.1177/1475921703036169
- Journal of civil structural health monitoring https://www.springer.com/journal/13349
- Structural control health monitoring https://onlinelibrary.wiley.com/journal/15452263
- International Workshop on Structural Health Monitoring, IWSHM, https://iwshm2023.stanford.edu/

There are also many books on this topic that are published lately.

7.1 Trends in publications related to SHM

There is a vast amount of literature addressing “structural health monitoring systems”, hence, a quick literature review has been done for illustration purposes and to provide the latest research fields within this topic.

While there were early efforts and research within this field, the formalization of SHM as a distinct concept gained momentum in the 1990s. Science Direct was used to search the publications related to “structural health monitoring systems” from 1990 to 2023, resulting in 289 000 papers. The increase seen lately is substantial as indicated in Figure 7-1. It confirms that the topic has become a focus area at many research institutes and universities around the world. More details of identified papers are listed in Appendix B.1.

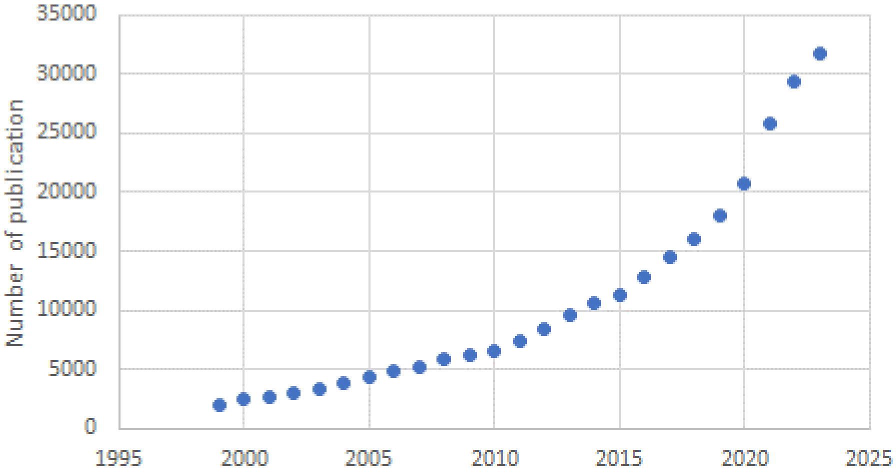


Figure 7-1 Number of publications per year containing "structural health monitoring systems" from Science Direct

7.2 Trends in publications related to population-based SHM

After looking into the topic of population based SHM it is evident that the terminology is mainly related to one research institute and that the topic is mainly related to the offshore wind industry and not the oil and gas industry. The topic is therefore perceived as a side track relative to the focus of this report, however it may be used also for similar structures within the oil and gas industry like for similar moorings, risers, flare towers or sister units in similar geographical area. Further details are given in Appendix B.3.

7.3 ISSC review

ISSC (International Ship and offshore Structure Congress) provide a summary of research in progress, including facilitation, evaluation, and dissemination of results from recent investigations (3 years terms) within the Maritime and Offshore structures /7/. The different committees (see overview in Appendix B.2) also provide overview of suggested improvements in design, production, and operations procedures. In general, many of the committees address SHM or monitoring, but to a varying degree and quality. In combination with digital twins the topic is regarded as hot and of interest for many of the committees. Further details are listed in Appendix B.2.

7.4 Learning from other industries

Learning from other industries is challenging and the marine environment makes a big difference from civil engineering, aircrafts, nuclear and other industries. For equipment and systems, it may be more learning / experience than for structural assets related to severe structural failures. Still the literature search suggested that most literature related to "SHM" came from other industries than the marine offshore industry. Distinguishing between ships and the offshore industry, it may be possible to learn something from the ship industry and DNV Class for ships and column stabilized units, see Appendix C.1. SHM methods for probability of structural failure and structural failure location are already used by DNV surveyors in terms of population based SHM although the units may not be identical.

8 SHM STRENGTHS AND WEAKNESSES

8.1 General summary of SHM approaches

Based on the SHM approaches in Section 6.2 some general considerations and opportunities will briefly be covered in the following subsections with focus of strength and weaknesses for input to structural failure detection.

8.1.1 Sensors

The sensors may have the following strengths and weaknesses listed in Table 8-1. For several of the strength and weaknesses we are thinking of strain sensors, so the list is not complete with respect to type of sensors. Strength and weaknesses may also be revealed more generally through the process of using:

- DNV-RP-0317 *Assurance of data collection and transmission in sensor systems*

Table 8-1 Strength and weaknesses of sensors

Strengths	*Weaknesses*
Accurate measurement of the structural response like strain, acceleration, velocity, deformation, quantification of coating breakdown, steel thickness, vibration level etc.	Measures only where sensor is located and cannot detect structural response s at other locations
Continuous collection of data with high sampling rate	Challenging to supply energy to the sensors May be costly to install cabling, where battery is not an option and data retrieval. Sensors may be difficult and costly to install below water surface and inaccessible locations
Can pick up vibration effects not covered in design models	May be challenging to “zero set sensors” to capture static loading
Can pick up nonlinear excitation not covered by design models	Bias is difficult to verify without similar sensor measuring same quantity
The strain sensor does not care about idealization on wave energy spreading and wave spectrum as well as bidirectional seas	May malfunction with loss of data; failing sensors may cause “noise” or costly maintenance
	Maintenance costs of sensors may be high
	Sensor may require additional postprocessing to evaluate the required quantity like fatigue structural failure accumulation which imply that data may have to be sent to shore if not evaluated onboard
Automatic processing may be done onboard.	Connectivity is still an issue, i.e. getting data to shore with the right format. The retrieval of data may be costly.

Vibration is one of the main features that sensors may pick up but that numerical twins or design models may not include. Regarding the signal processing techniques (SPT) these may be in frequency domain (FD) or in time domain (TD) and there are several techniques with their respective strengths and weaknesses, see Table 8-2.

Table 8-2 Strength and weaknesses for signal processing techniques for sensor measurements (taken from /12/)

SPT	Method	Strength	Weaknesses
TD	AR - autoregressive model	Low computational cost	Lacks spatial information of vibration response (i.e., model parameters); unable to model nonlinear behavior of structures
TD	ARMA - autoregressive moving average	Low computational cost; classification of time series; predicting the future data values based on their past values	Lack identification of model parameters; unable to model noise contaminated information; unable to model nonlinear behavior of structures
TD	ARIMA – autoregressive integrated moving average	Used to model nonlinear and nonstationary systems	Difficult to understand and usually computationally expensive
TD	ARX – autoregressive model with exogenous input	Simplicity; Low computational cost	It lacks spatial information of vibration response; used only for analyzing of vibration data with a constant signal to noise ratio (SNR)
TD	ARMAX – autoregressive moving average with exogenous excitation	Used to model nonlinear and nonstationary systems; efficiently mitigates noise of signals	Low level of adaptability and applicability for qualitative modeling of nonlinear processes
TD	ARV - vector autoregressive model	Easy implementation; sensitive to changes in mode shape; used in structural failure localization	Lacks description of the linkages between variables
FD	DFT – discrete Fourier transform	Simplicity; computational efficiency; it can model both linear and nonlinear systems; easy implementation	Unable to adequately capture the original information of nonlinear and noisy signals; only frequency representation of data; unable to observe closely spaced modes
FD	FRF – frequency response function	Capability in analyzing noisy vibration responses with high SNRs; It can provide more effective information in a desired frequency range of signal	Requires long data sequences for the multivariable case and uncorrelated inputs; It cannot efficiently obtain important information about structural failure type, size, location.
FD	SFRF – strain frequency	It is computationally inexpensive; it can effectively localize the structural failure; Fast implementation	Strongly influenced by noises; requires many locations for measuring data

SPT	Method	Strength	Weaknesses
	response function		
FD	FDD – frequency domain decomposition	Efficiently recognizes closely spaced modes; easy and fast application	Low resolution in frequency domain
FD	MUSIC - multi signal classification	High resolution in frequency domain; closely spaced modes can be estimated; Capability in analyzing noisy vibration responses with high SNR	High computational cost

8.1.2 Indicators

Indicators are often thought of in relation to fatigue and overloading which may be response based, however examples of additional indicators are provided on https://store.veracity.com/nerves-of-steel. The indicators may have the following strength and weaknesses listed in Table 8-3.

Table 8-3 Strength and weaknesses of indicators

Strengths	*Weaknesses*
Scalable solution which may be applied to a huge number of assets	May not point at specific structural detail, so do not know where e.g structural failure can be located
This may easily be applied to different responses for different concerns	May not provide an absolute level of fatigue structural failure or overloading (e.g buckling) but a more relative level.
It may be useful for benchmarking and making information transparent to other stakeholders without much technical knowledge by standardized delivery	The strength of the asset may not be known, so it may not distinguish between a strong and a weak design
Easy to send data back and forth since data amount is limited	
High efforts in relation to design model is not necessary, so this is a relatively inexpensive solution	
More available than numerical twins	

8.1.3 Numerical twin

The numerical twin may have the following strength and weaknesses listed in Table 8-4. This may be applicable both to the numerical twin and the hybrid twin in Section 8.1.4. For further details related to strength and weaknesses see also DNV-RP-A204 *Assurance of digital twins.*

SRS (structural reanalysis system) is a variation of digital twin where the model is updated with time to account for modifications of the structure and degradation due to corrosion with reduced wall thicknesses. This is especially relevant for the NCS and it implies basically a design recalculation. However, with the numerical twin, the design environment is replaced also for the SRS, to account for both change in structural arrangement and change in environment. This is the ultimate goal for all the numerical twins, but accounting for the corrosion process is actually the most cumbersome part based on ultrasonic thickness measurement (UTM). Automated process from UTM reporting to model update is a key function.

Table 8-4 Strength and weaknesses of numerical twins

Strengths	*Weaknesses*
May cover all inspection points in critical areas for each compartment and subject to NDT	Designer may be negative to share design model which may cause additional modelling efforts especially for existing assets
Robust solution which may be available from day one based on the available design model	Linear analysis-based solution neglecting nonlinear effects which may be important and overlooking vibration effects
Marginal additional cost if design model is available	Uncertainties related to both structural response and the assumption taken reflecting the environmental loading
If structural failures occur at “another” location, then local model may easily be modelled and implemented for further follow up	Limited loading conditions may be incorporated which may lead to inaccuracies and slightly conservative results
Useful visualization possible by using design model as concept model for inspection planning	Splash zone effect may be idealized and may be inaccurate for sea states different than most expected contributing sea states
Material degradation, including wall thinning from global corrosion may be incorporated (like for structural reanalysis system (SRS), on NCS)	AIS data must include heading and preferably also for TLP, SPAR and FPSO accurate draft illustrating loading condition, or loading condition input and heading must be provided separately
May provide live solution including live dynamic update of inspection intervals for specific inspection points	Wave data quality may depend on the supplier and especially the extreme storms may be associated with relatively higher uncertainties, if not measured locally
Numerical twin may use forecast data exactly as hindcast data and may then look into the future to provide decision support to take actions when necessary. This may basically be used as part of routing tools for marine operations including drilling (and other moving units during transport like jack-ups)	It may be difficult to evaluate the value of the decision support versus the costs of having the decision support from the numerical twin.
More available than hybrid twins	Does not pick up structural failures initiated in the construction phase like welding defects, large eccentricities, misalignments due to poor workmanship

Strengths	*Weaknesses*
	Does not necessarily pick up structural failures caused during transport to site
	Does not necessarily pick up structural failures during installation
Numerical twin may capture much more inspection points than the highest utilized details by the design model.	Design model may focus on only highest utilized details but for numerical twin the screening model should be used more extensively to scale different “identical” structural details. This takes additional efforts.

8.1.4 Hybrid twins

The hybrid twins have the following strength and weaknesses listed in Table 8-5.

Table 8-5 Strength and weaknesses of hybrid twins

Strengths	*Weaknesses*
Several of the strengths for the numerical twin also apply to the hybrid twin	Several of the weaknesses of the numerical twin also apply to the hybrid twin
Sensors with dynamic response is regarded more accurate than hindcast environmental data	The sensor setup is often not ideal versus the use case as the instrumentation may have been planned without considering the use case of a hybrid twin relative to inspection points
Sensors may capture nonlinear excitation, vibration, and do not care about inaccuracies in wave spectrum and wave energy spreading and may handle multidirectional seas	The sensor installation may come at a significant cost, and the cost of making data available to shore may be significant. The maintenance of the sensor system may also be significant for extensive and electromechanical systems
Solution is covered by several of the Class Societies	The sensor data needs to have a data management arrangement in place including cyber security management and data profiling (condition monitoring of the data quality)
In some cases, a very simple sensor system may be sufficient for maintenance and inspection planning	Without using the hybrid twin for defining the sensor set up the installation costs may increase due to likelihood of over-instrumentation
Using the hybrid twin system to define sensor set up and location of sensors may provide a robust and accurate system for the inspection points to a minimum installation cost	Reliable estimation of the primary wave heading may be important, and this may be less robust for a non-ideal sensor setup

Strengths	*Weaknesses*
Vibration modes may be separated from wave induced modes to reveal the importance of the vibration at different locations.	The “zero” setting of the sensors may be challenging and sensors may drift
Comparison with numerical twin may highlight the effect of nonlinear excitation but also uncertainties to the idealization of design considerations related to wave spectrum and wave energy spreading	Time series of the sensors have to be retrieved and used for the analysis which may make the online solution lag depending on the availability of the time series and the computer time for updating.
Potentially more available than data driven models	Loss of sensor data may imply loss of condition monitoring data and occasionally the down time may be significant and a backup solution with the numerical twin should be in place
	It may be difficult to install sensors where needed, proper documentation of the sensor location is needed
	Must adjust numerical mesh at sensor locations to achieve higher accuracy and sensor input at the right node and direction.
	Data quality from different suppliers vary a lot and planning may often be done without the right personnel or advise, and communication between decision responsible at early design phase and user in operation may be poor
	Does not pick up risk of structural failures caused by progressive failure like mooring failure that may affect probability of wellhead failure if systems are not coupled together

8.1.5 Data driven models

The numerical data driven models may have the following strength and weaknesses listed in Table 8-6. Further details can be found in the DNV recommended practices listed below:

- DNV-RP-510 *Framework for assurance of data-driven algorithms and models*
- DNV-RP-0671 *Assurance of AI-enabled systems*
- DNV-CG-0557 *Data driven verification*

There is a difference between data driven models used for hull structures and the use case of data driven verification by class as a survey provider, where DNV class assesses provided data as complimentary approach and part of a compliance-based regime to consider need for additional physical survey.

Table 8-6 Strength and weaknesses of data driven models

Strengths	*Weaknesses*
Data driven models may provide knowledge which is not possible to retrieve by other means due to the strength of providing results from a vast amount of data which also may come from different sources	Data driven verification with class notation DDV in DNV does currently not apply to hull structures but only standard systems and equipment.
Data driven models may be useful to bring knowledge from a large number of similar units together, like for wind turbines, wave energy devices, floating solar plants, sister units etc.	Using the right model may be essential to avoid unreliable results
The data driven model may become better and better with time as more data becomes available	A lot of data may need to be available to train a model for a specific unit or for a specific methodology
Data driven models and AI systems may look into the future for decision support on actions or making actions in due time	The decision support from the data driven model may not extend much beyond the training data
	Setting up the model and training it for a specific purpose may be time consuming also because data may not be available in the beginning.
	It may be difficult to reveal and understand the level of uncertainty in the outcome from the data driven models
	The data driven models may require standardization of the data used as input to the model to improve the outcome of the model
	It may be time consuming to have a data driven or AI approach to be properly assured for reliable use

8.1.6 Population based SHM

Population based SHM may be relevant for many identical or similar units like wind turbine structures in a wind farm, wave energy devices, or floating solar panels. Compared to the traditional SHM approaches, population based SHM employs spatio-temporal propagation models to transfer data and knowledge between units operating in a similar environment, in order to account for the causal interference between responses and excitations. The propagation models can be either based on physics, physics-informed, or data-driven, aiming at increasing the accuracy of mapping the environmental conditions to the responses. The NGI guideline 16-1036 deals with SHM for offshore wind turbine towers and foundations but does not describe how to deal with monitoring on a whole farm except that it mentions that mobile monitoring systems may be rotated between units.

Based on the recent publications one of the non-trivial aspects that must be addressed within the use of population based SHM is the spatiotemporal variation of the environmental conditions and operational variations among multiple units. There is a causal interference between the responses and the environmental and operational variations, which should be comprehensively investigated to understand and quantify the uncertainties among different units of the considered population for structural condition assessment. More research and development are required on the improvement of the spatio-temporal model to transfer knowledge across the population. Those can be either based on physical models, physics-informed, or data-driven.

It is further worth noting that in the case of offshore wind farms, almost all the newly installed wind turbines are provided with the SCADA (supervisory control and data acquisition) system. This system records the statistical summary of environmental and operational quantities every ten minutes /23/. Consequently, the valuable SCADA data could be used to enhance SHM for each unit within the considered population. Thus, for removing the uncertainties within the employed spatiotemporal model used to transfer advanced monitoring knowledge across the population. The strength and weaknesses of population based SHM is listed in Table 8-7.

Table 8-7 Strength and weaknesses of population based SHM

Strengths	*Weaknesses*
Accurate transfer of data and knowledge between different units within the same population using spatio-temporal propagation models	Non-stationary behavior of the environmental conditions should be properly addressed when mapping the measured quantities from the highly instrumented units to the basic instrumented units
Population based SHM represents a promising approach to reduce the number of sensors required to instrument systems of identical or similar units	More research and development are required for heterogenous populations with significantly different behavior among units.
	It may be difficult to transfer data and knowledge between two fundamentally different units located in different environments
	Without using the design models for defining the sensor setup, the installation costs may increase due to the likelihood of over-instrumentation. At the same time, the benefit of using population based SHM may be significantly reduced in case of wrongful instrumentation

9 SHM TO CAPTURE SAFETY CRITICAL BEHAVIOR OF OFFSHORE STRUCTURES

Design according to rules and regulations are believed to be conservative when it comes to the accidental limit state of offshore units, however the magnitude of the conservatism is difficult to quantify. Sensor data in combination with accurate numerical models (twin models) representing a system’s ultimate capacity has shown that capacity estimated by deterministic design standards may be overly conservative. However, using complex numerical models and sensor data as an alternative poses some challenges, as illustrated in Figure 9-1. To apply such an approach safely, it is essential that relevant uncertainties (both in models and data) are treated appropriately.

Marie Lindmark Sandoy, Lundin Energy Norway /51//50/: *Current methods seem to be conservative compared to what we observe from sensor data while models based on sensor data do not capture safety-critical behaviour not yet experienced. Neither models give optimal decision support and we are left with conservatism to offset the uncertainty*.

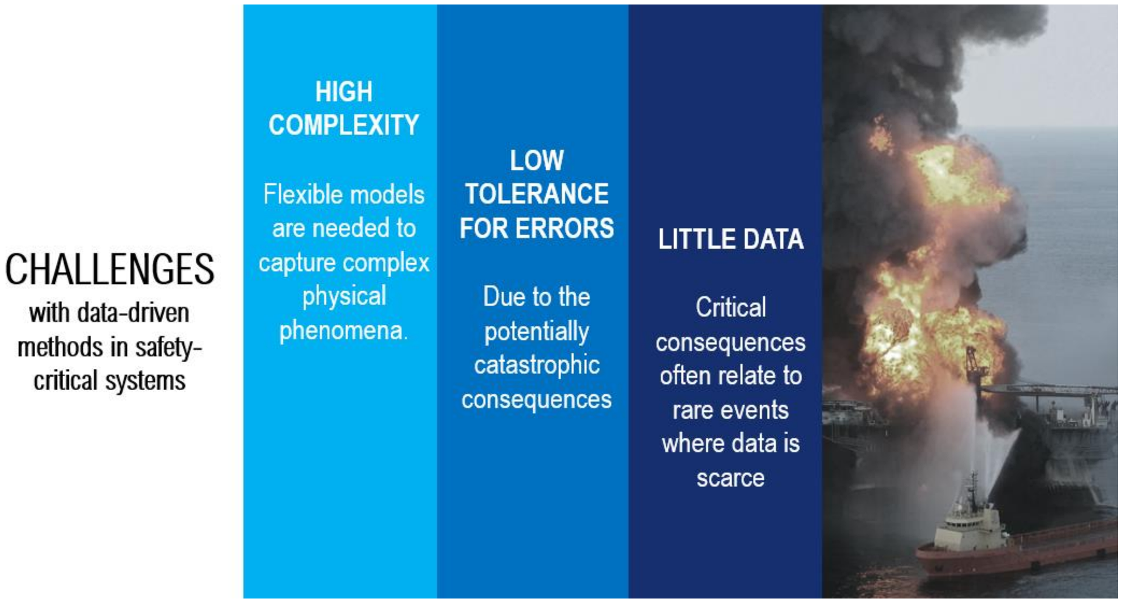


Figure 9-1 Combining data-driven and physics-based modelling for safety-critical applications.

9.1 Combining data-driven and physical-based modelling for safety-critical applications

In the following an example of data-driven and physical-based modelling of safety critical applications and quantification of uncertainties related to the likelihood of a hazard to take place is presented. The goal for the operator would be to create tools, methodologies for faster, better and safer decisions based on physics, data and uncertainty assessment built into the SHM regime to evaluate critical operations and events where the uncertainties of the event and process are captured, see Figure 9-2.

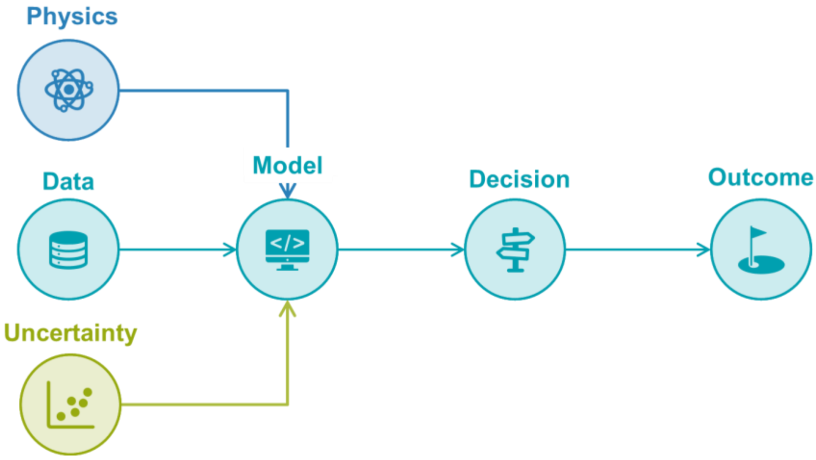


Figure 9-2 Model-informed decision support tool

Well control incidents are defined by PSA as one of the DFUs where Loss of well control could lead to a blowout. Such an incident has the potential to cause substantial harm to people, the environment and material assets. I the following an example of how uncertainty is addressed in a critical offshore workover operation where the aim is to reduce the uncertainty of critical weather scenarios which are stochastic in nature by use of simulations and probabilistic machine learning. The operator needs to control any situation that might induce critical relative motions and the related potential failure modes are sufficiently understood and controlled, in the following a drilling case is evaluated, see Figure 9-3.

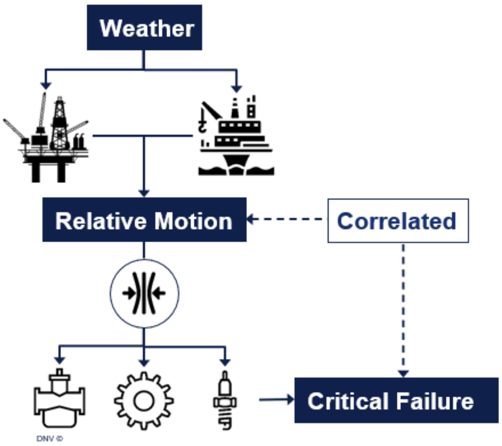
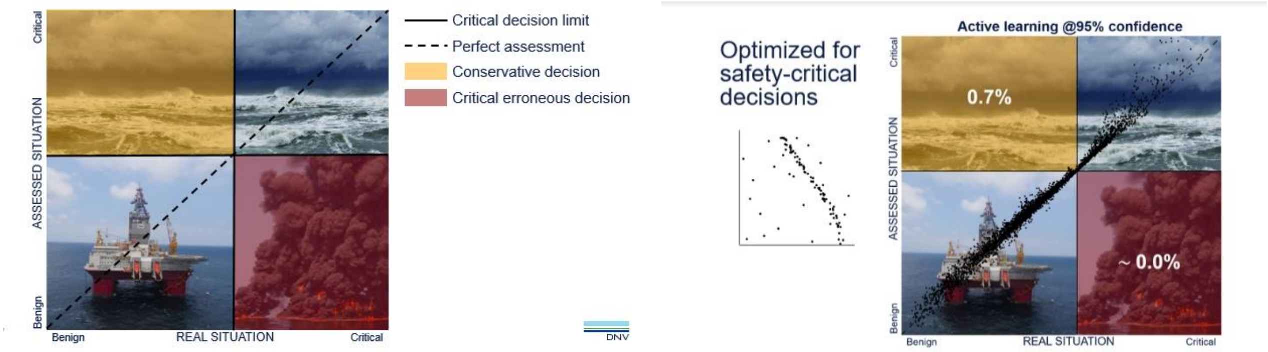


Figure 9-3 Case study drilling operation in /49/.

For many weather scenarios the integrity of the riser system and wellhead is the limiting factor, and accurate estimation of the capacity and utilization of these are critical to optimal and safe operation. Due to the complex process with several influencing parameters (wind, wave, current, structural response, and capacity), detailed simulations prior to operations are needed. The example in Figure 9-4 shows the quantification of uncertainty for a critical event to occur, by combining a Gaussian Process with online forecast services, further details is found in /49/. When a trustworthy model is representing the critical operation, it can act as a real-time tool for decision-support with the added capability to suggest which new simulation scenarios should be run to reduce prediction uncertainty on-demand. An example of how this can be implemented is documented in /51/.



a) Assessed situation versus critical situation

b)Utilization prediction of 5000 random scenarios vs. actual simulation results from the AL trained GP model adjusted to upper 95% confidence level /49/

Figure 9-4 Safety critical drilling operation, reducing uncertainties in operational limit.

9.2 Use of sensors data for decision support of safety-critical applications

The example above, underline the importance to understand safety critical operations. Current engineering practices may not reflect this as it is often based on either physics-based models or data-driven models alone, and not the combination of the two. Hence, to increase the confidence in decision support tools, and reduce the uncertainties for critical operations use of sensor data may play an important role. Use of sensors for structural failure identification where any situation that might induce critical motions and the related potential failure modes are sufficiently understood and controlled by the operator, an example being drilling operations, lifting operations, boat impact etc.

Some design aspects are unknown during the design phase of an assets, but as one gain experience during operation, one can gather evidence and update the knowledge to reduce the applied conservatism without compromising the acceptable risk level of the system. In the following example sensor data in combination with advanced modelling to make decision whether or not to continue drilling operations through upcoming bad weather for at the Edvard Grieg field, see Figure 9-5.

Figure 9-5 The Rowan Viking jack-up drilling rig is positioned immediately next to the bottom-fixed Edvard Grieg Platform /51/

Sensors were used to logged relative motion between the jack-up and the bottom-fixed structures was measured using a laser-based sensor system. By combining machine-learning and physics-based models to benefit from the strengths of both domains, guidance on wave height (Hs) could be established, detail of the assumptions and modelling can be found in /51/ . Based on the study, the authors concluded that models based on sensor data do not capture safety-critical behaviour not yet experienced, and thus critical decisions based on a purely data-driven model are associated with considerable uncertainty the FE model has been updated, and the prediction model is based on both operational experience and calibrated physics-based modelling for scenarios not yet experienced".

There is currently research ongoing looking into new methos for data-driven decision-making in safety-critical systems like scenario optimization, however no relevant publications have been found that are relevant.

9.3 Possibility to prevent major accidents by use of SHM?

History has revealed that structural failures in the oil and gas sector do occur, ranging from minor to major structural failures. Luckily, very few incidents has led to a catastrophic failure over the last 10 years. As discussed in this report, reduction of risk of structural failures shall be handled through requirements to design and workmanship during the fabrication phase to ensure a robust structure. During the operational phase, inspection programs and maintenance schemes shall be used to manage the risk of structural and component failures.

In the following two incidents at the Norwegian continental shelf is discussed in the context of SHM:

1) The largest industrial accident in Norway was the capsizing of Alexander Kjelland platform back in 1981. The loss of the platform was due to a progressive failure traced back to a small 6 mm fillet weld which joined a non-load-bearing

hydrophone support to the D-6 bracing and subsequent fatigue cracking of the brace. This led to loss of one leg (collapsed D-leg) and due to lack of redundancy, the platform capsized /55/.

It is the authors' opinion that a SHM system by use of sensor data most likely could not have prevented the accident of Alexander Kjelland. The platform was a non-redundant structure, where a small fatigue failure led to a large structural loss. However, SHM can support decision making to minimize the probability of structural accidents by capturing failure's/ structural degradations, prior to development into a rupture. For the case of Alexander Kjelland, a local fatigue crack had to be discovered before it developed into a fatal failure. But the likelihood of placing sensors at welds defined as non-critical or even assessing an originally non-critical detail (as the 6 mm fillet welds that was the crack initiation site) is small, and it will only be speculations if a sensor system on the pontoons would have managed to detect anomalies like a 100 mm crack prior to the sudden collapse of this platform and then understanding that this would lead to the progressive failure. Figure 9-6 show a photo of a piece of the failed pontoon, showing rupture and large plastic deformations.

Figure 9-6 Alexander Kjelland (picture taken at the Oil Museum in Stavanger)

2) Another incident happened in 2009 on the Norwegian continental shelf were a boat impacted the Ekofisk 2/4 W platform, which caused severe damage to the platform, the bridge between 2/4 X and 2/4 C and well equipment /56**/.** It is the authors' opinion that a SHM system could have been useful as a decision support tool to evaluate the first extent

of the structural damage), prior to a more detailed inspection. SHM can for such a case provide real time support to the evaluation of the structural degradation and remaining structural capacity with the aim to evaluate e.g. the safety of having personal entering the facility for detailed inspection, however, this requires that the:

- sensors are set up to capture large deformations from a possible boat impact scenario
- a digital twin of the assets will then need to be in place to calculate the remaining structural capacity of the facility implying that all these scenarios have to be planned for

9.4 Reflections of use of SHM and use of sensor data

It is foreseen that towards 2030, SHM by use of sensor data will be more commonly used than what is seen today as input to SIM. Several projects are already ongoing. Data analytics and machine learning coupled with specific domain knowledge will give insight and decision support in a completely new manner compared with today’s practices for design, verification, validation and maintenance of components and assets. Sensors will play a key role in this respect, and there is a rapid development in sensor technologies, algorithm development, data storage systems, data transfer, data processing and computing power.

- It is important to emphasize which **degradation mechanisms are relevant to detect**, and one should have detailed object-specific knowledge about the consequences of the various failure modes on the system level.
- Sensor data gives location-specific system response, however, when assessing locations away from a sensor, the uncertainty become greater. Hence, **a hybrid SHM solution with a physics-based model that is calibrated to measurement**, will increase confidence when extrapolating outside the sensor location.
- **Hybrid solutions couple both analytical predictions with sensor information** of a given system to assess its integrity which is believed to be the most viable option for asset integrity for complex systems like piping and process equipment subjected to fatigue loading.

It is recommended that a unified and harmonized guidance addressing SHM by use of sensor data is established within the offshore energy communities to accelerate the process to include this technology into the SIM system.

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APPENDIX A

Definition of SHM

Some examples may be useful as input to defining SHM:

- Wikipedia defines SHM as: “SHM involves the observation and analysis of a system over time using periodically sampled response measurements to monitor changes to the material and geometric properties of engineering structures”.
- NORSOK N-005:2017 does not define it! It however defines *monitoring* “as a supplement to inspection to provide more information of the condition of a structure”. Monitoring refers to sensors like strain gauges and accelerometers for use of measuring changes in the response, fatigue, leakage, movements, natural periods and to calibrate and validate analysis methods etc.
- The PSA/DNV report no 2021-3187 “Structural health monitoring of topside piping systems” assumes that the term is well understood and puts it in the context of digital twins for decision support using various methods including machine learning (ML) and artificial intelligence (AI).
- The PSA/Rambøll report /3/ relates SHM to digital twins and emphasis that “value of using SHM typically depends on several factors, such as the experience of the user and the complexity of the technology used” and including use for “unexpected future events”.
- NGI (Norwegian Geotechnical Institute) report “BSEE Offshore Wind Recommendations - Guidelines for structural health monitoring for offshore wind turbine towers & foundations”, /4 / starts with a statement: “the value in a SHM program is determined by the use and the benefits that can be obtained by the data. The monitoring system is only a tool and an investment to gather the data” and relates it to “verification and investigation of uncertainties in design as well as provide input for possible future design optimization” with other objectives as “warning of progressing degradation that allows for condition-based maintenance and status evaluation for possible lifetime extension or changed operational conditions”. Why and how is essential and experience is emphasized as important.
- DNV rules, standards and guidelines. The term SHM is not defined but used in DNV-RP-0675 *technical ship performance* suggesting that there may be synergies between sensors used for SHM and technical ship performance, i.e,. the same sensors may serve several purposes. SHM is also used in DNV-ST-0164 *tidal turbines* in relation to monitoring structural failure development giving several examples related to strains and accelerations in addition to lifetime predictions and prevent catastrophic failures. Monitoring is used frequently in different contexts and sensor monitoring is used many places for different systems including hull monitoring systems according HMON class notation.
- To be a bit modern also the answer from ChatGPT (GPT-3.5) is provided to what is structural health monitoring: “Structural Health Monitoring (SHM) is a field of technology and engineering that involves the use of various sensors and monitoring techniques to assess and manage the health of structures such as buildings, bridges, dams, and other infrastructure. The primary goal of structural health monitoring is to detect and evaluate changes in the structural properties or behavior of a system over time. Key components and concepts of Structural Health Monitoring include:
    - Sensors: Various types of sensors are employed to collect data on the structural response. These sensors can measure parameters such as strain, displacement, acceleration, temperature, and more, depending on the specific needs of the structure.

- Data Acquisition Systems: These systems are responsible for collecting, processing, and storing data from the sensors. They are often connected to a central monitoring station.
- Data Analysis and Interpretation: The collected data is analyzed to identify any deviations from the expected or normal behavior of the structure. Advanced algorithms and models are often employed to interpret the data and provide meaningful insights.
- Real-time Monitoring: In some cases, SHM systems operate in real-time, allowing for immediate detection of structural issues or changes in behavior. Real-time monitoring is crucial for quickly responding to potential safety concerns.
- Communication Systems: SHM systems may include communication systems to relay information to relevant stakeholders, such as structural engineers, maintenance personnel, or decision-makers.
- Predictive Maintenance: By continuously monitoring the structural health, it becomes possible to predict potential issues and schedule maintenance activities proactively, reducing the risk of failure and minimizing downtime.
- Applications: Structural Health Monitoring is applied in various sectors, including civil infrastructure, aerospace, automotive, and more. It can be used for monitoring the health of bridges, buildings, pipelines, aircraft, and other critical structures.

The implementation of SHM systems can enhance safety, extend the lifespan of structures, and reduce maintenance costs by allowing for a more targeted and efficient approach to maintenance and repairs. It is particularly valuable for structures that are subject to aging, environmental factors, or dynamic loads." The answer from ChatGPT in this case is well in line with what we would expect.

A good definition of SHM for offshore units and marine structures may be useful and should be included in relevant rules, standards, and guidelines to recognize the topic.

APPENDIX B
Literature study

B.1 Trends in publications related to SHM

Using only these four words in the title, abstract and key words narrow the search down to 2295 papers, where several of these papers are addressing other industries like bridges, civil buildings and aircrafts. By excluding those assets, one end up with 1373 papers. Using only these four words, i.e., structural health monitoring system, in the title only we end up with 88 papers, but in this case, papers are more evenly yearly distributed, and it may not really show a trend. Several of the 88 papers covers the wind turbine industry. If we should judge the quality based on number of citations, there are 10 papers with more than 50 citations, see Table B-1 This may however not be an accurate way to judge quality.

Table B-1 Example of titles of papers on structural health monitoring with many citations

No.	*Title*
1	Gorgin, R., Luo, Y., & Wu, Z. (2020). Environmental and operational conditions effects on Lamb wave based structural health monitoring systems: A review. *Ultrasonics*, *105*, 106114
2	Huan, Q., Chen, M., Su, Z., & Li, F. (2019). A high-resolution structural health monitoring system based on SH wave piezoelectric transducers phased array. *Ultrasonics*, *97*, 29-37.
3	Yan, W. J., Zhao, M. Y., Sun, Q., & Ren, W. X. (2019). Transmissibility-based system identification for structural health Monitoring: Fundamentals, approaches, and applications. *Mechanical Systems and Signal Processing*, *117*, 453-482.
4	Kudela, P., Radzienski, M., Ostachowicz, W., & Yang, Z. (2018). Structural Health Monitoring system based on a concept of Lamb wave focusing by the piezoelectric array. *Mechanical Systems and Signal Processing*, *108*, 21-32.
5	Mieloszyk, M., & Ostachowicz, W. (2017). An application of Structural Health Monitoring system based on FBG sensors to offshore wind turbine support structure model. *Marine Structures*, *51*, 65-86.
6	Hu, W. H., Thöns, S., Rohrmann, R. G., Said, S., & Rücker, W. (2015). Vibration-based structural health monitoring of a wind turbine system. Part I: Resonance phenomenon. *Engineering Structures*, *89*, 260-272.
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8	Smarsly, K., & Law, K. H. (2014). Decentralized fault detection and isolation in wireless structural health monitoring systems using analytical redundancy. *Advances in Engineering Software*, *73*, 1-10.
9	Chen, H., Kurt, M., Lee, Y. S., McFarland, D. M., Bergman, L. A., & Vakakis, A. F. (2014). Experimental system identification of the dynamics of a vibro-impact beam with a view towards structural health monitoring and structural failure detection. *Mechanical Systems and Signal Processing*, *46*(1), 91-113.
10	Swait, T. J., Jones, F. R., & Hayes, S. A. (2012). A practical structural health monitoring system for carbon fibre reinforced composite based on electrical resistance. *Composites science and technology*, *72*(13), 1515-1523.

These papers are generally addressing the sensor methodology rather than the value of using the SHM on real structural applications although structural failure detection is mentioned. Many of the papers reviewed with less citations are just as relevant. There is however a sense from reflecting more of these papers that there is a trend towards wireless and IoT, but that there are also several papers addressing issues with sensor quality and degradation of the monitoring system itself and how to reproduce results from failing sensors. Robust systems and good quality are essential. Another main takeaway is however that the focus on SHM systems is increasing faster year by year. It is also illustrated that a quick approach to literature research is challenging.

If we search for “structural health monitoring offshore” in title, abstract and key words we end up with 112 papers. Using this in the title we end up with 16 papers. 12 of these papers are related to offshore wind, so SHM is most popular within this sector. The four papers not dealing with offshore wind are listed in Table B-2. Two other papers were found using “SHM offshore” instead of “structural health monitoring offshore”. Additional papers are added based on “SHM offshore” in the abstract and key words. Basically, there are few SHM papers on offshore structures although many SHM papers may be applicable to offshore technologies.

B-2 Offshore related SHM papers with offshore in title or abstract

No.	*Title*
1	Nichols J.M., 2003, Structural health monitoring of offshore structures using ambient excitation, Applied Ocean Research, June 2003
2	A. J. Hillis, C. R. P. Courtney, 2011, Structural health monitoring of fixed offshore structures using the bicoherence function of ambient vibration measurements, Journal of Sound and Vibration14 March 2011
3	M. Hassan Haeri, Alireza Lotfi, Kiarash M. Dolatshahi, Ali Akbar Golafshani, 2017, Inverse vibration technique for structural health monitoring of offshore jacket platforms, Applied Ocean Research, January 2017
4	Rostam Rahgozar, Maryam Bitaraf, 2022, A summary evaluation of output-only structural failure-sensitive features for structural health monitoring of offshore platforms subjected to ambient loads, Ocean Engineering, 4 November 2022
5	Da Tanga et al., 2020, Research on sampling rate selection of sensors in offshore platform shm based on vibration. Applied Ocean Research, 26 June 2020
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9	Mingyang Li, Adnan Kefal, Erkan Oterkus, 2020, Dent structural failure identification in stiffened cylindrical structures using inverse Finite Element Method, Ocean Engineering, 20 January 2020
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No.	*Title*
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15	Adnan Kefal, 2019, An efficient curved inverse-shell element for shape sensing and structural health monitoring of cylindrical marine structures, Ocean Engineering, 15 September 2019
16	S. Carrino, A. Maffezzoli, G. Scarselli, 2020, Active SHM for composite pipes using piezoelectric sensors, Materials Today: Proceedings16 January 2020
17	Maor Farid, 2021, Data-driven method for real-time prediction and uncertainty quantification of fatigue failure under stochastic loading using artificial neural networks and Gaussian process regression, International Journal of Fatigue, 22 July 2021
18	Keith Worden, Elizabeth J. Cross, Ifigeneia Antoniadou, 2015, Structural Health Monitoring: from Structures to Systems-of-Systems, IFAC-PapersOnLine2015

Finally, for an overview of the recent progress within the field of structural health monitoring, the following state-of-the-art review papers should be mentioned, see Table B-3.

Table B-3 Recent published review papers on the structural health monitoring

No.	*Title*
1	Pezeshki et al (2023) - *State of the art in structural health monitoring of offshore and marine structures*. Proceedings of the Institution of Civil Engineers – Maritime Engineering 176(2): 89–108, doi.org/10.1680/jmaen.2022.027
2	Cunha et al (2023) - A review of machine learning methods applied to structural dynamics and vibroacoustic. Mechanical Systems and Signal Processing 200, doi.org/10.1016/j.ymssp.2023.110535
3	Azimi, et al (2020) - Data-driven structural health monitoring and structural failure detection through deep learning: State-of-the-art review. Sensors 20.10, doi:10.3390/s20102778

B.2 ISSC review

Considering the resent ISSC report 2022 and the committee on dynamic response addressing literature from 2017 to 2021, SHM and digitalization are addressed in a special chapter due to the interest of the members of the group. Ships and offshore monitoring systems are handled separately while no separation is made to digital twins and digitalization. Systems for ship like structures are pointed out as more standardized while for other offshore units it is more tailormade. For ship like structures systems according to hull monitoring rules from different class societies are more used including more automatic processing of data onboard with and without vibration, with the latter often disregarded in design but may occasionally be important. Main takeaways from monitoring systems are:

- Hull monitoring systems are classified more as decision support systems both for safety and degradation (fatigue) also acknowledged by the Class Societies

- Fibre optical systems may be beneficial in case many sensors are necessary, for hazardous environments, when submerged, for maintenance purposes and when integrated in composites.
- The use of virtual monitoring with hindcast wave data is increasing fast and at lower costs but at lower accuracy, but wave data may be obtained at good accuracy. This latter is also supported by the latest development of IACS Rec.no.34 for North Atlantic design wave environment where also extremes are well covered and not only regarded good for fatigue assessment. The virtual monitoring may be limited to linear analysis.
- Combination of virtual and physical monitoring seems also to be growing, where the latter may include vibration effects and corrections for nonlinearities. The virtual monitoring appears to have a better success onshore due to availability.
- More particular for offshore units, response monitoring has been more used to reduce uncertainties present during the engineering phase, but more as basis for condition monitoring, inspection planning, lifetime extension and improvement of response models for future applications. This implies also more coupling between finite element analysis and sensors with various techniques.
- Fair agreement has however been demonstrated between virtual and sensor-based monitoring, but for offshore structures it is pointed out that for especially local details the continuous change in loading conditions may introduce more uncertainties although stated as small.
- For marine operations a focus has been to predict the future fast enough. Statistical predictions of the future when the process is non-stationary should be done based on forecast input to be more reliable. Technology based on wave measurements at a distance from the asset and the study of the propagating wave process and prediction is also a focus, but time is an issue.
- Coupled motion measurements and doppler current profilers are more frequently used to investigate response of risers and mooring loads. Several implementations exist already including warning systems, and many different approaches are used. Focus is both on fatigue and vortex induced motions.

SHM is included in several other ISSC committees, and a short summary is provided in Table B-4.

Table B-4 ISSC ccommittees addressing of SHM /7/

Committee	*Feedback*
I.1 Environment	Nothing on SHM, but some on remote sensing and measurements of waves, current and ice.
I.2 Loads	Nothing specific on SHM, but some on full-scale measurements of ice loading on offshore structures. (A digression based on ice load monitoring is that DNV uses the term “ice response monitoring” rather than ice load monitoring where the objective may be to find the ice loads while the structural response is the result. Ice response monitoring is part of the DNV hull monitoring rules DNV-RU-SHIP Pt.6 Ch.9 Sec.3.)
II.1 Quasi-static response	SHM is mentioned under the topic of reliability approaches for fatigue as “an important tool for those managing the service life of vessels” related to inspection intervals. It also mentions “full scale tests and monitoring” but mainly related to ships and ice load monitoring.
II.2 Dynamic response	Mentioned above

Committee	*Feedback*
III.1 Ultimate strength	Mentions “smart SHM and digital twins have become popular topics enabling safer operations and longer service lives” related to offshore wind farms reaching their lifetime in Europe. They put the topic into the content of life-cycle management.
III.2 Fatigue and fracture	Nothing specific on SHM but mentions “in-service measurement of fatigue load” and puts this in relation to inverse finite element method (iFEM), virtual hull monitoring method and also data driven methods (e.g., neural networks) with data from different sources including maintenance reports. Most is related to ships, but wellhead fatigue is mentioned and also wind farms. Climate change effects are also pointed out as a concern making the environment worse which is especially relevant for fixed offshore structures that cannot avoid storms.
IV.1 Design principles and criteria	SHM is not explicitly mentioned in the text, but two references are included with reference to a Navy ship /8/ and shell structures in general /9/ . Digital twin, monitoring and in-service updating is however covered in more detail. They refer to both LR and DNV’s activities on the field of digital twins and several class societies (ABS, BV, CCS, DNV, LR) in terms of hull monitoring activities. ABS and DNV have recently updated their standards. In particularly ice load or response monitoring is mentioned. They also mention iFEM and RAO based virtual twins based on hindcast and forecast data including model updating related to repair and corrosion. Most references are however referred to ships. Sea state estimation is also provided a lot of attention, as well as application of data including data quality profiling and inspection updating (Bayesian updating). It also contains an appendix on structural reliability on wellhead fatigue (search in Science direct on “wellhead fatigue” in title, abstract and key words you find 21 references), where measurements may play a role, where design assumptions may deviate a lot from real conditions.
IV.2 Design methods	The report mentions SHM tools under data driven models for lifecycle data management. It mentions digital twins (DT), big data, machine learning (ML), artificial intelligence (AI) in the same context and divide DT’s into structural models and ML models **/**10**/**. It defines SHM as systems to detect or predict structural failure on marine structures and emphasize that this may be referred to as condition monitoring (CM). Lifetime extension and predictive maintenance is stated as the drivers. A guidelines for life extension process management in oil and gas facilities /11/. It includes also references to riser monitoring, model updating on a jacket structure of a wind turbine, but also imagine recognition tool based on ML for detecting coating failures and corrosion. A concluding remark is also “the major players in the marine industry must put their hands together and start collaborating on many aspects. They must overcome their fear of sharing essential information. Establishing these partnerships is the key to success”. “DTs will enable a fundamental paradigm shift” and “It would enable unprecedented levels of safety and reliability”, so here there are authors believing in it.
V.1 Accidental limit states	The report does not include the phrase SHM. It however emphasis the risk associated with autonomous or remotely controlled assets from control centers related to human failures, incompatibilities of monitoring systems, cyber-attacks, lack of redundant systems onboard etc. It raises a good point for unmanned assets like offshore wind structures and unmanned platforms. DNV-CG-0264 “Autonomous and remotely operated ships” is addressing the equivalent safety principle but is not mentioning the SHM.

Committee	*Feedback*
V.2 Experimental methods	This report mention “SHM” frequently and has a separate section devoted to “health monitoring and digital twin models”. It has 14 references with “structural health monitoring” in the title or as part of a dedicated workshop: • Structural health monitoring (SHM) and determination of surface defects in large metallic structures using ultrasonic guided waves • SHM of offshore wind turbines using automated operational modal analysis • SHM data fusion for in-situ life prognosis of composite structures • An experimental study on the data-driven SHM of large wind turbine blades using a single accelerometer and actuator • SHM for Advanced Composite Structures: A Review • An efficient curved inverse-shell element for shape sensing and SHM of cylindrical marine structures • An application of SHM system based on FBG sensors to offshore wind turbine support structure model • SHM and Seismic Response Assessment of Bridge Structures Using Target-Tracking Digital Image Correlation • System Identification of Steel Jacket Type Offshore Platforms using Vibration Test • Vibration-response-only statistical time series SHM methods: A comprehensive assessment via a scale jacket structure • SHM of grouted connections for offshore wind turbines by means of acoustic emission: An experimental study. • Research of SHM system for stinger of large deep water pipe-laying ship • **SHM of Offshore Jacket Structure** • Baseline model based SHM method under varying environment. These covers also composites, wind turbine blades and other non-offshore structures, but also provides input on various methods like acoustic emission (AE) and digital image correlation (DIC). The latter is specially covered in the report and has a growing trend looking for cracks and may be combined with SHM. It is stated that “selection of a proper SHM method must be made in accordance with the material type, experience, known failure modes of the structure and the limitations of the SHM sensors and devices”. It mentions only one wireless sensor network for offshore applications, so wireless is apparently not high on the agenda. Data driven methods, AI neural network methods, semi-supervised learning methods and iFEM methods are referenced. Digital twin is somehow treated as the next step with input from SHM and for different purposes. Some criticism is made on their equivalence to current inspection techniques and stating that it has been discussed in IMO at MSC 103 and in the relation to the EU funded Horizon 2020 ROBINS project.

Committee	*Feedback*
V.3 Materials & fabrication technology	The report mentions “corrosion coatings and corrosion prognostic health monitoring” in relation to navy but does not deal with it in detail. It mentions condition-based monitoring, but only in relation to digital twins with illustration from DNV internet page.
V.4 Offshore renewable energy	The report mentions SHM and DT but does not have a dedicate section for it. It mentions it in the context of operations and maintenance and emphasis the future relevance for wind farms on a system level approach and for the two types of models: physics-based and data-driven.
V.5 Special vessels	The report mentions SHM in relation to stinger operation of cable laying vessel for pipeline installation. Digital twins are however devoted a separate section but is on a very general level.
V.6 Ocean space utilization	The report does not mention SHM or DT. It does not mention even sensors and barely measurements, but it mentions DIC (Digital Image Correlation). This lack of focus on SHM, inspection and maintenance are maybe a bit strange on a report which should deal with many innovative structures like very large floating structures (VLFS), which may have a substantial inspection need. It illustrates however the regulation regime for offshore wind dominated by UK, US and Norway and with IEC 61400 standard and rules, standards and guidelines from main class societies like ABS, BV, CCS, DNV, NK, RINA.
V.7 Structural longevity	The report mentions multi-sensor and hybrid sensor nodes as well as embedded sensors. It connects SHM with digital twin and inspection results with balance on computational efforts and give advice on future work like focus on lifecycle management and maintenance including a combination of probabilistic and non-probabilistic approaches.

B.3 Trends in publications Population-based SHM

Searching for the free terms “population-based structural health monitoring” in Science Direct resulted in 152 000 papers since 1990, as this is not specific enough. Using it only in the title, abstract and keywords result in 90 publications since 1990 with 64 after 2018. Using only these terms in the title results in 2 publications only, but also, the short term “SHM” should be used resulting in 7 publications. All publications are from 2020 and more recent with the following titles:

1. On Population-based SHM for bridges
2. On the application of kernelised Bayesian transfer learning to population-based structural health monitoring
3. A population-based SHM methodology for heterogeneous structures: Transferring structural failure localisation knowledge between different aircraft wings
4. Foundations of population-based SHM, Part I: Homogeneous populations and forms
5. Foundations of Population-based SHM, Part II: Heterogeneous populations – Graphs, networks, and communities
6. Foundations of population-based SHM, Part III: Heterogeneous populations – Mapping and transfer
7. Foundations of population-based SHM, Part IV: The geometry of spaces of structures and their feature spaces

It should be noted that all these publications come from the same authors from The University of Sheffield, UK who may have “invented” this terminology “population-based SHM”. More recently, some papers have been published on the same topic using the keyword PBSHM or PB-SHM. It is also applied to different industries. Free search in Google Scholar results in 18000 references and by using the exact phrase results in two publications; number 1 above and a chapter in a book from 2022 called exactly "Population-Based Structural Health Monitoring" from the same authors. The book is called "Structural Health Monitoring Based on Data Science Techniques". This suggests that there is a group of people specifically using this terminology. Further searching on "population-based SHM" results in 166 papers, revealing other papers from the same author group but also from other institutions. Among them, the most recent ones are:

1. Towards risk-informed PBSHM: Populations as hierarchical systems
2. A Brief Introduction to Recent Developments in Population-Based Structural Health Monitoring
3. Towards Population-Based Structural Health Monitoring, Part V: Networks and Databases
4. On an Application of Graph Neural Networks in Population-Based SHM
5. A decision framework for selecting information-transfer strategies in population-based SHM
6. An Experimental Investigation of Feature Availability in Nominally Identical Structures for Population-Based SHM
7. Towards Population-Based Structural Health Monitoring, Part VI: Structures as Geometry
8. A mapping method for anomaly detection in a localized population of structures
9. Domain-adapted Gaussian mixture models for population-based structural health monitoring
10. The Astir Glider Wing Dataset for Population-Based SHM
11. On Aspects of Geometry in SHM and Population-Based SHM
12. Population-Based SHM Under Environmental Variability Using a Classifier for Unsupervised Structural failure Detection
13. A Gaussian Process Form for Population-Based Structural Health Monitoring
14. Comparison of bridge topology before and after repair using attributed graph comparisons towards population based SHM
15. Towards A Population-Based SHM: A Case Study on An Offshore Wind Farm
16. Towards Population-Based Structural Health Monitoring, Part VII: EOV Fields – Environmental Mapping
17. Automated Feature Extraction for Structural failure Detection: A Pseudo-fault Framework for Population-based SHM
18. Investigating Experimental Repeatability and Feature Consistency In Vibration-Based SHM
19. Assessing The Likelihood of Structural failure At The Start Of A Structural Health Monitoring Campaign
20. On metrics assessing the information content of datasets for population-based structural health monitoring
21. Towards risk-informed PBSHM: Populations as hierarchical systems
22. On the Application of Domain Adaptation in SHM (2019; one of the earlier papers without "population-based" from the same group)
23. Population Based Structural Health Monitoring: Homogeneous Offshore Wind Model Development

The key point is that there may be other terminology that is also useful for structural health monitoring of many similar assets which is related to different terminology, and these should not be excluded. Based on this, it is recommended to have a more holistic view of the "population-based structural health monitoring," not excluding those papers, but those papers may not fully cover the intention of looking across similar structures. The University of Sheffield is apparently "missioning" this terminology.

However, it is important to mention that whatever the methodology is called population based SHM or simply SHM, the aim is to explore the combined use of data sourced from multiple structures. Hence, the purpose is to avoid scarcity of data and thus to transfer data and knowledge from identical or similar structures. The best example of how population based SHM can be employed in real life is within the offshore wind industry, where the features extracted from one or several wind turbines could be used to assess and predict the behaviour of the entire wind farm. Among the recently published papers, it can be inferred that both homogeneous and heterogeneous populations are used in the monitoring of multiple structures. Several papers recently published address the use of population based SHM-like methods as listed in Table B-5.

Table B-5 Population based SHM papers

No.	*Title*
1	d N Santos, Francisco, et al. *Data-driven farm-wide fatigue estimation on jacket foundation OWTs for multiple SHM setups.* Wind Energy Science Discussions 2021 (2021): 1-36.
2	Lin, Weijiang. *Monitoring a population of structures from a spatiotemporal perspective: an application to offshore wind farms*. Diss. University of Sheffield, 2023.
3	Bull, Lawrence A., et al. *Data-Centric Monitoring of Wind Farms: Combining Sources of Information*. Data Driven Methods for Civil Structural Health Monitoring and Resilience. CRC Press, 2023. 120-180.

APPENDIX C

DNV rules

C.1 DNV rules

Many of these digital features are common for a SHM system and any other type of system for performance monitoring or condition-based maintenance or condition monitoring. These features may serve as the foundation for using data in a reliable way, also by class in a survey regime. DNV class has flexible hull monitoring rules (DNV-RU-SHIP Pt.6 Ch.9 Sec.3) which includes SHM systems. The class notation is called HMON. It should be stated that there is not a common IACS standard for these hull monitoring rules, but that other class societies have something similar. Focus is on functional approval of these systems including components, documentation, and the system itself with processing and storing capabilities as well as display. DNV hull monitoring rules states clearly that structural response and fatigue structural failure should be automatically calculated with and without vibration. Many other rules refer to this HMON standard.

DNV are already using a methodology called “Hull Insight dashboard” also called externally “conditions based hull scheme” and “risk based hull scheme”. This is used internally for the surveyors. The methodology is based on four main elements:

- IHS fairplay data; characteristics of vessel data and class notations
- Scalable digital twin indicators based on wave and AIS matching to determine relative level of wave-induced loads
- Product model of the asset; defining compartments relevant for inspections
- Past inspection findings from the whole DNV fleet from DNV surveyors

All these data are merged, and a certain machine learning algorithm is used to rate the relative risk between different vessels which again is used in a pragmatic inspection plan to determine the focus of the inspection. A main idea is that all the positive findings should be found by a fraction of the efforts. In this regime, it is also important to report negative findings, which confirms that you have done an inspection, but that implies additional reporting efforts. Another aspect is that better reporting tools are necessary to follow such a regime, but with better reporting also that validity of findings becomes more useful in the machine learning. All of this is possible without a detailed design model of the asset. It is related to the product model which defines compartments.

DNV class is also moving forward with an “umbrella” class notation called “Connect” which is expected for hearing in 2024. This implies that data from OEMs, service suppliers and vessels are provided as input to the survey regime in class for different types of systems, equipment and hull. Class then needs to determine exactly what they need as input data which may not only be sensor data, and an API needs to be well defined for each system, equipment and hull. DNV class may then use this data in a compliance-based regime that may provide input to a more conditions-based survey regime with potential remote surveys in between physical surveys. The survey intervals may deviate from the more rigid 5-year survey intervals depending on the asset type, hull, systems and equipment. Both regimes may be relevant also for stakeholders like PSA which may require to have overview of many offshore assets focusing attention to candidates with a high-risk picture.

DNV ship class has also a set of digital features in DNV-RU-SHIP Pt.6 Ch.1 related to

- Data collection infrastructure (class notation D-INF) which includes data quality monitoring and data management maturity, cyber security management system and initial audit
- Data driven verification (class notation DDV) which includes methods of verification for different types of standard systems
- Remote witnessing (class notation REW) which includes different level of online witnessing and control
- Nautconnect for data driven compliance of navigation systems

In addition, DNV class supports smart technology in DNV-RU-SHIP Pt.6 Ch.5 Sec.24. This is basically related to sensor-based systems related to:

- Operations and maintenance of machinery, equipment and systems
- Operation and maintenance of hull and structures
- Energy efficiency and environment more related to performance monitoring systems and IMO's regime on design and operational indexes to reduce CO2 emissions.

A last item which is missing and rarely covered by literature is the connection between monitoring and advanced complex numerical analysis. Measurements like model tests and full-scale measurements are often used in validation of numerical software. When measurements are used for the purpose of condition monitoring in terms of fatigue structural failure, they are often quite useful. When it comes to extreme loading the issue is that the SHM may lack the data at extreme response levels, but it may provide response levels at intermediate level, or the system may be set up to show the structural utilization in percentage and provide warning against exceeding design levels (required by hull monitoring rules). The latter is directly related to safety, but it could be questioned if the design levels may be exceeded in the future as harsher environment than what is encountered so far may be exceeded. The design of the asset may not be based on the state-of-the-art design tools based on analytical formulas, but more commonly used simplified numerical tools. The simplified numerical tools could again be validated and tuned for specific parameters against measured responses. Then the simplified tools may be used to assess an extreme number of potential future scenarios including nonlinear waves to reveal a limited number of critical wave and response episodes. These episodes may then be analyzed by more accurate computational fluid dynamics (CFD) tools to determine more reliably and statistically the extreme response. CFD methods are much more used the recent years to arrive at a more accurate physical solution, and this is now feasible with respect to modeling and computational time. The method has now been used many times for ships and offshore units, and the method goes under different names like HOSM (higher order spectral method). This has been developed in DNV since 2012 /16/ and /17/. Wave in deck problematic is generally evaluated by use of CFD to gain the necessary accuracy to estimate the structural integrity of the support structure.

It should, however, be emphasized that there are two main types of digital twins based on design models developed by DNV Class (generally offshore oil and gas units are not classed):

- *Numerical twin* (also called virtual twin) where the design model is used and the wave environment in design is replaced with encountered wave data from AIS (automatic identification system called also an anti-collision system which even fixed installations should have) and global wave matching. Position or GPS may be used as an alternative to AIS and for installation with fixed position the AIS must include heading if it is weather vaning.
- *Hybrid twin* where the design model is used in combination with (strain sensors) replacing the design wave environment. An inverse finite element technique is used. This is presented in two papers and there are two techniques, one that is RAO based and one that is spectrum response based (short term statistics). The latter appear to be more robust for zero speed cases. It is also possible to separate vibration response with specific modes from wave induced response. For two different approaches see /14 and /15 / using RAOs or short term response to calculate short term data which is thereafter aggregated.

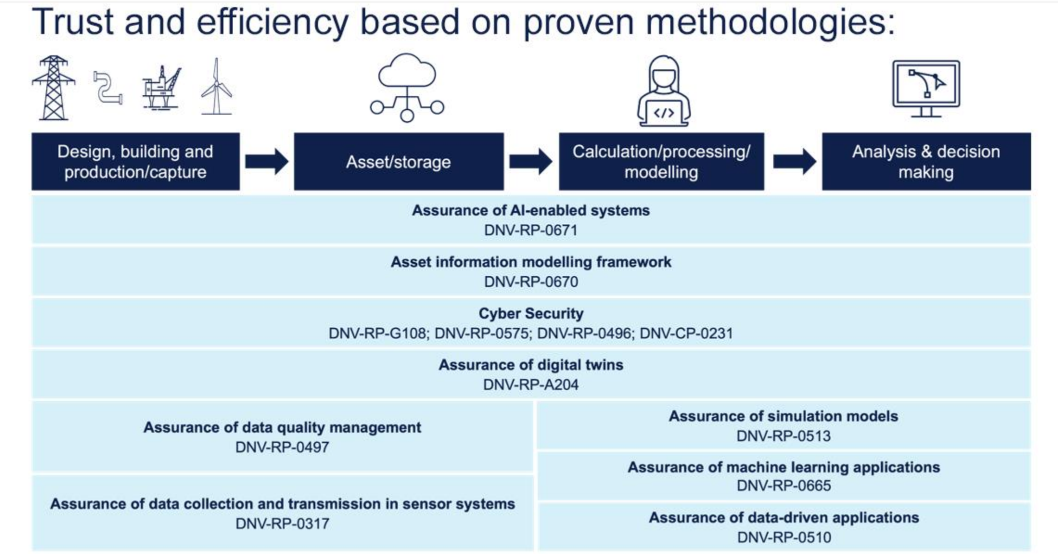
These two methods are reflected in the class notation FMS(NUM) and FMS(SENS) covered by DNV-RU-OU-0300 for fleet in service for offshore units. FMS(SENS) notation implies that also the numerical twin is included as a back-up solution and for comparison. The sensor-based solution may capture vibration and is regarded as more accurate although multidirectional seas of equivalent magnitude may pose a challenge. Also, non-linear effects like the splash zone effect needs to be properly handled and multiple loading conditions may reduce the accuracy, but ballast and full load tends to be conservative. The class notation FMS(SENS) focus also on data quality, corrosion and extreme loading, while the primary focus is on fatigue, and it should result in an asset specific inspection plan. The screening model is given more focus to cover similar details in different compartments or locations rather than the design focus which is primarily for the worst details of each type. The focus here is on floating units, while for certain units like fixed monopile soil stiffness may pose a significant uncertainty giving reason to use sensors for tuning design assumptions.

FMS(NUM) and FMS(SENS) are also reflected in DNV-RU-OU-0512 for floating wind installations. Both this reference and DNV-RU-OU-0300 includes HMON notation for hull monitoring systems according to DNV-RU-SHIP Pt.6 Ch.9 Sec.3. Such systems may include the sensors that provide input to these digital twins. It is emphasized that FMS(SENS) states that sensor setup should be optimized and planned based on evaluation of the design model and the locations of the critical inspection points to ensure that the sensor setup is minimized and robust, but still accurate. This is in practice never done since request for sensor installations are normally done without proper planning and aligning with maintenance plan and hull integrity management. Still limited and existing sensor installation may be proven to be useful for most assets.

A digression from DNV is also the definition of the concept “probabilistic digital twins” for “bringing risk assessments on-line to support risk informed decisions in operation” covered by a white paper https://ai-and-safety.dnv.com/probabilistic-twin/. Similarly, the whitepaper on “AI + Safety, Safety implications for artificial intelligence, why we need to combine causal- and data-driven models”, may be relevant, https://ai-and-safety.dnv.com/. This is also related to the first standard on assurance of AI systems, DNV-RP-0671 *Assurance of AI-enabled systems*. The latter does, however, not specify SHM, but mentions “prognostics and health monitoring” as an example use case.

C.2 List of DNV Recommended Practices supporting digital transformation

Figure C.1 provides a summary of DNV’s Recommended Practices which may support implementation of SHM as part of a digital transformation.


Trust and efficiency based on proven methodologies:

Design, building and production/capture → Asset/storage → Calculation/processing/ modelling → Analysis & decision making

Assurance of AI-enabled systems
DNV-RP-0671

Asset information modelling framework
DNV-RP-0670

Cyber Security
DNV-RP-G108; DNV-RP-0575; DNV-RP-0496; DNV-CP-0231

Assurance of digital twins
DNV-RP-A204

Assurance of data quality management
DNV-RP-0497

Assurance of data collection and transmission in sensor systems
DNV-RP-0317

Assurance of simulation models
DNV-RP-0513

Assurance of machine learning applications
DNV-RP-0665

Assurance of data-driven applications
DNV-RP-0510

Figure C.1 Recommended practices which may support digital transformation.

APPENDIX D

Supplier reference lists of sensor systems

Table D-1: List of some monitoring projects for offshore bottom-fixed and floating units

Project Name	Location	Year	Structure type	Sensor Provider
9 confidential projects + Hywind Scotland	UK		Floating and fixed	Strainstall
2 confidential projects	Germany		Floating and fixed	Strainstall
Greater Changhua offshore wind	Taiwan	2020	Wind Turbine Jacket	Pulse Monitoring
Forties Bravo	UK	1982	Oil and Gas Jacket	
Ekofisk 2/4H and Valhall QP	North Sea	1984	Oil and Gas Jacket	FORCE Technology
Kvitebjørn	North Sea	2005	Oil and Gas Jacket	FUGRO
Vattenfall Windpower	Denmark		Wind Turbine Monopile	Force Technology
Goliat	Barents Sea	2016	FPSO	SENSFIB Plus
Johan Castberg	Barents Sea	2024	FPSO	SENSFIB ILM+HSM
Nexus I		2014	Vessel	SENSFIB Plus
Mariner	UK North Sea	2016	Oil and Gas Jacket	SENSFIB Plus
Gina Krog	North Sea	2017	Oil and Gas Jacket	SENSFIB Plus
Knarr	North Sea	2015	FPSO	SENSFIB Plus
Pazflor	Angola	2011	FPSO	SENSFIB Global
Egina	Nigeria	2018	FPSO	SENSFIB Plus

About DNV

DNV is the independent expert in risk management and assurance, operating in more than 100 countries. Through its broad experience and deep expertise DNV advances safety and sustainable performance, sets industry benchmarks, and inspires and invents solutions.

Whether assessing a new ship design, optimizing the performance of a wind farm, analyzing sensor data from a gas pipeline or certifying a food company's supply chain, DNV enables its customers and their stakeholders to make critical decisions with confidence.

Driven by its purpose, to safeguard life, property, and the environment, DNV helps tackle the challenges and global transformations facing its customers and the world today and is a trusted voice for many of the world's most successful and forward-thinking companies.