SENSORBASERTE LØSNINGER FOR TILSTANDSOVERVÅKING OG SKADEIDENTIFIKASJON AV MATERIALER, SAKSNR. 2021/582

Structural Health Monitoring of topside piping systems and equipment

Petroleumstilsynet

Report No.: 2021-3187, Rev. 1
Document No.: 1229178
Date: 2021-12-17

Project name:	Sensorbaserte løsninger for tilstandsovervåking og skadeidentifikasjon av materialer, saksnr. 2021/582	DNV AS Energy Systems Materials & Structural Integrity - Oslo Veritasveien 1 1363 Høvik Norway Tel: +47 67 58 99 00 945 748 931
Report title:	Structural Health Monitoring of topside piping systems and equipment	
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Date of issue:	2021-12-17	
Project No.:	10297943	
Organization unit:	Materials & Structural Integrity - Oslo	
Report No.:	2021-3187, Rev. 1	
Document No.:	1229178	

Applicable contract(s) governing the provision of this Report:06746 DNV – Sensorbaserte løsninger for tilstandsovervåking og skadeidentifikasjon av materialer

Objective:

DNV has made this report on behalf of the Petroleum Safety Authority (PSA). The report highlights the most common and promising monitoring solution technologies that can be used for topside facilities with focus on piping systems. This report focuses on different sensor detection system for fatigue, corrosion, and moisture penetration through isolation on topside piping process systems. Further developments and trends related to monitoring systems are discussed in combination with the main elements in an integrity management system, including data quality and data processing.

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Keywords:
Sensors, online monitoring of fatigue, CUI and corrosion, data processing of measured data, topside,

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
0	2021-11-25	Issued for comments	Agnes/ FWIG	GABO / GAST	GHEI
1	2021-12-17	Final issue	Agnes/ FWIG	GABO / GAST	GHEI

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1 EXECUTIVE SUMMARY

The main principle of the Petroleum Safety Authority's (PSA) requirements is that the operators shall know the condition of their equipment both individually and collectively and work continuously to reduce risk. To prevent unwanted incidents to happen with focus on piping and equipment installed on offshore installations and onshore facilities, this report explores the use of sensor-based solutions for condition monitoring and damage identification in materials. The use of sensor technologies is crucial for better prediction of an asset's condition and integrity and to reduce risks from fatigue failure and corrosion, especially having in mind that the life span for many topside installations can exceed 50 years in service.

Digital technologies offer great opportunities for real-time asset integrity management where different information systems can be linked together. Important parameters influencing a system's integrity can be controlled and measured in real time, e.g. corrosion, pitting, wall thinning, chemical analysis of internal media, temperature, pressure fluctuations, structural stresses and strains. Digitalization is currently boosting this technology both within model-based prognostics, data-driven prognostics, and hybrid solutions. Hybrid solutions couple both analytical predictions with sensor information's of a given system to assess its integrity which is believed to be the most viable option asset integrity for complex systems like piping and process equipment's subjected to fatigue loading.

Fatigue due to severe vibrations either due to external loading or flow-induced, is an area which can be challenging to assess properly during design due to lack of adequate design tools and/or understanding of dynamics and excitation sources for the given component and piping system. There are numerous sources of excitation on a platform, from environmental loads to flow induced and process induced vibrations. Changes to a system as a consequence of design, fabrication errors or age either by changed equipment, aging of resilient mounts or wear, tear and corrosion may suddenly change characteristics of a system and cause vibrations which the system was not designed for. Degradation and changed conditions are important elements for an industry with aging assets and use of sensor technology is an enabler in such respect to better know the asset condition in real time and enhance for safe operation and life extension.

1.1 Asset integrity management by use of sensor data

In the Energy sector, as well as Maritime and onshore process facilities, planning and execution of structural inspections and the safety and operational risks related to structural integrity and cost are two main drivers which push for the development of new ways of monitoring process facilities:

- There is a rapid development in sensor technologies, algorithm development, data storage systems, data transfer, data processing and computing power. The robustness and reliability of electronic components is constantly improving while the cost is decreasing. To make use of this development, classical understanding of fatigue, corrosion and moisture penetration through isolation on piping systems must be combined with several IT-related disciplines. As sensors become smaller, smarter, cheaper and consume less energy, the energy sector will definitely see more use of them.
- Further, the advancement in new inspection technologies, where the present trend is increasing efforts towards automatization and computerization, is driven by increased access to computational power and storage. This allows for capturing and processing of large amounts of data, with more consistency and repeatability in the inspections than with the conventional manual inspections.
- Use of more insight and knowledge of an asset's condition allow asset owners to develop effective long-term strategies and take preventive measures in due time to ensure continued safe operation and prevent accidents from happening. It is important to emphasis 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. Once

this is in place, one can proceed to the choice of log frequency, selection of sensors and their locations and data transmission. This will be input to the data analysis which are input to the final decision step: structural integrity evaluation.

- In general, it may be stated that the digitalisation framework related to condition monitoring is in place through e.g. classification rules, however, a uniform regulatory regime for exploiting this may not always be in place and standardised applications are not fully developed for all disciplines.
- Planning for instrumentation serving the needs during operation is often forgotten and retrofit solutions on existing assets are associated with substantially higher costs. For many disciplines instrumentation is used for trouble shooting and validation of design assessment rather than active use in operation as part of long-term structural integrity management.

1.2 Sensor technologies for monitoring fatigue and corrosion

Sensors is an emerging technology for detection of fatigue cracks, water in insulation and final leakage, and different types of sensors have been evaluated and discussed. The following highlights are summarized from the study:

- For fatigue monitoring, several sensor concepts already are in use and under development with sensor-based rules already developed about 30 years ago. The most common and reliable solution is to document the response of the system (piping and components) by use of sensor data, which are then used to calibrate a numerical model. This model will then be used to document fatigue life by use of design S-N curves or crack growth models applicable for the component and structural detail where sensor data is not available. Different strain types can be measured by more traditional strain gauges. Strains can also be measured by more advanced methods like fibre optics and use of digital image correlation (DIC). Accelerometers and velocimeters are also to a large extent used to measure vibrations in process piping and other topside equipment's like valves and process modules, however, the measurements need to be correlated to stresses and strains in the structure for fatigue damage calculations. One concept under development for detection of crack growth is the use of acoustic emission, however, as the method is very sensitive to background noise and need carful calibration to provide reliable information on fatigue crack growth.
- For corrosion under insulation (CUI), moist monitoring systems will give valuable information needed to identify a degradation mechanism that is difficult to predict. Also, when considering the extent of hydrocarbon leaks due to corrosion under insulation this should be seen as an important element to reduce the risk of major accidents.
- Corrosion monitoring systems in general give the condition at the exact location where the sensor is installed and might give limited added value unless sensors are covering larger areas. The systems produce results that represent the corrosive environment or reduced wall thickness in a well-documented manner.

Data collection, processing and quality will be utmost important in order to draw conclusions on final output data whether they are based on local and global models, expert opinion, real-time measurements or (as in most cases) a combination of some or all of them. In section 7 of this report, data collection, processing, quality, management and security are briefly discussed in relation to use of sensor data for decision support.

1.3 Experience by use of sensor data

Sensor based condition monitoring are already being used today for various industries, and especially the aerospace industry is relying heavily on sensor data for safe operation of an aircraft. Another industry that relays on use of sensor technology for monitoring of assets is the offshore wind industry, with special focus to detect and prevent generator, gearbox and rotor bearing failure. Also, the maritime industry aims at holistic structural health monitoring of structures and structural components allowing for use of sensor data for decision support. For the oil and gas sector limited use of sensor data are used today to measure structural response in-real time related to process piping and equipment for topside and onshore facilities. The experience is mostly gained from pressure, flow and temperature controls of pressure equipment.

Although a lot of research is put into the field of developing smarter, more robust and cost-effective sensors, the processing and interpretation of the measured data still need further development to establish sound decision tools. One challenge is that models based on sensor data do not capture safety-critical behaviour not yet experienced by the structure or component. Another challenge is that experience shows that physics-based methods in general are too conservative compared to behaviour recorded from sensor measurements. One example is the prediction of flow induced vibrations from multiphase flow in process pipes, where sensor measurements have shown lower stresses than model predictions.

Sensor data gives location-specific system response, however, when assessing locations away from a sensor, the uncertainty become greater. Hence, a hybrid solution with a physics-based model that is calibrated to real-world data, will increase confidence when extrapolating outside current experience.

For structures this is already described in current rules for fleet in service of offshore units and floating wind turbines for fatigue resulting in inspection plans also covering other failure modes.

1.4 Future trend

Data, algorithms, and artificial intelligence (AI) will pose a great number of opportunities for an asset owner to increase the knowledge of an asset and to prevent risks over the next ten years. The energy producers will instrument their process operations with sensors providing data representing a greater variety of physical properties, convert manual data entry from e.g operation and physical inspection to digital data entry, and implement more automation to increase operational performance. 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.

Internet of things (IoT) is a key element of compositional architectures providing insights on the status of a physical asset. The dramatic increase in types of sensors and the quality of information generated may create a need for edge computing capabilities where processing of the information close to the point of generation, understanding the input, and instructing systems to act if necessary, may be a viable future option /18/.

For novel as well as highly optimized designs, sensor data can be an enabler from prescriptive rules and towards database-driven safety factors.

2 INTRODUCTION

2.1 Background

The Petroleum Safety Authority (PSA) has commissioned DNV to perform a study on how to improve technical integrity of topside facilities in the operation by use of sensor technology. The use of sensor technologies to better being able to predict the asset integrity to reduce risks from fatigue and corrosion are crucial, especially having in mind that the life span for many topside installations can exceed 50 years. A similar study was undertaken in 2020 for Subsea structures "How digital tools and solutions can improve Subsea Integrity Management" /1/ which focused on the management system part among many other subjects. Hence, for more information related to integrity management systems please see /1/ for guidance.

The wish to better know the condition of equipment and thus be able to plan and perform maintenance before a critical failure occurs has existed for many years. It is crucial to understand the condition and ensuring control of the integrity in the operation phase through the systems entire lifespan is a key prerequisite for;

- avoiding loss of containment,

- reducing the risk of adverse events in the operation phase

- maintaining a high level of safety in the petroleum industry

- ensure production and up-time.

Early leak detection of liquid and gas from topside process piping is a critical task for safety and economic reasons. For an operator, there is a need to accurately detect, and localize leaks to timely recover them safely and cost-effectively, or the most viable solution is to be able to prevent leaks to happen. The latter named prognostic maintenance, condition-based maintenance or predictive maintenance represents well-known methods where the goal is to ensure that preventive measures are taken in due time where leak may happen at a piping process system.

The PSA report 'RNNP 2020: Summary Report 2020 The Norwegian Continental Shelf - Trends in risk level in the petroleum activity' /2/ is by the industry considered to be an important tool for helping to establish a common picture of developments of selected conditions which affect risk and in addition, illustrates safety trends in the petroleum activity. The following is concluded in the report related to presents hydrocarbon leaks greater than 0.1 kg/s in 2005–20. Five leaks with a rate above 0.1 kg/s were registered in 2020, with two in the 0.1-1 kg/s category and three in the 1-10 kg/s category, see Figure 2-1.

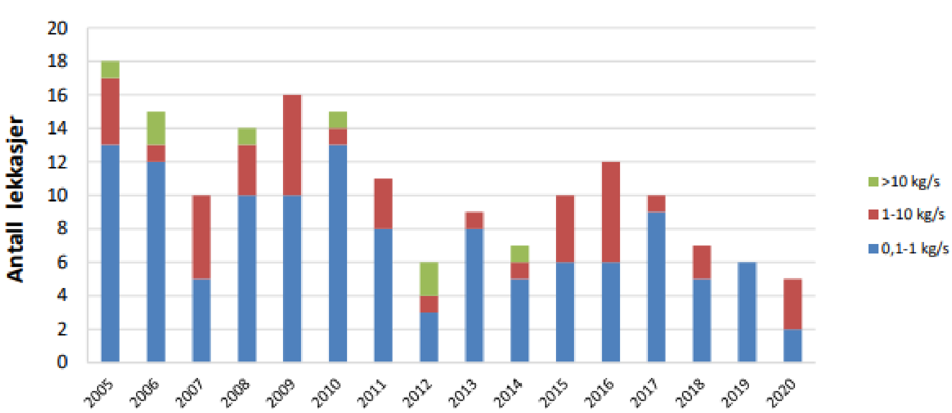

Figure 2-1 Hydrocarbon leaks exceeding 0.1 kg/s, 2005-20 /2/

The most common failure locations will be areas of wall thinning from corrosion or locations where cracks are developing. To reveal hidden failures through condition knowledge and thus reduce inspection and unnecessary repairs and testing efforts on critical (e.g. safety) equipment is a compelling need for the Energy sector today. However, the technology is complex, but there are many opportunities to significantly reduce uncertainties from sensor data. Measurement data, if they do not come from reliable sources, can create greater uncertainty and force owners to spend time answering questions that do not improve safety or reduce risk. For example, data from a faulty or uncalibrated sensor can lead to many questions and wasted time if the person assessing the measurement data does not have tools that allow incorrect or inaccurate measurement data to be easily discarded.

In the following, different sensor technologies are presented and discussed more in detail for application on topside piping and equipment installed on offshore installations and onshore facilities.

2.2 Petroleum Safety Authority 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 (ref. the management regulations § 10). 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's regulations can be downloaded at PSA - Home (ptil.no). In the following, regulations where use of sensors technology will be an important technology to support the decision management making are listed.

The Management Regulations:

§ 5 'Barriers'

Barriers shall be established that at all times 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 have been defined in respect of the concrete technical, operational or Organisational barrier elements necessary for the individual barrier to be effective.

§ 19 'Collection, processing and use of data'

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'

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'

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.

2.3 Objective and scope

2.3.1 Objective

The objective of this study is to gain knowledge about development and use of sensor-based solutions for condition monitoring and damage identification in the materials. The study is limited to corrosion, corrosion / moisture under installation and fatigue of pipes and equipment installed on offshore installations and onshore facilities.

2.3.2 Scope

The scope addresses knowledge gathering on historical developments and to investigate the opportunity room for the use of sensor-based solutions for condition monitoring and damage identification in the field of material degradation. The presented work is limited to corrosion, moisture penetration and fatigue of pipes and equipment installed on offshore installations and onshore facilities. The report maps available methods and technology for collection, storage, efficient use of data and possible importance for security. In addition, the study elaborates on a high level the strengths and weaknesses with the methods evaluated and the purpose of technology, how they can contribute to better safety and the extent to which they have been tested in actual use.

The purpose of monitoring, inspection/maintenance and testing is to detect existing or developing threats and failure modes that can result in a leakage or burst and to validate the integrity or function of barriers and equipment. All the monitoring, inspection and testing activities generate a large volume of data that needs to be analysed in order to determine if the integrity of the system is jeopardised and what potential actions that should be carried out. Figure 2-2 illustrates the general high-level process for condition monitoring of topside processing systems. This report addresses the data gathering part by investing different sensor technologies to evaluate fatigue, corrosion under installation and corrosion.

The class notations referenced in this report is DNV notations, and similar notations consist in rules of other class societies.

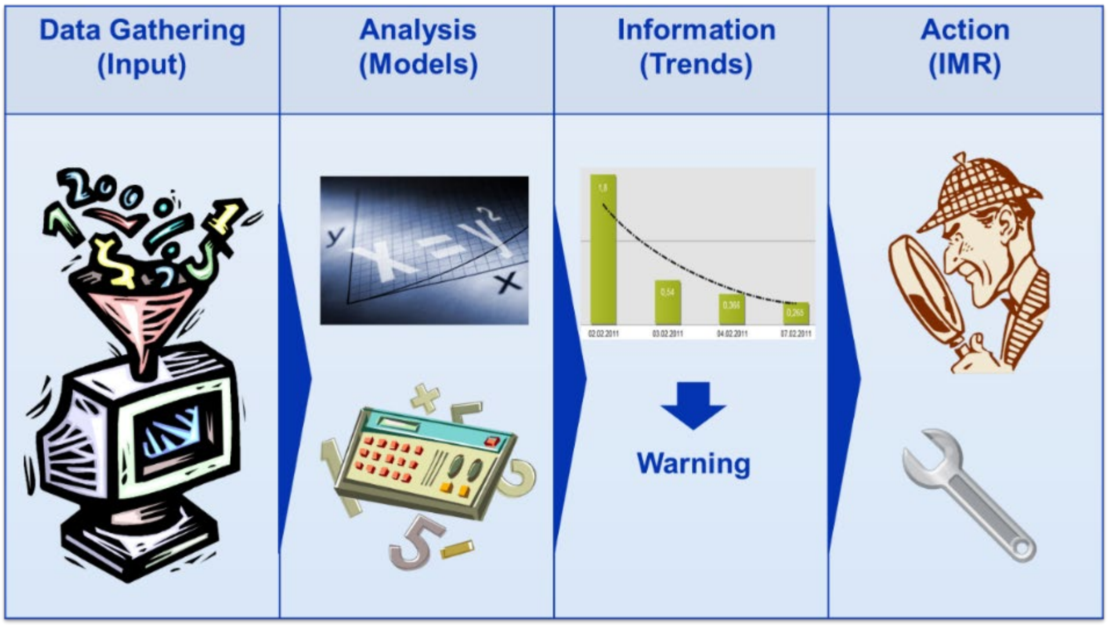

Figure 2-2   Monitoring, Inspection and Testing process /19/

• Data gathering: Data is collected from sensors, inspections and integrity tests of the system. The data is then stored in a database or repository.

• Analysis: The data is analysed to e.g. determine a reduction in capacity or performance, which could be loss of wall thickness due to internal corrosion.

• Information: The result of the analysis may be compared to earlier results to determine a trend. If possible, the remaining life should be estimated. If the result exceeds a given threshold then an assessment of the situation should be initiated and possible mitigating actions to reduce risk should be described.

• Action: If deemed necessary then an appropriate action like inspection, maintenance and repair (IMR) should be initiated. This could include increased surveillance, immediate or planned maintenance, mitigation, intervention or replacement. Generally, the requirements to inspection and test intervals are guided by internal requirements, standards and legislations and shall be complied with.

3 STRUCTURAL HEALTH MONITORING OF TOPSIDE PIPING SYSTEMS AND EQUIPMENT

Topside piping is the single largest source of hydrocarbon releases (HCRs) on the offshore oil and gas (OOG) platforms in the North Sea region /3/. Degradations of piping structure are caused mainly by corrosion and fatigue crack growth, or due to internal aggressive fluid. The effect of corrosion is normally designed for by corrosion allowance or a protection system, which makes the corrosion development gradual and rather easy to control. The fatigue crack growth can be more critical because cracks can result as function of time in-service and in a worst case in a sudden fracture. Moreover, cracks are often hard to detect because they are rather small for a significant part of the crack growth time. Defects much larger than those implicit in fatigue design curves are also of concern as observations of some cracks found during inspections can be attributed to such defects. Such large defects are also sometimes denoted as gross errors.

Risk based inspection and reliability centred maintenance (RCM) are used today to assess critical part of an asset, however they are often qualitative in nature and requires experts from different disciplines to review each of them, hence the complete holistic approach is still lacking to certain extent today. Today, we mostly base our judgment on experience, design analysis and testing when we design and operate an asset, and limited decision is taken based on prediction models, where e.g advanced material models are input to detailed structural analysis including process parameters.

Facility regulation § 17 'Instrumentation for monitoring and recording' specifies that "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" (see section 2.2 for further details). In practice, this is in general fulfilled by collecting weather data and use of installed corrosion probes on process facilities. Hence, it is not common practice today for oil and gas assets to plan for continuous use of sensors during operation to address structural integrity, and today monitoring systems are mainly planned and installed when something unexpected happens (often related to quality issues during fabrication in combination with higher utilizations or dynamic loads under operations). This late planning can be challenging to optimise a sensor system due to accessibility to install due to isolation, paint, closed systems and limited infrastructures to handle the measured data. Reduced cost and increased reliability of sensor systems, combined with digitalization will boost asset integrity management technologies both within model-based prognostics, data-driven prognostics and (perhaps most importantly) hybrid solutions based on a combination of the two. The limited industry use of sensor data today for prognostic maintenance is rooted in **inadequate** guidance in rules and regulations, **lack of** detailed material resistance models combined with developed safety factors and **poor** data management. It is foreseen that in the future data driven safety factors can be applied together with sensor data to assess the integrity and also used in the design phase of a system for design optimisation. In the following section, the digital twin concept is discussed as one viable option where both measured data and analytical predictions are input for decision making, such a system can be classified as a hybrid solution. Today, the digital twin concept is industrialized for the Maritime industry with rules and regulations supporting this technology with the new class notations for different digital features (DNV).

New developments into unmanned assets will also drive the development and implementation of monitoring technologies and new digital solutions to manage technical integrity of the assets.

3.1 Digital twin

Implemented correctly, a digital twin could potentially become a platform combining real-time simulations, advanced artificial intelligence, and machine learning to analyse and generate data to support decision-making. However, the track record of digital twin projects in the oil and gas industry indicates risk related to expectation and trust of such a technology, guidance to for buyers of digital twin technology has been published /7/. Guidance on qualification and assurance of digital twins can be found in DNVGL-RP-A204.

A physical oil and gas asset is designed and built to perform to the highest standards. It must go through rigorous assurance processes to meet regulatory requirements, company and industry standards. In stark contrast, there is no requirement for an asset's digital twin to obtain the same seal of approval, despite potential problems in implementing and using this technology. Problems may also emerge if a digital twin is inadequately maintained and updated as its real-world sibling evolves. Even with correctly-specified digital twins, problems can arise in operation, as physical assets undergo many changes during their lifecycles. Development of suitable platforms for digital twins are needed to guarantee security, availability, scalability, connectivity and verifiability within a standardized interface can challenge the use of digital twin concepts. However, in order to establish a hybrid solution for condition monitoring with use of analysis in combination with sensor data, agreed platform structures need to be in-place.

3.2 Typical degradation mechanisms for topside processing and equipment systems

A failure mode can be defined as a condition where the equipment for some reason is no longer able to fulfil its intended purpose. A failure mode can be e.g. loss of containment (burst or leak), loss of function, clogging etc. Table 3-1 gives an overview of the most typical failure modes with a description of the failure modes and possible causes. This report will focus on sensor technologies that can provide better insights for decision support with focus to evaluate and prevent fatigue failure, monitor corrosion under insolation and corrosion in general. It must be noted that different threats may lead to different types of failure modes for topside process and equipment systems offshore and onshore. For instance, corrosion may lead to leak, burst, cracking, metal loss and loss of function. When assessing different threats to a piping or equipment systems, the associated potential failure modes need to be assessed individually.

Table 3-1 Typical failure modes for topside processing systems

Failure mode	Description	Cause (Damage/ Abnormality)	Consequence	Degradation Mechanisms
Cracking	Fracture capacity exceeded	Overload, vibrations, fatigue loadings	Large spill	HISC, environmental cracking, fatigue
Metal loss	Reduction of system pressure containing capacity	Coating damage, wall thinning	Wall thinning, reduced load bearing capacity	Wall thinning, reduced load bearing capacity
External leak	Failure jeopardizing system pressure containment	Localized corrosion attack, small crack, damaged seal, loss of external corrosion protection	Small spill	Material ageing, corrosion, erosion, fatigue
Material ageing	Delamination of polymeric materials reducing e.g. strength or protective capability. Ageing of elastomeric material due to chemical and thermal exposure	Material degradation due to exposure to conditions outside of qualified range e.g. UV, temperature, chemicals	Loss of function, internal and external leak	Ageing
Yielding	Too high utilization of the material due to overload	Dent, overload, displacement	Loss of function, loss of functionality	Corrosion, erosion

4 EXCITATION VERSUS RESPONSE

When planning to instrument an asset or its equipment by a sensor system like a hull monitoring system for a piping system it may be questioned what the purpose is and what is the value. Answering this may also explain if it is purely the response or also the excitation source that needs to be revealed. The latter tends to increase the instrumentation scope but also bring more understanding and knowledge of an asset.

4.1 Value – business case

Instrumentation comes at a cost which relates to initial instrumentation costs but also maintenance cost of the system. The benefit should be larger than the costs over the lifetime, although it may be difficult to quantify values as control, transparency, awareness, best practise, experience feedback, loss of reputation and improved safety. More tangible benefits may be reduced inspection planning, reduced inspection, reduced repairs and reduced downtime. Sometimes the latter is enough and in certain cases being a preferred partner with transparency and control can be enough. In other cases, it may be a requirement.

The reason for instrumentation may also vary. It may be a deliberate choice during design phase to design for a flexible inspection regime. It is not often done, but it should be done as the inspection program is basically a result of choices made to the design assessment. Use of sensor data may also support operations outside a design envelope or where fabrication errors may degrade the original design life or capacity substantially. Instrumentations may also be used to monitor damages for trouble shooting and then frequently not as permanent state-of-the-art instrumentation solutions. The results may reveal if damages are a result of poor design, poor workmanship or high loading, which may affect the repair solution.

Lifetime extension is also a potential good reason for instrumentation as well as redeployment. It is often observed that this is done a bit late in the process. Having some experience before lifetime extension or redeployment may affect associated decisions, so instrumentation at the decision date is not typically desirable.

In any case the business case should be evaluated to defend the choice of instrumentation.

4.2 Excitation

With reference to e.g. damages to pipes related to fatigue from quasistatic loading, low cycle loading or vibration it may be many different excitation sources like:

- Wave induced loads like inertia from self-weight or deformations of the structure affecting the boundary conditions of the pipe system
- Wind induced loads due to gusts
- Heating cycles due to internal fluid flow at changing temperatures
- Wave induced vibrations due to resonance or transient wave impacts
- Wind induced vibrations due to turbulence of the wind passing the structure or vortex shedding
- Vortex induced vibrations for pipes in fluid
- Sloshing of pump towers in membrane tanks of LNG or other types of fluid like ammonia (a future fuel)
- Flow induced vibrations like flutter due to high flow rates and instability for pipes with one free end and the other well supported. Flow induced vibrations may also occur due to slug flow and bends and multiphase flow

- Equipment induced vibrations. This may be related to equipment having nothing to do with the specific pipe but all the excitation sources on the assets causing parts of the structure to vibrate. It may also relate to the type of pump or compressor connected to the pipe and how the resilient mounts are arranged.
- Ice induced vibration with different ice crushing regimes where frequency lock in is related to violent ice induced vibrations of the whole structure or part of it.

Overall, there are many sources that may excite vibrations on a case-by-case basis. An apparent trend is that aging structures with tear and wear and change in equipment and process parameters may introduce vibration issues later in the lifetime. For several of the excitation sources design tools may be inadequate and many cases may also not be considered during design. Vibration is a field which is related to considerable amount of trouble shooting during the lifetime of an asset compared to design assessment.

A method that are used to a frequently to confirm vibrations issues is through the class notation VIBR (DNV) notation that also applies to electrical equipment, but acceptance criteria is related to steel and aluminium and criticality for fatigue. The critical against this notation is that it is based on spot checks during sea trail / start up and permanent sensor systems may be needed due to material degradation mechanisms and wear and tear.

4.3 Response

Responses of a pipe system or process equipment are best measured directly on the system itself. A response is due to an excitation, where the excitation source may be the system itself (e.g. from flow induced vibrations in process piping) or from external excitation sources as e.g. vibrations in equipment that again influence other components response. The response as measured strain may be used directly to quantify annual fatigue damage as input to a fatigue assessment often including fracture mechanics to calculate optimal inspection intervals. This may be done based on design calculations, which in certain cases may be far from reality and then often also on the very conservative side. An inspection plan needs to consider other damage modes as well from e.g. corrosion, wear and tear of materials, often in combination with fatigue loading. Hence, when using sensor data more insights are gained which may determine more accurately the system responses which can be input to an asset management decision support. If improvements in operation are made or excitation for some reason is reduced during operation, the sensor systems will capture this operational change which may result in extended inspection intervals and increased fatigue performance.

4.4 Mitigation actions

If it turns out that the situation is too severe and damages have occurred or will likely occur in the near future, then measuring only the response may not be enough to ensure safe operation. For a piping system based on the response, a solution may be to strengthen the piping system. However, by measuring the excitation part and changing that instead the response may approach acceptable levels. Hence, the instrumentation may depend on the exact purpose of the instrumentation and the relevance of mitigating actions.

5 SENSOR SYSTEMS

Sensors become smaller, smarter, cheaper and consume less energy. With the additional enabler technology like communication networks and the general possibility of handling large amounts of data, sensors can be made useful in many areas which were earlier unthought of. Obviously, such applications create new possibilities related to asset integrity management by use of e,g energy-autarkic sensors, nano-sensors, biosensors, and sensors for chemicals. In the following, different sensor technologies most applicable for topside piping is presented and discussed, in addition to some promising technologies still in its exploratory stage. Guidance on sensor system quality can be found in DNVGL-RP-0317 /2/.

5.1 Sensor system definition

A sensor monitoring systems consists of three main system components: the sensor, data transfer of data and hardware. The conceptual sensor system is schematically shown in Figure 5-1 and consist of:

A sensor (*instrument*) is a device, module, machine, or subsystem whose purpose is to detect events or changes in its environment and send the information to other electronics. The smallest change that can be detected in the quantity that it is being measured is named the sensor resolution or measurement resolution of the system. For a sensor with digital output, this usually corresponds to the numerical resolution of the digital output. The accuracy of a sensor may however be considerably worse than its resolution. Today, the use of smart sensors is more and more used, this is a sensor that may have added functionality such as built-in -tests and self-calibration options.

1) Data from sensors (*local asset component* & *data relay component*) can be stored locally or sent either consciously or at an interval defined by the system/user. Sensors can either be wired (i.e. tethered) or wireless. Wired sensors generally transfer data to a data collector faster, more reliable and more securely than wireless sensors. Wired sensors are often more expensive to install due to expensive cabling systems often needing scaffolds and maintenance during operation. Wireless sensors possess advantages of more flexibility in installation and may hence cost less. Wireless data transfer however poses concerns on data security and signal transfer reliability including limited bandwidth, latency, data aggregation, environmental conditions.

2) Hardware and software (*remote data centre component*) for data analysis and storage are the final part of a sensor system, which is critical for a useful monitoring system. Raw data obtained from sensors is abundant in both amounts and formats and to check and verify the quality of the data collected, pre-processing and filtering is required. Data quality is addressed in e.g. the recommended practice DNVGL-RP-0497 Data quality assessment framework from 2017.

In addition, a sensor system may also include a “*source system*” which is typically an automation or safety system responsible for real-time control or monitoring of the equipment instrumented with sensors.

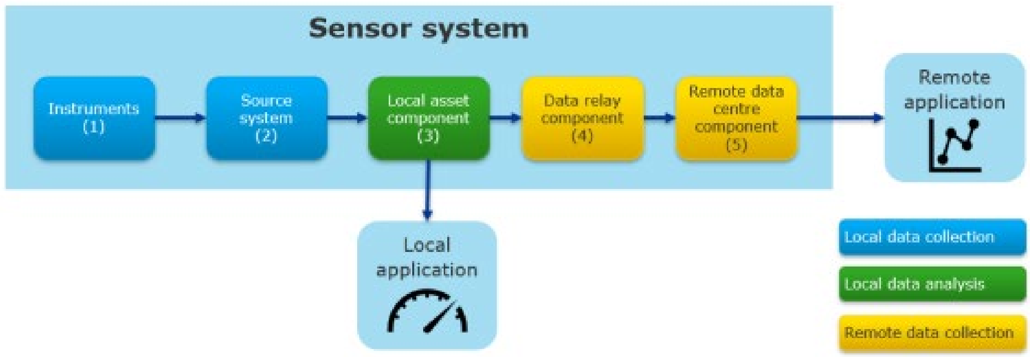

Figure 5-1 The conceptual sensor system /3/

Data consumers can be data export tools, various types of software applications including digital twins as described in DNVGL-RP-A204 or data driven models as described in DNVGL-RP-0510. General principles and best practices for sensor systems are listed in Appendix A.

Figure 5-2 illustrates an offshore rig communicating data to a remote data centre onshore. The rig may be equipped with multiple instrumented subcomponents such as different types of machinery, pumps, valves, heat exchangers, as well as pipelines and tanks. These subcomponents are instrumented with sensors for e.g. measuring pressure, temperature and flow.

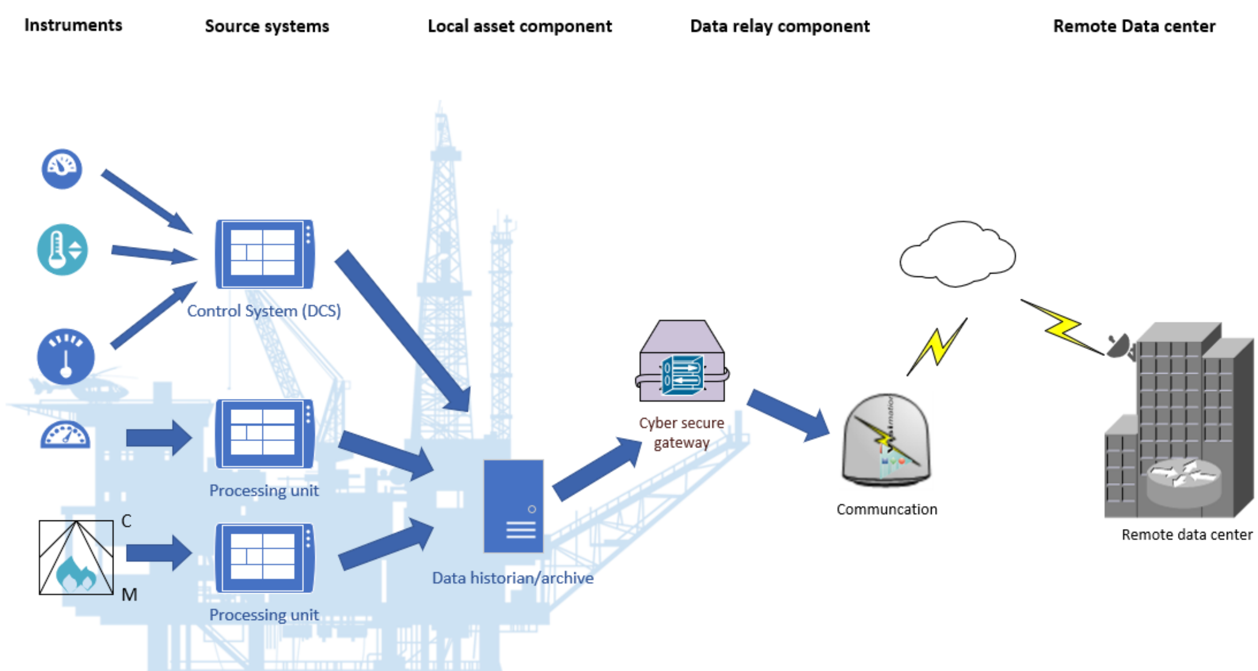

Figure 5-2 A sensor system on an offshore rig /19/

It should be emphasised that there are rules available for the sensor monitoring system through hull monitoring rules associated with the class notation HMON where the parenthesis includes the qualifiers describing which sensors and how many are installed. Hundreds of assets (mostly ships) are installed with such systems, but not necessarily with a piping monitoring system. In addition, there are data infrastructure collection rules related to the class notation D-INF (DNV). This is related to everything from data relays to data formats, data quality and cyber security a lot based on recent ISO standards also developed by DNV like ISO19847/19848 for data formats and communication. D-INF is intended as a yard delivery getting the asset with all subsystems ready to send data to shore and act as a centralised onboard hub, but it includes standardised or proprietary solutions which also may be retrofitted. The data may be further used independent of class systematics for any purpose related to Smart notation for innovative, digitalised, and green services or towards class related to DDV notation for data driven verification or REW notation for remote witnessing. This is basically a framework in place which may locate data on a data platform like Veracity, www.veracity.com. These examples of class notations are from DNV but other classification societies may have something similar. The progress on use of sensor technology has seen an increasing growth the 5 last years. Almost any system may be approved subject to technology qualification, system qualification, type approval (standard systems) or class approval based on class and offshore design rules.

5.2 Sensor system failure modes

Different threads can jeopardize a sensor system and need to be evaluated carefully in the planning phase of a system. DNV RP-0317 /3/ provides a detailed list of different threads, below is some of the significant once listed which should be evaluated for a topside sensor process system.

Table 5-1 Sensor system failure modes, examples /3/

Threat	Failure Mode	How to detect
Allowing data server clock to drift	Incorrect time stamping	Compare data server clock to satellite/GPS time
Sensor drifting over time	Inaccurate data	Periodic calibration using reference instruments. Comparing readings with multiple sensors
Allowing clock on control nodes or smart instrumentation to drift	Incorrect time synchronization	The degree to which sequentially received events are received out of order in accordance with source time
Poor calibration of measurement equipment	Incorrect value reported	Compare drift in sliding average between adjacent/ similar transmitters (where possible). Monitor the time since the last calibration (compared with calibration recommendation)
Network link from collector to source system or between nodes in collection infrastructure is broken	No new data is received while the link is broken	No new data is received from the system. A heartbeat signal would stop updating. If no recovery is configured, there will be a long-term data gap
Data collection settings in a source system are inadvertently changed or omitted during system maintenance	The data point (tag) stops updating or updates too infrequently	The amount of raw data from a particular tag starts reporting less frequently over a period of time, compared with prior periods. The amount of raw data for a tag stops correlating with the amount of raw data for other tags (which had prior correlation).
Data collection node configuration is inadvertently changed or omitted during system maintenance or upgrade.	Data archive settings become incorrect or source systems data providers may be omitted	Data archive size stops growing, or the growth rate changes. One monitoring possibility is to have diagnostic tag in the source system which alternates in a known way between showing valid data and all the possible diagnostic states in a controlled manner and to monitor continuously that these diagnostic states can be retrieved by data consumer at the other end.
Data collection settings for an individual tag is configured to use too much filter compression	Imprecise data is recorded for a tag	End-user feedback.

Threat	Failure Mode	How to detect
Data volumes exceed the available bandwidth	Missing data or gradual increasing latency	The latest value recorded by the data collection infrastructure lags behind current time by a predefined time interval threshold
Underlying data quality information is dropped by collection infrastructure	Bad data is reported as good	All values are reported as "OK/good" to data consumers. Finding extreme outliers with "OK/ good" quality coding is an indication of this problem
Desired instrumentation missing	No value being measured	It is difficult to detect that a sensor e.g. doesn't exist or that a candidate sensor is located in the wrong location. A manual assessment is required

5.3 Strain gauges

The strain and stresses of a material are measured by use of strain gauges, and works such that when the material deflects, the strain gauge will vary in its resistance. They are generally installed on the surface and one can measure tension, compression, torsion, torque, force, weight, and pressure. The most common used strain gauges are wired bounded gauges. Several thousand different wired strain gauge types exist, they have a long track record and easy to install. To attach the bounded strain gauges to the structure, a film coating or adhesives must be applied. These additional inelastic materials tend to degrade over time which changes the characteristics of the strain gauges. The bonded strain gauges can be classified into single (linear), double, shear strain gauges, rosettes with several measurement directions. When the structure where the strain gauge is attached start to deform, the foil is deforming which cause the electrical resistance to change. Wheatstone bridge is usually used to measure the resistance change and is related to the strain by the quantity (gauge factor – see Table 5-3). Strain gauges has a linear characteristic where the variation in resistance must be a linear function of the measured strain.

Some of the pros and cons are listed in the table below for wired bounded strain gauges. It should be emphasised that maintenance may be an issue for electromechanical sensors while lifetime can be good when maintained and not the cheapest sensors are used.

Table 5-2 Advantages and disadvantages of bounded strain gauges

Advantages	Disadvantages
• Strain gauges – easy to extract strain measurements • High accuracy • Quite cheap • Long track record • Easy to install	• Life-time of the gauges can be limited if not maintained and less quality sensors are used • Sensitive to temperature shifts • Often use of cables for data transfer • The “glue substrate” tend to degrade over time which changes the characteristics of the strain gauges

To increase the safety of personnel both during cabling, maintenance, and potential for cables to loosen during operation and minimize the cost associated with this, especially for large structures, wireless measurements of the strain gauge sensor response can be a desirable option. Wireless strain gauge sensors exist, and different vendors claims they are maintenance free with long battery time of maybe up to a few years. A wireless system consists of strain gauge sensors and a wireless transmitter, which can have a communication range of up to 1 km. A cable transfers the signals from the strain gauges to the transmitter which can be placed outside the area of strain measurements.

The following advantages for wireless sensors can be summarised as:

- Continuous monitoring of strain (stress)
- Fatigue awareness, fatigue life analysis from strain / stress measurements
- Fast, easy-to-install adhesive mounted
- ATEX/IECEx certified transmitters available

These wireless sensors are in practise currently rarely used for monitoring structures.

Figure 5-3 Picture of a wireless stain sensor mounted on a bridge /17/

Piezoresistive thin-film strain gauges have more stable performance than boned strain gauges, as they prove less noise in the output signals and have a higher mV/V sensitivity. They are based on the piezo-resistive effect which is the effect due to change in value of the resistance due to change in the semiconductor's resistivity. They are made of silicon and can be manufactured as separate elements bonded to a sensing diaphragm or embedded into a silicon sensing diaphragm. Piezoresistive thin-film strain gauges / semiconductor gauges have a high gauge factor of approximately 50 times higher than for wire gauges.

The Gauge factor (GF) or strain factor of a strain gauge is the ratio of relative change in electrical resistance R, to the mechanical strain, ε and is given by the equation (1). A high value of the GF indicates a large change in the value of resistance for a particular strain, and depends the materials system and chemical composition of the resistor. The definition of the gauge factor (**1**) does not rely on the influence of temperature, and the gauge factor only relates resistance to strain if there are no temperature effects. Hence, one needs to evaluate the need for temperature compensation of the measured strain. It can be noted that most manufacturers minimize the sensitivity to thermal expansion of the specimen material for which the gauge is intended to be used, e.g. aluminium, steel etc.

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon} = 1 + 2\nu + \frac{\Delta\rho/\rho}{\varepsilon} \quad \textbf{(1)}$$

Where:
ε = strain
ΔL= change in length
N = Poisson's ratio
P=resistivity
ΔR=change in strain gauge resistance due to axial and lateral strain
R= unstrained resistance of strain gauge

Table 5-3 Strain gauge factors

Strain gauge sensor	Gauge factor	Comments
Bonded metallic strain gauge / Metal foil strain gauge	2	Active areas of about 2–10 mm^2 in size, mostly used for measuring structural strain
Thin-film metal strain gauge	2	Thickness in the order of 0.1 um or smaller, is accurate and stable, better temperature coefficient, used when high precision is needed like monitoring equipment, medical and audio applications
Semiconductor strain gage bridges, Single crystal silicon strain gauge	-125 to +200	Piezoresistive strain gauge, measurements of small strain temperature-sensitive and difficult to compensate, their change in resistance with strain is also nonlinear, relatively expensive
Polysilicon strain gauge	±30	Better sensitivity than metal foil strain gauges
Thick-film resistors strain gauge	Up to 100	Applications where high requirements are not critical, low price, most widely used gauge, thickness ±100 (µm), resistant to moisture

Mounting of strain gauges are very important in order to measure correct strain. The strain gauge must be properly mounted onto the test specimen so that the strain is accurately transferred from the structure, though the adhesive and strain gauge backing, to the foil itself. Guidance for mounting strain gauges is provided by the different manufactures of strain gauges. Another aspect is the "zero setting" of the static stress level which may depend on good knowledge of the loading condition during installation. This is often called calibration, but calibration also applies to correct measurement of dynamic response. This static measurement may be important if effects like mean stress effects play an important role in fatigue, while zero-setting does not affect the dynamic response which is more easily calibrated and may not need calibration on board.

Emerging technology is the nanoparticle-based strain gauges, which has a high gauge factor, a large deformation range and they have high impedance and hence use a small electrical consumption only. They active sensor area is assembled by use of nanoparticles like gold and carbon. Other technics to measure strain are use of fiber optic sensing and digital image correlation and, see 5.10 and 5.11 respectively for further details.

5.4 Accelerometers

Acceleration may be considered to relate to the vibration or motion times the frequency squared and measured by use of accelerometers. Vibration is the movement of a body about its reference position, and a process piping can start to vibrate because of an excitation force that causes motion to the pipe like e.g. wind (vortex induced vibrations) or internal flow (flow induced vibration). Acceleration is the second derivative of displacement and is the rate of change of velocity, where the velocity is the first derivative of the displacement. Accelerometers are in general easy to install and can be attached directly to the piping without removing e.g paint or isolation. Vibrations can be measured by use of accelerometers where:

- Vibration amplitude indicates the severity of the problem.
- Vibration frequency indicates the source of the problem.

Several vendors provide accelerometer sensors with the possibility to assess the measured data either by built in or custom-made algorithms or use of data analytics like e.g. machine learning for health monitoring. Such systems often consist of the measurement device (Predictor) attached to the structures and a receiver (e.g. a GateWay):

- Predictor: which is attached to the piping and measurers vibrations in X, Y og Z axis. The predictor communicates via BLE (Bluetooth Low Energy) to a Gateway.

- GateWay: Collect raw data from Predictors via BLE and transfer these data to a server via 4G IoT. The GateWay can also be programmed to do some data processing prior to export data to a server. In general, the predictor and Gateway have a long battery life (5++ years) but this depends on data transfer.

A majority of existing wireless accelerometers predominantly use microelectromechanical systems (MEMS) for sensing. They are often designed to allow a number of devices to be interconnected, each operating as a node. Each of these nodes consists of processor, memory and radio. The manufacturers have developed a complete sensor network system that includes a gateway and a program with a simple user interface.

5.5 Velocimeters

Velocimeters are sensors which measures the deflections and vibrations in mm/s, which may be associated with acceptance criteria in different rules and standards. These may be well suited for piping vibrations. For local vibrations high acceleration may be measured simply because of high natural frequency excited by some equipment nearby. High acceleration is therefore not necessarily related to high stress and curvature of the pipe under bending. For this reason, acceleration is perceived as sensitive and may need careful filtering of the measured data to reveal the consequence of the pipe vibration. A better option may then be to use a velocimeter which is less sensitive and more reflecting the consequence of the vibration response. Velocimeters are frequently used in the ship industry on a daily basis especially related to sea trials and verification of vibration level of equipment and structures. As for accelerometers it is a qualifier related to this sensor in the hull monitoring rules associated with class notation HMON which is also referenced in the offshore rules (DNV RU-OU-0300). Acceptance criteria for vibration related to either acceleration or velocity is included in class notation VIBR which is applicable to vibration of structures related to fatigue and also electrical equipment. As for accelerometers, velocimeters are off-the-shelf sensors frequently certified. While the certification of a single sensor may have limited value, the hull monitoring rules associated with HMON implies that these sensors belong to a system that is functionally approved towards the purpose of the use of the sensors. These HMON systems are mainly used for the hull of FPSOs, but may very well be used on equipment as piping system as well.

5.6 Motion reference unit

A motion reference unit (MRU) can be useful for measure global response of a piping system or process equipment of extensive size where inertia from the self-weight is substantial or wave induced vibrations are important because of the asset global motions. If only vibration from flow or wind induced vibrations are driving the fatigue loading, then an MRU may be omitted. An MRU is often a relatively expensive sensor which measures all the 6 main motions: Surge, sway, yaw, heave, pitch and roll of FPSO’s and ship structures. It is often connected to a GPS to avoid drift. An MRU typically measures velocities and accelerations in 6 degrees of freedom as well, and it may be set up to measure motions in an asset specific or to a earth specific reference system. Calibration of the MRU may also be regarded relevant with some yearly interval specified by the manufacturer.

5.7 Wave radar

Similarly, to an MRU, a wave radar may be important if inertia effects are significant for a piping or process systems behavior. A wave radar or similar simpler wave measurement devices are often used onboard offshore assets and may be connected and used for the purpose of evaluating and correlating the measured response of a given piping or equipment system to the wave conditions. Wave radars is regarded as the most expensive sensor unit. A wave radar may provide characteristics wave data as heading, significant wave height and peak period (or zero up-crossing period) but may also provide more advanced data as directional wave energy spectra capturing wind sea and swell. In certain cases, the asset may be exposed to wave induced vibrations or other global and local vibrations affecting the response of the piping or equipment systems through resonance in worst case, but also forced vibrations due to inertia effects. This may then be related to special periods which may be revealed through correlation with other affected responses and wave conditions.

Wave radar is related to the qualifier S1 in HMON(S1) notation and requires a short-range X-band radar, which typically is used for navigational purposes on a navigating ship.

5.8 Flow meters

Ultrasonic flow meters, Coriolis flow meters, thermal flow meters, differential pressure flow meters and some other types are used to measure the flow velocity in a pipe in e.g. m/s. If the flow is homogenous, one phase flow as opposed to multiphase flows, a certain type of flow meter may be sufficient while in other cases more advanced flow meters may be needed. Some can also measure the density of the transported fluid. It is essential to understand the application when choosing the right flow meter. It is not uncommon to discover that it is necessary to change the type of flow meters delivered originally through the yards because of poor performance for certain purposes. In any case, flow meters are relevant as it may be related to the risk of flutter, understanding of slug flow or multiphase flow, pressure drop through the pipe, internal fouling and blockage and pulsations or simply the performance of the pipe system. The flow may be related to the performance and excitation of the compressor, pump or piston pump technology and the effect of bends etc., but it may be difficult to pick up the pressure pulses from the excitation. However, some flow sensors are exactly intended for this purpose. A clear specification of the flow meter therefore depends a bit on the intention of its use and the type of flow and fluid being transported.

5.9 Fibre optic sensors

Fibre optical sensors consists of optical fibre connected to a light source. A sensor that uses optical fibres as a sensing element is classified as either an intrinsic sensor which utilize that change that takes place within the fibre itself or an extrinsic sensor in which the change is outside the fibre and the fibre itself remains unchanged. Fibres are small in size and no electrical power is needed at a remote location, they can be applied in challenging environments since they can be used in high voltage electricity or flammable materials. Another benefit by using them is that fibre-optic sensors are immune to electromagnetic interference. Strain, temperature, and pressure can be measured by optical fibres, in addition, fibres can be modified to measure intensity, phase, polarization and wavelength or transient time of light in the fibre.

Typical applications are:

- Strain sensing
- Acoustic sensing: hydrophone and geophone

Fibre Bragg Grating (FBG) is an optical sensor which is illuminated by a light source with a broad spectrum, where the reflected wavelength is measured and connected to the local measurands of interest. Fibre Bragg grating sensor technology has been developed over the last 40 years, nevertheless, the system is not used much at all for structural health monitoring of equipment in the Energy sector due to lack of both awareness and trust in the technology and of long-term stability, cost and complexity.

Fibre optical strain sensors as for other strain sensors are part of the qualifier Lx for x local strain sensors within HMON(Lx). These are relevant for, e.g., pipe systems. For ships and FPSOs also global strain sensors are frequently used with associated with HMON(Gx) for global hull girder loading.

5.10 Digital image correlation (DIC)

Digital image correlation (DIC) can also be used to measure strain, deformation and contours on almost any material in a structure or component by monitoring the relative movement of a component or structure. Small motions on the surface can be detected by cameras and the pictures are processed by a software where the accuracy of commercially available tools ranges from 1/100 to 1/30 of a pixel for displacements measurements, which correspond in a typical strain sensitivity between 20 to 100 µm/m. It can be used to measure high strain and high cycle fatigue of a structure or component. Several DIC systems exist, one is the Aramis Digital Image Correlation system (GOM Aramis 5M). Depending on the system reduced frequency during the DIC recording are often needed due to slow image acquisition time of the system.

Prior to DIC measurements, the interested area of a structure or component needs to be painted on the surfaces with white and stochastic black dot's distribution. DIC provides a full-field picture with a coordinate system easily matched to FEA, with ref to Figure 5-4. However, if the strains are too small to be measured, discreet luminous targets can be glued on the surface which is a more appropriate method for 3D/2D motion detection.

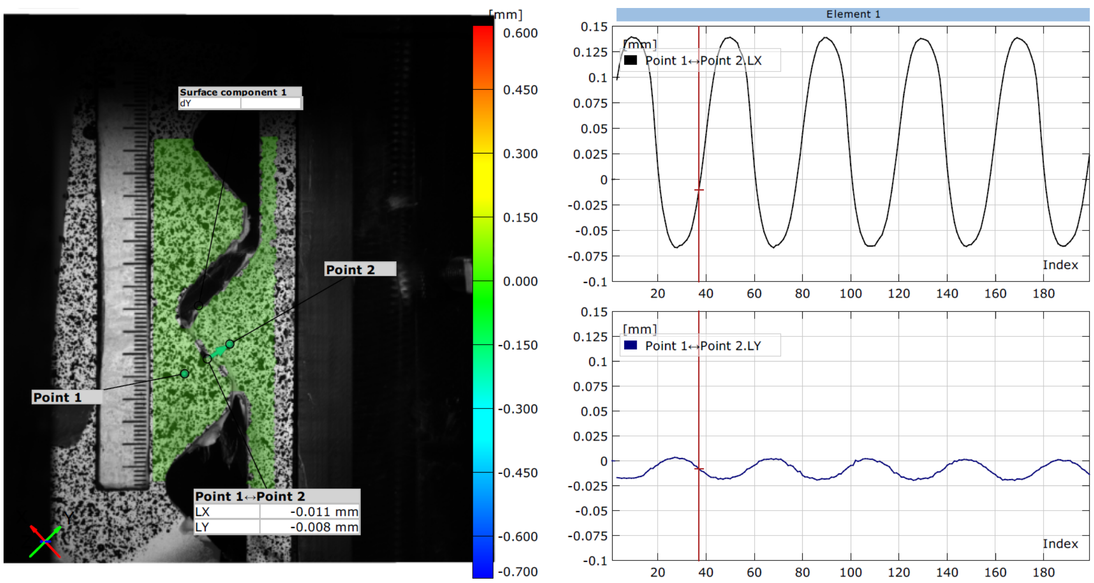

Figure 5-4 Example use of DIC (Aramis) to monitor the relative movement between two contact areas /12/

5.11 Acoustic sensors

Acoustic-based leak detection is a challenging multidisciplinary technology which requires skill within signal processing, wave propagation modelling and sensor development. The applicability of use of this method on topside processing systems may encounter the challenge associated to noise and vibrations of a piping system which may pose sound that can lead to fault interpretation of the acoustic signals. Acoustic sensors assumes that there is no passive source (e.g. compressor, pump, or obstructions) in the system or near-by, this is due to the sensitiveness to vibro-acoustic signals which can be confused with leak-generated signals. The technique is more suitable for steel-made pipes rather than plastic-made pipelines since the leak noise does not propagate easily through plastic-made pipelines.

Today, acoustic-based leak detection by acoustic sensors is applied for pipelines, however the use requires a proper modelling of the pipe system by accurately measuring simultaneously the temperature, pressure, and flow rate of the fluid, since both elastic waves generated by the wall of the pipe and acoustic waves generated in the transported fluid are aggregated to generate various kind of acoustic waves. Acoustic based sensors can detect and localize both liquid and gas leaks and are mostly used for buried and unburied pipelines but is still in the development phase. Ultrasonic sensors are used today to measure acoustic waves within a pipeline carrying liquid fluid, and since, acoustic sensors need to be installed into the pipe, the system cannot easily be installed for a system already in operation. However, the accuracy is dependent on a deployment of many sensors to achieve accurate acoustic-based leak detection and localization since the leak can be detected only in the vicinity of these sensors. Different acoustic sensors exist and the most common once are tabulated in Table 5-4.

Acoustic sensors may allow for an early warning related to micro cracking of a given material, /8/9/ and hence is presented as a viable future option, especially within processing of signals to be able to interpret the acoustic results in a sound way.

Table 5-4 Features of various acoustic sensors used in leak detection /10/

Gas Leak technique	Advantage	Disadvantages and features
Piezoelectric-based acoustic sensors	• Can be applied to detect and accurately localize leaks for both buried and unburied liquid over very long pipelines (i.e. up to 10 km) using few sensors only (typically 3 sensors). • High frequency ultrasonic sensors can detect very small leaks (for short range. e.g. few meters range).	• Most adequate for steel-made pipelines, with low sensitivity for plastic-made pipeline. Acoustic sensors are bandwidth limited. • Not able to detect small leaks for long ranges and to detect multiple leaks. • Not adequate to detect leaks of gas or high viscos liquid since the acoustic signal is usually weak. More adequate for water and light crude oil. In, general can't operate with the presence of man-made noise (e.g. compressor and pumps)
Magnetic-based acoustic sensors	• Omnidirectional sensors can sense ultrasonic waves generated from different angles. More suitable than piezoelectric sensors for measuring low frequency sonic waves (i.e. down to 3 Hz). • Membrane-based sensor provides the highest sensitivity of measurement. • Needle based sensors adequate for measuring continuous waves, and is the best option to measure broadband acoustic waves.	• Not able to withstand high temperature and high pressure variations, because of the thin layer of the sensing membrane. • Consume relatively a large amount of power, hindering their deployment in wireless sensor network infrastructures. • Technology still in research and development phase for leak detection application.
Extrinsic optical fibre-based acoustic sensors	• Can operate in high temperature and high-pressure conditions.	• Costly sensors. • Technology still in research and development phase for leak detection application.
Acoustic sensors	• Detect defined static noise or switch-sounds on machines, devices and plants.	• Associated with noise sensors in the hull monitoring rules HMON(Nx).

5.12 Optical-based leak detection systems

Another technique that is also mostly used for onshore pipelines are optical based-techniques of gas leaks. Optical-based leak detection systems may use two dimensional (2D) or three dimensional (3D) cameras to acquire images of specific wavelengths, especially in the long and medium IR ranges (LWIR and MWIR waves respectively).

Since various gases have different gaps between energy states, they exhibit a unique absorption behaviour. IR sensors can detect any molecule which has a dipole moment such as methane and butane, which is not the case of hydrogen leaks. One of the challenges facing active-based optical leak detectors is the temperature dependent drift of the light source which negatively affects the accuracy of the measurements.

Table 5-5 Features of various IR sensors used in leak detection /10/

Gas Leak technique	Advantage	Disadvantages and features
LWIR sensors	• Thermal detectors do not require cooling system and provide flat response for wide temperature change, offering good quality images. • Suitable for outdoor leak detection where temperature variation is significant and where the range distance less than 2.5 km in humid atmosphere with longer range for a dry environment.	• Active leak detection systems are not appropriate for liquid leak detection since LWIR/ MWIR absorption is very high for liquid. High power consumption. • Can't detect gas of high temperature (i.e. exceeding 400°C). Limited to ppm order sensitivity
MWIR sensors	• Can remotely detect gas and liquid leaks. Exhibits less signal reduction in fog and humid atmosphere than LWIR. • Able to operate for higher range distance than LWIR cameras. • Remote detection and quantification of high temperature gas leaks (up to 1500 °C temperature)	• Active leak detection systems are not appropriate for liquid leak detection since LWIR/ MWIR absorption is very high for liquid. • Significant terrestrial solar radiance causing large artifacts in the image space • Limited to ppm order sensitivity

5.13 Temperature Sensors

A temperature sensor is a device that are used to measure temperature like air, liquid, or the temperature of solid materials. There are different types of temperature sensors available with different requirements to accuracy and they use different technologies and principles to take the temperature measurement. Temperature sensor is often also integrated into other monitoring systems as accelerometers, flow sensors and strain exposed to heat expansion etc. In the following, some of the most common systems used to measure metal and flow temperatures are presented below:

- The most used type of temperature sensors are thermocouples. They are widely used in industrial, automotive, and consumer applications. A thermocouple consists of two wires of different metals electrically bonded at two points, where the varying voltage reflects proportional changes in temperature created between these two dissimilar metals. Thermocouples are nonlinear and require a conversion with a table when used for temperature control. Accuracy is low, from 0.5 °C to 5 °C but thermocouples operate across the widest temperature range, from -200 °C to 1750 °C. Thermocouples are self-powered. Thermocouples are resistant to vibrations.

- A resistance thermometer or resistance temperature detector (RTD) consists of a film or, for greater accuracy, a wire wrapped around a ceramic or glass core. Platinum provides the most accurate temperature measurements (across -200 to 600 °C), while nickel and copper cost less but are not as stable or repeatable as platinum.
- A thermistor is a thermally sensitive resistor that exhibits a continuous, small, incremental change in resistance correlated to variations in temperature. They are usually made from a polymer or ceramic material. In most cases they are cheaper but are also less accurate than RTDs. The effective operating range is -50 to 250°C for glass encapsulated or 150°C for standard thermistors.
- A semiconductor-based temperature sensor is usually incorporated into integrated circuits (ICs). These sensors utilize two identical diodes with temperature-sensitive voltage vs current characteristics that are used to monitor changes in temperature. They offer a linear response but have the lowest accuracy of the basic sensor types and have the slowest responsiveness across the narrowest temperature range (-70 °C to 150 °C).

Temperature sensors are associated with qualifier Tx for x temperature sensors according to HMON(Tx) notation.

5.14 Limitations of wireless sensors

Wireless sensors offer many benefits as simplified installation and the avoidance for the need for long cables that can cause signal degradation and noise

- Although wireless sensors seem to have many advantages, there are challenges to consider due to data bandwidth, power and while wireless communication for static and quasi-static sensing is relatively simple, it is far less straightforward for dynamic signal measurement
- Power consumption is a critical challenge when using wireless sensors and power management is an important issue to deal with. Consumption is highest during data transfer, so handling wireless communication is important to extend battery life
- There is no "ideal" wireless sensor that can be used for all plausible applications. The development of any wireless sensor requires a thorough understanding of the environment, usage and expectations of the device
- Wireless sensors may be problematic when submerged in liquid
- Wireless sensors may be problematic when located within a faraday cage, so transfer of data through the steel structure must be arranged

For this reason, wireless sensors are currently not that much used for long term installations but more for trouble shooting short term.

6 USE OF SENSORS FOR STRUCTUAL HEALTH MONITORING AND DAMAGE IDENTIFICATION

In the following, the most viable option for structural health monitoring and damage identification of pipes and process equipment on topside and onshore facilities to address fatigue, corrosion under isolation and corrosion are presented.

6.1 Fatigue monitoring

Use of sensors to predict the fatigue condition and set inspections intervals are a powerful option today to increase the knowledge about a structure and to perform predictive or prognostic maintenance. The sensor systems to monitor fatigue performance of a structure need to be accurate and reliable, have high mechanical strength and be maintenance free and cost-effective in order to compete with traditional inspection regime.

6.1.1 Fatigue sensors

There are several concepts used and under development for fatigue monitoring. The most common and reliable solution is to document the response by use of sensor data, which are used to calibrate a physical model of a given system. This model will be used to document fatigue life calculated by use of design S-N curves or crack growth curves applicable for the component and structural detail where sensor data is not available. Different strain types can be measured by more traditional strain gauges discussed in section 5.3 like axial strain, bending strain, torsional strain, shear strain, and compressive strain. Strains can also be measured by more advanced methods like fibre optics discussed in section 5.9 and use of digital image correlation (DIC) in section 5.10. Accelerometers are also used to a large extend to measure vibrations in process pipelines and other topside equipment like valves and process modulus, however the measurements need to be correlated to stresses and strains in the structure for fatigue damage calculations. Concepts under development for crack growth is the use of acoustic emission as discussed in section 5.11, however as the system is very sensitive to background noise it will need carful calibration to provide sound information of fatigue crack growth.

To enable sensor technology for fatigue prediction several elements, need to be considered. Some of these are:

- Installation method
- ATEX certification (see section 6.2.3)
- Measuring method / technology
- Calibration to verify the output of the sensor to a known, expected value
- Measurement performance by selecting the right strain sensor, signal conditioning, wiring / wireless, and Data Acquisition System (DAQ)
- Coverage, number of sensors and location
- Communication and data management
- Data interpretation (filtering to remove external, high-frequency noise) and decision support

6.1.2 Measurement technology

The sensors used for fatigue evaluation of a component or system are mostly used by strain gauges and accelerometers, strain gauges give the strain in one location, and depending on the systems several needs to be used for a complex structure. Hence in order to reduce the number of sensors, a calibrated physical model should be in place.

Each of the different monitoring technologies need to be qualified and tested under realistic conditions preferably in field. Such qualification program should include elements like accuracy, robustness and battery lifetime but also consider suitability for the different solution.

6.1.3 Coverage

Monitoring results from a sensor will in general only provide results representative for the area where the sensor is installed. Strain gauge sensors are typical mounted close to or in a fatigue critical location of a structure, often close to welds. While fibre optic sensors (like fibre Bragg sensors) can have a larger coverage of a structure.

6.1.4 Data communication

Both wired and wwireless technology can be used for sensors for fatigue loading prediction. For wireless technologies, the most common is to use Cellular (5G) or Bluetooth Low Energy (BLE), see section 6.2.6 for further guidance.

6.1.5 Data interpretation and decision support

The process in getting from monitoring data to good decision support include several elements to be considered and depends on the monitoring system used (strain gauges, accelerometers, DIC and Fibre used). The most important ones are:

- Data quality and how well the data represent the actual movement of the structure
- To estimate the fatigue performance of a piping system that vibrates, a correlation between vibrations and stresses needs to be established. This can either be done by an analytical model of the system (twin-model) or by use of strain gauges in addition to an accelerometer to establish a correlation between vibration and stresses at a given location in a system. Vibrations of a process piping system may be very sensitive to the details of the system and its supports, hence, to accurately model a system that represents the vibration measurements from flow induced vibrations can be challenging and requires very detail and refined analysis model.

6.2 Moist monitoring

Corrosion Under Insulation (CUI) is one of the industries major risk and moist or free water is one of the significant contributors to start corrosion. To identify locations with the potential for CUI there are now several industry initiatives to monitor moist or free water in the insulation system. There are in general two monitoring principles that are developed

- Installed sensors through cladding, punctual sensors
- Installed sensors that is aligned longitudinal to the pipe, cable-based sensors

Each of these will have their specific limitations and application.

In addition to monitoring, moist or free water can be identified by visual inspection supported by thermographic infrared cameras or neutron back scatter inspection.

6.2.1 Moist sensors

There are several concepts under development for moist monitoring. The concept consists of a mechanical or electronic sensing device installed through or under the cladding to monitor the situation inside the insulation solution. Sensors where water accumulate into the sensor from the inside and a signal are shown on the outside has been available for a long time but has not proven very efficient. Recent development focus on deploying electronic sensors through the insulation or along the pipe to detect moist or water. To enable such technology several elements, need to be considered. Some of these are:

- Installation method
- ATEX certification
- Measuring method / technology
- Coverage, number of sensors and location
- Communication and data management
- Data interpretation and decision support

6.2.2 Installation method

Installation of punctual sensors that penetrate the cladding or longitudinal cable based sensors that follow the pipe is very different. For installation of punctual sensors there need to be drilled a hole through the cladding followed by installation of sensor. This often need to be performed under a hot-work permit from a scaffold at a high cost. This operation can also be performed by a pipe-climbing installation robot which has been recently developed by a Norwegian company. For the installation of longitudinal cable-based sensors, the insulation has to be removed and reinstalled after the sensor has been mounted. This is a costly approach and might be better fitted for new builds than for old asset in operation.

6.2.3 ATEX certification

As the sensors in most cases will be installed in hazardous areas both operation and installation need to be performed without any ignition risk.

Sensors and data communication system placed in hazardous areas need to hold necessary ATEX certification.

Several types of protection are available for electrical equipment and the specific requirement for design, selection and erection of electrical installations applies.

6.2.4 Measurement technology

The sensors might measure on different parameters such as percentage humidity, free water (yes/no), conductivity or simple breach of signal alarms. Temperature measurements are also often included as an additional feature to the moist monitoring results.

Monitoring data might be changes showing increased moist in short period of times due to weather conditions and it is therefore in most cases recommended to also use external reference sensors to reflect external weather conditions like heavy rain.

Each of the different monitoring technologies need to be qualified and tested under realistic conditions preferably in field. Such qualification program should include elements like accuracy, robustness and battery lifetime but also consider suitability for the different insulation solution.

6.2.5 Coverage

Monitoring results from a longitudinal cable-based sensor will provide results representative for the area where the sensor is installed while results from punctual sensors will be less representative as a function of increased distance between the sensors. In short this means that a large amount of spot sensors needs to be installed to achieve reliable results.

For installation of punctual sensors there should be made an evaluation to identify the most probable location where water can accumulate. Such locations will typically include low points, locations with nearby penetrations of insulation cladding, insulation termination points, areas with damage to insulation cladding, complex geometries. Transportation of water in the insulation material will also be an element to consider when identification of water under insulation shall be monitored.

There are ongoing projects funded by The Research Council of Norway to identify the best locations for sensors to identify moisture or free water in insulation, the “MÅSSO-project” as well as a project on how water is distributed in the insulation, the “PredictCUI” project. Detailed information can be found at The Research Council of Norway (forskningsradet.no)

6.2.6 Data communication

The fourth industrial revolution comprises the digital transformation and intensive integration of advanced information and communication technologies. Wireless technology has made huge advances in the last couple of years, and are quickly turning into the standard when it comes to communication protocols used for gathering sensor data in industrial systems. There are in general 3 types of communication protocols used for moist sensors today, these are:

- LoRaWAN
- Cellular (5G)
- Bluetooth Low Energy (BLE)

LoRaWAN is a low-power, wide area networking protocol built on top of the LoRa radio modulation technology. It has three different communication classes, Class A, Class, B and Class C, that provides various communication schemes depending on power consumption and latency requirements.
Even though LoRaWAN is an open network protocol, the underlying LoRa radio modulation is a proprietary technology. This can, in some cases, limit the availability of devices suited for especially harsh environments or requirements such as ATEX.

5G is a new global wireless standard of mobile network that enables a new kind of network that is designed to connect virtually everyone and everything. It’s designed to provide a massive increase in traffic, higher speeds, vastly better latency and has been developed with IoT and other distributed systems in mind.
It will still require the use of SIMs as well as a network provider that has the proper license to operate in the necessary frequency band in the country of operation. This means that deployment of 5G systems will be dependent on 3rd parties (Network Operators) and their plans for infrastructure development and coverage.

The key difference between Bluetooth and BLE is with how they operate and maintain connections. Both Bluetooth and BLE operate in the same 2.4GHz band, but to ensure a low energy consumption BLE devices remain in sleep mode unless a connection initiate. While a regular Bluetooth-device maintains connections for a few seconds up to a few hours at a time, BLE-devices will only communicate for a couple of milliseconds at a time.

Table 6-1 Technology and implementation data communication

	LoRaWAN	**5G**	**BLE**
Frequency band	Unlicensed sub GHz	Licensed cellular	2.4GHz
Transmission rate	300 bps to 37.5 kbps	20Gbps	3Mbps
Range	2-5km	N/A	< 100m
Security	High	Very high	Low
Installation	Easy	Easy	Easy
License management	Depending on implementation	Depending on network provider	Easy
Hardware (ATEX, high temp etc.)	Available	Unknown	Available

6.2.7 Data interpretation and decision support

The process in getting from raw moist monitoring data to good decision support include several elements to be considered. The most important ones are:

- Data quality and how well the data represent the actual situation in the insulation
- Duration of wetness and development over time, time-of-wetness
- Water wetness related to other elements that influence the risk of CUI

Where sensor data indicate continuous dry or continuous wet situation the conclusion will be easy to make, and these situations might also be where industry can benefit the most. Difficulties in decision making will occur when the sensor data indicate partly wet situation for part of the time. In such cases there need to be develop decision rules, guideline or supporting algorithms to help user to make correct and conservative decisions. In a risk evaluation such decisions shall also include other elements like consequence of failure, operational data, material data and condition of coating.

6.3 Corrosion monitoring

Corrosion monitoring can be performed by use of several different technologies. Most of these are well established and many of these can be summarized as in table below:

Table 6-2 Type of corrosion monitoring technologies /6/

Type	Measurement element
Corrosion coupons	Weight loss, visual appearance, corrosion rate
Electrical resistance (ER)	Change in Ohmic resistance, metal loss, corrosion rate
Linear polarization resistance (LPR)	Potential and current, instantaneous corrosion rate
Zero-resistance ammeter (ZRA)	Galvanic current, corrosion rate
Potential monitoring (PM)	Potential of materials
Electrochemical impedance spectroscopy (EIS)	Current through the cell induced by an AC potential, corrosion rate of coated substrates
Potentiodynamic polarization	Current response as a function of potential, passivation, breakdown and repassivation potentials, critical current densities of passivation
Thin-layer activation (TLA) or gamma radiometry	The change in gamma radiation, metal loss, erosion and pitting corrosion
Hydrogen probe	Hydrogen diffusion through metal
Ultrasonics	Wall thickness and cracks
Radiography	Wall thickness and cracks
Thermography	Local hot spots and leaks
Acoustic emission	Impingement, leaks and cracks
Eddy current	Wall thickness and cracks

All these technologies listed above will have different use cases and will in general represent the condition at the specific location where the sensor is installed.

For monitoring of corrosion over a longer distance there has been developed technology based on guided ultrasonic waves that propagate over tens of meters to monitor the cross-sectional area of the pipe. Recent development has increased accuracy and gross general corrosion will be detected while local but deep corrosion attacks might be missed. Defects in the range of 2-5% cross sectional wall loss might be detected. If this detection criteria are translated to a 8” pipe a local corrosion attack of 12 mm diameter will not necessarily be detected before loss of containment.

7 DATA COLLECTION, PROCESSING AND QUALITY

Sensor systems typically produce large amounts of time-series data that are used for condition monitoring, operations, and analytics and the reliability of these systems will have an increased influence on the operational risk of a piping and other topside system as the integrity relies on the measured data.

A sensor systems reliability can be defied as the ability of the sensor system to deliver sensor data with the required data quality under given conditions for a given time interval. Insight into sensor based operational data becomes vital to evaluate the integrity of the piping system and prevent leak or rupture of the structure causing leakage. Figure 7-1 shows the structure for data management to ensure data quality of sensor systems (IoT) from the enterprise on the top, then to the management, data quality and finally the application itself. Information security is covered in DNVGL-RP-0496 /13/ and ISO 27000 /14 /.

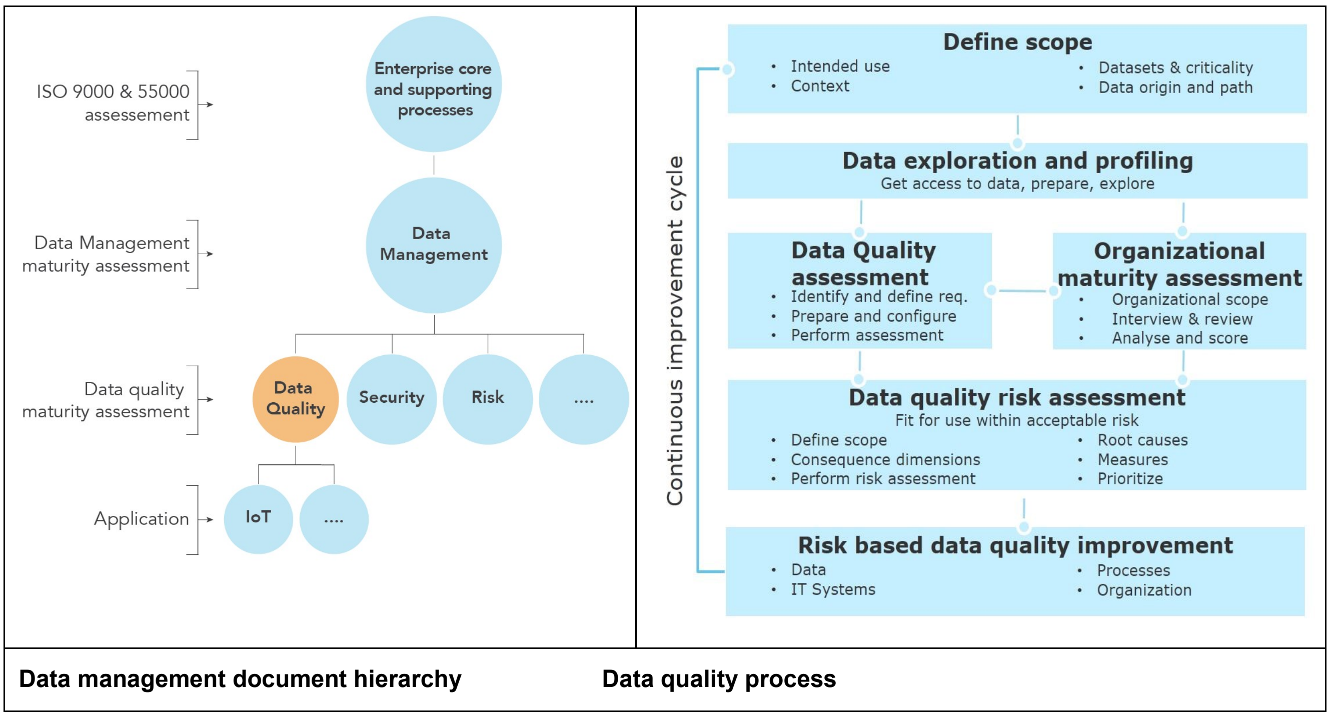

Figure 7-1 Document structure for data quality and sensor systems (IoT) /15/

A schematic showing the layers between data sources and applications is given in Figure 7-2. The bottom layer is the data sources, where data from sensor measurements is one type of data. For the data to be useful, it must be copied and transferred to a raw data storage. The asset owner must decide how frequent the data shall be copied and whether the data shall be condensed or thinned before transfer to the raw data storage. One decision can be to only store data which represent extreme values or to remove data points which are very similar.

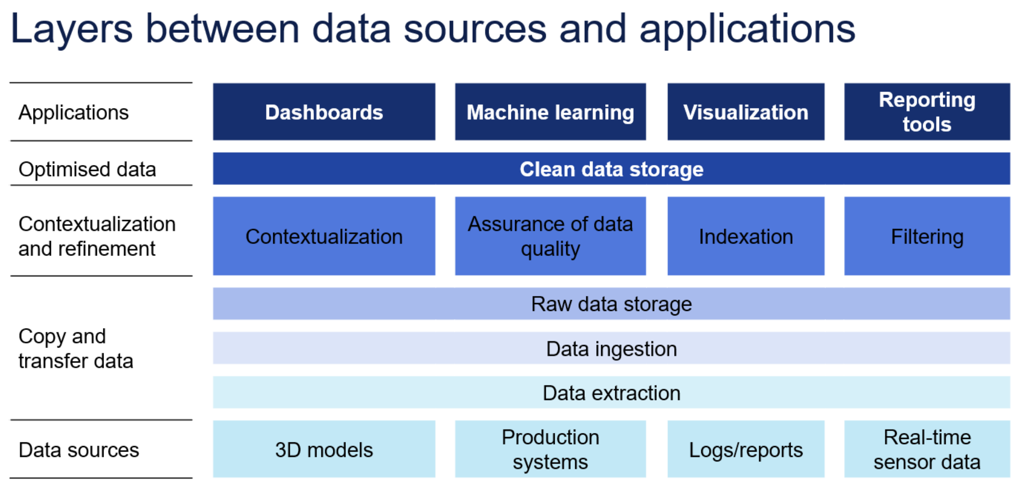

Figure 7-2 Layers between data sources and applications

7.1 Data collection

The goals of data collection must be defined; what is acceptable data quality and which indicators can be measured and acted upon to improve data quality. Another necessity when collecting and handling large amounts of data is automation; the data quantities could be too large and complex for efficient manual handling or by traditional IT.

7.2 Data Processing

Data exploration and profiling are used method to investigate potential quality issues empirically in datasets with little or no metadata available. The method is an efficient means to reengineer metadata for a dataset and to detect possible inconsistencies, such as illegal values, outliers, or other statistical anomalies. Data profiling is often used in the early stages of data activities, such as migrations, integrations, and analytics, in order to be able to anticipate whether actions might be necessary to address the quality issues. Several statistical and counting techniques can be used to explore datasets, both for single datasets and for connected datasets, in the table below (Table 7-1) some common profiling techniques are listed.

Table 7-1 Profiling techniques /15/

Profiling techniques		
Generic data types	Foreign key flag	High value count
Declared data types	Null flag	Mean value
Declared maximum length	Low value	Median value
Declared precision	High value	Minimum, maximum, mean, median string length
Primary key flag	Low value count	Distinct count, percentage
Null count, percentage	Zero count, percentage	Blank count, percentage
Pattern count	Valid count, percentage	Distinct valid count, percentage

7.3 Data quality

For data-driven services, data quality is one of the essential pillars for the success. The intended use of the data for the given application needs to be considered when judging the data quality. Decision makers need to have a common understanding of data quality, how it affects operations, and why it is necessary to monitor and assess data quality continuously. ISO 8000-8 “Information and data quality”, addresses concepts and measuring and specify data quality where data quality issues are categorized into syntactic, semantic, and pragmatic data quality, see Figure 7-3 for an overview.

ISO 8000-8 assessment model and principle of evaluating data as correct (good) or incorrect (bad)

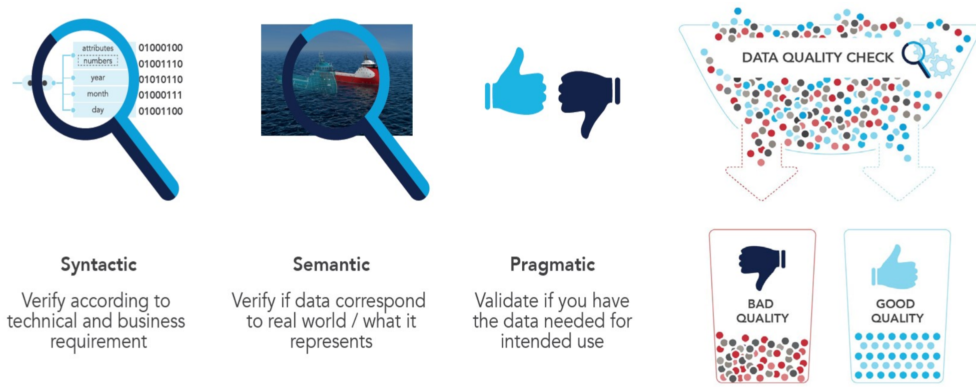

Figure 7-3 Data quality check outcome //14/

Many factors affect the data quality /15/, such as sensor properties, location, data collection equipment, timestamp handling, data gaps, data compression schemes, the quality of the metadata that describes the signals, and much more. Analytic algorithms and automated processes are impacted differently by different types of data quality, and the relationship is not thoroughly studied and understood.

7.4 Data management and security

Data management ensures that important data assets are formally managed throughout the enterprise and that information governance goals are achieved. data management also covers management of: data storage, retention, life cycle, legal compliance and intellectual property rights, value chains, metadata, business vocabularies, information risks, and information security etc. Data management establishes and utilizes processes, controls, and technologies that operate on data and enable the data maintenance and data value chain in the enterprise to be compliant with policies and governance directions.

Data security mechanisms (encryption, access control) needs to be in place, both when transferring the data and at storage of the data. The data source of the metadata should be documented as part of a dataset. When considering the data source as an asset like a physical object, it is worth documenting key attributes in the metadata for traceability. The source system should support logging functions for all the above information.

Example: A data recorder logs temperature, vibrations and strains from a process piping. The metadata should contain information that enables identification of the piping location, sensor identification, time, duration of measurements etc. This makes it possible to filter out and post-process (or discard) the data at a later stage if e.g. an accelerometer or strain or temperature sensors are found to exhibit a quality problem. Such traceability and transparency also contribute to credibility.

8 DISCUSSION

The monitoring methods available for piping systems with regards to fatigue, moisture penetration and corrosion, based on DNV's internal global expertise and openly available literature, have been presented below. The different systems elaborated on can of course be used for other components as well.

8.1 Technical assessment

The technical assessment of a sensor system is of importance in order to ensure a reliable and robust sensor system. The four steps consist of:

1. define scope of the system and subsystems that are going to be put under scrutiny
2. establish requirements,
3. evaluate design
4. evaluate operational monitoring.

Once there is a defined scope, the data quality requirements need to be established. Then it is necessary to evaluate the design to ascertain technically that the system is designed to satisfy the data quality requirements of the data needed for the use cases. Finally, there is a need to establish that the continuous operation of the sensor system is likely to keep that level of data quality over time. Further guidance can be in DNVGL-RP-0317 /3/. In appendix A, a list of sensor system quality best practices which may be used to inspire the overall definition of data quality requirements to the system.

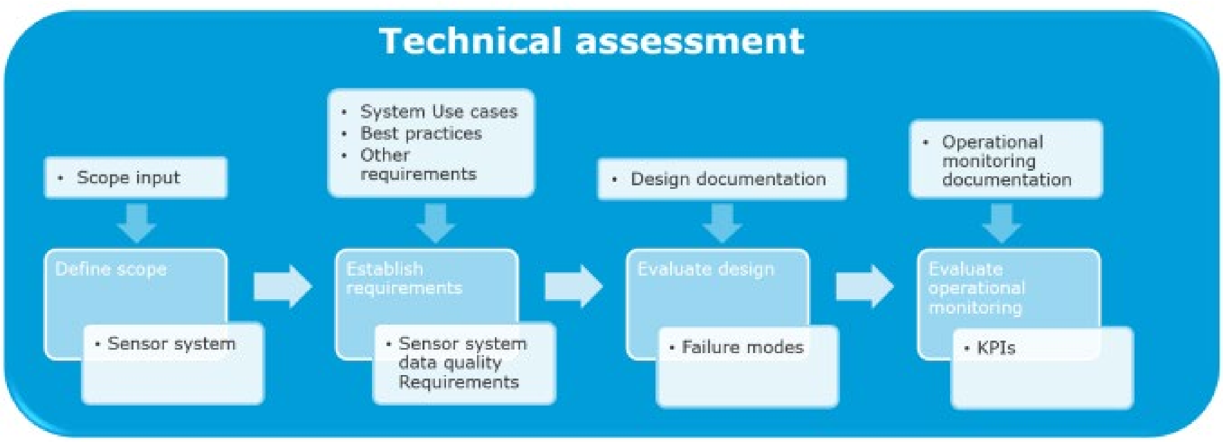

Figure 8-1 Technical assessment process /3/

8.2 Technology readiness level

In the following, the maturity of the different sensor technologies are presented. Technology readiness levels (TRLs) are weighted according to ISO 16290. TRLs are based on a scale from 1 to 9 with 9 being the most mature technology. In general, all the sensors have a high TRL level, often from other industries' like e.g. fibre optic sensors, however in the context of topside process facilities, limited industry experience exist for measuring e.g fatigue.

Table 8-1 Maturity of the sensor technologies

Monitoring type	Description	Technology readiness level ref ISO 16290
Strain gauges	Measure strains either with wires or wireless	Ready and available with extensive well documented use.
Accelerometers	Measure accelerations due to vibrations	Ready and available with extensive well documented use.
Fiber optic sensors	Strain sensing and acoustic sensing	The sensors are available however and have a track record from telecommunication, automotive and aerospace, in the content of use for topside processing system, TRL 6
Digital image correlation	Used to measure strain, deformation, and contours on almost any material in a structure or component by monitoring the relative movement of a component or structure	Used a lot in test laboratories especially as a replacement or supplement to strain gauges.
Acoustic sensors	Acoustic based sensors can detect and localize both liquid and gas leaks. The methods may allow for an early warning related to micro cracking of a given material	Mostly used for buried and unburied pipelines. To monitor crack growth – TRL 4
Optical-based leak detection systems	Optical-based leak detection systems may use two dimensional (2D) or three dimensional (3D) cameras to acquire images of specific wavelengths	TRL 6
Temperature sensors	Used to measure temperatures	Ready and available with extensive well documented use
Moist Monitoring	Moist monitoring sensors have been available for other purposes for a long time but application to detect moist or free water in insulation has been developed over the past 5 years. Present technology readiness level to be considered as Technology demonstrated in relevant environment	TRL 6
Corrosion Monitoring	Corrosion monitoring sensors for containment systems has been used for ages and are consider mature and available technology	Ready and available with extensive well documented use

8.3 Sensors - Enablers for the future

Developments within Industry 4.0, which includes advanced sensor technology and machine learning algorithms, and strengthened inclusion of feedback loops within systems and processes, will be an enabler for prognostic maintenance. Good coupling of materials and structures is essential, and model-based prediction tools will be an enabler in this respect. Modelling, simulations and use of data analytics, combined with judicious testing and analysis, allow us to gain insight and to verify new manufacturing strategies, design load scenarios etc. in an efficient and well documented manner. Traditionally material properties have been established using experimental testing. This approach has some limitations, e.g. time consuming, expensive and covers only the tested conditions, hence the material knowledge may gained during qualification testing may not be suitable for evaluating life extension of a system. More active use of modelling of material properties based on a more generic understanding and models to predict properties will allow more room for design optimization and life extension in the future. The key building block will be a more generic approach to materials understanding and an effort to translate material knowledge into quantitative properties for stiffness, resistance to plastic deformation and fracture, corrosion, etc. It is foreseen that towards 2030, virtualization will connect all elements and dimensions of a system life cycle, aided by digital twin technologies. These will function as a collection of all available system data and the models used for decision support throughout the life cycle and made available to dedicated stakeholders /18/.

Sensors will play the key role in this respect, however, several key technologies will be needed to be in-place to build such a maintenance scheme, where some are visualized in Figure 8-2 and have been discussed in this report.

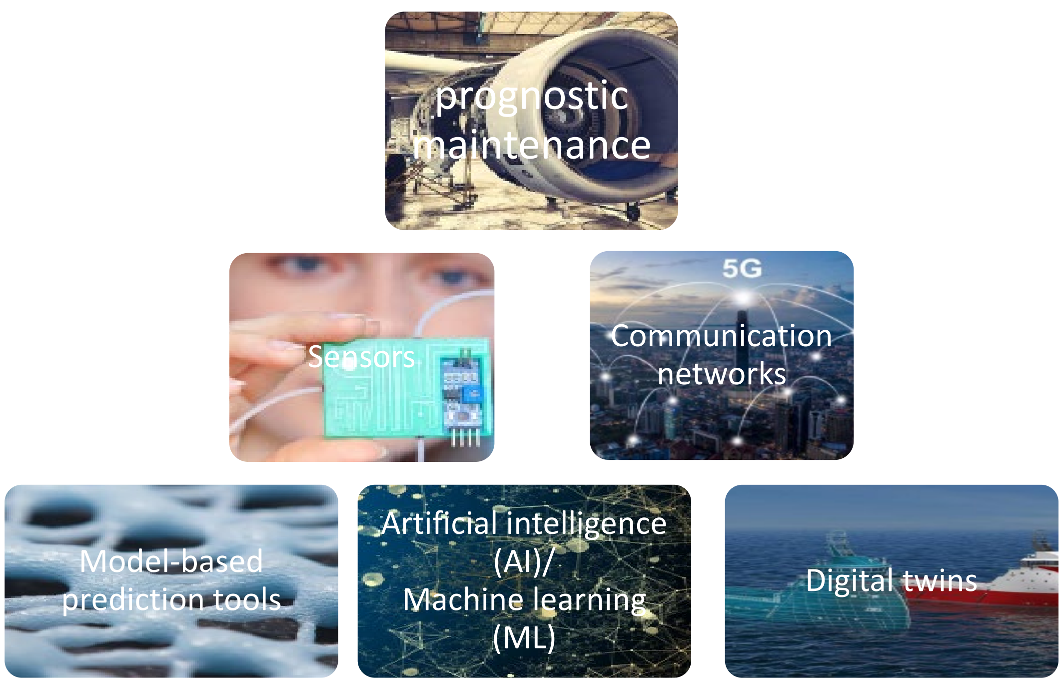

Figure 8-2 Technologies that matters for prognostic maintenance /18/

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APPENDIX A
General principles and best practices for sensor systems

The purpose of this appendix is to provide a list of design principles that may have negative impact on sensor system data quality if handled poorly and a positive impact on sensor system data quality if handled well /3/

Table A-1 General principles and best practices for sensor systems /3/

Data chain extent	The number of hops in the data historization infrastructure between the point of data collection and the point of consumption is a key contributor to deterioration in data degradation. Intermittent interface outage between any to links in the data chain can cause data loss at higher levels. Good data quality is easier to maintain when data passes more directly to the data consumer.
Historization aggregati on and resampling fre quency	When collecting historized data for long term storage, each parameter being collected is collected at a certain predefined polling frequency. The historians generally also use filter compression techniques which lowers the rate of values stored. Proper configuration of polling or - even better - publishing values into the infrastructure allows for better data quality. Filter compression should be use consciously to avoid significant signal quality loss
Latency prevention	When data is collected and transferred through different nodes in an infrastructure, there is an increase in latency as the data moves further and further from the point of origin. The interfaces configured to replicate, and poll data can usually be configured to execute the data replication more often (more optimized) in order to reduce latency. However, there may be certain trade-off issues with such latency prevention efforts. If replication is too immediate, there is a risk that the underlying source hasn't yet been updated with all the relevant values applicable to the span for which data is fetched. Efforts to reduce latency at each step the data flows through is recommended.
Graceful buffering and recovery	In order for data collection schemes to have high quality, there needs to be robust data collection recovery mechanisms in place. Recovery mechanisms ensures that data replication is realigned with the source (including intermediate raw values) after an interface outage has happened. Robust recovery schemes ensure that data recovery is facilitated between multiple nodes downstream to where the interface experienced downtime. Each node in the infrastructure should have buffering capabilities harmonized with the risk of experiencing certain periods of disconnection
Redundancy	The more redundancy, which is built into a data collection infrastructure, the better data quality of that infrastructure is. But introduction of redundancy mechanisms may also cause additional failure modes to be considered. On level 1 & 2 in the Purdue reference model it is common for both hardware and network infrastructure components have redundancy and failover mechanisms in place. This can be redundant services in DCS setup or redundant I/O which can be updated without disconnection of this instrument. Hence, the reliability of data flow from these sources is good. Data collection mechanisms further up the value chain can benefit from using data collection drivers that leverage the underlying redundancy when fetching data. The data collection infrastructure could also benefit from using virtualized hardware, database clusters, storage devices running in a RAID setup etc. More design redundancy typically mean less downtime and better data quality.
Dynamic flexibility	When instrumentation and data collection infrastructures are designed and planned there can be significant differences between infrastructures that adapt well to dynamic changes in configuration versus infrastructures that are difficult to manage when dynamic changes happen. Using templates for defining equipment types, synchronizing changes and having excellent change management routines are key to achieving such flexibility. Designing the sensor system to be adaptive to change is a best practice. It which impacts the sensor system's ability to deliver high data quality over time.

Legacy system debt	Over time a big plant usually accumulates many generations of technology in multiple layers of the data collection infrastructure. Legacy components might have a particular way of relaying information, whereas more modern components might have different data communication signatures. The problem tends to grow with the number of vendors involved in the sensor system. Equipment that conceptually should belong to the same class or category often end up appearing to be different to end users of the sensor system. This makes data difficult to interpret and use confidently. It is difficult to avoid legacy system debt entirely, but good planning of upgrades to an installation, and consistency requirements stated to system and instrument providers can delay the onset of legacy system debt.
Maintenance and service contracts	The nature and legal structure of maintenance and service contracts may be key to having either poor or high data quality. Poorly designed service contracts may reward vendors who repeatedly have to intervene to troubleshoot the same problem instead of vendors who fix the problem once and for all. Making vendors responsible for good data quality and rewarding vendors who deliver on this performance indicator is a key element to maintaining good data quality. Contracts should be set up with incentives that focus on the best possible data, and not create contracts that increases the subcontractor's revenue due a to high number of service calls to fix data quality problems.
Upgrade and refitting practices	When planning and executing an upgrade or refitting project it is important to assess the consequences that this may have for the data collection infrastructure, its integrations and its data consumers. Act towards mitigating any negative impacts and plan for changes in advance.
Initial planning and development practices	When planning and implementing completely new industrial projects it is key to start thinking about data collection and preparation for data analytics in the early phases of the project. Even before the automation and control systems have matured to a point where templates can't be changed. This allows for the right type of instrumentation to be included and the proper data to be collected by the automation systems.
End user feedback systems	End user feedback on data quality issues is a valuable source of corrective input into a sensor system infrastructure. End users need to have a channel and the technical tools available to report poor quality when they encounter it.
Heartbeat signals	Heartbeat signals, or signals communicated simply for the purpose of communicating that the sourc e system services are running, can be valuable diagnostics in complicated infrastructures. Lack of heartbeat signals from interfaces increases the likelihood that interface failures go undetected and that prolonged periods of data loss may happen.
Asset management systems	Asset management systems that are set up and used correctly are themselves key drivers to improve the data quality from the sensor system. When used properly, such systems allow for defective instruments to be addressed quickly and erroneous signals to be subjected to root cause analysis. Additionally, specialized tools for centralized calibration and maintenance of field devices can be key enablers to good data quality.
Alarm management, monitoring and statistics solutions	Alarm management solutions allow for master management of alarm levels and for monitoring the statistics related to alarms and events occurring in the system. Such solutions are excellent for detecting and eliminating bad actors and data noise which constitute poor data quality. Design to avoid that the management system becomes overwhelmed with a heavy alarm load scenario (i.e. alarm flood).
Infrastructure monitoring systems	A good infrastructure monitoring system which collects system health and diagnostics as well as heartbeat signals from all nodes in the sensor infrastructure is a key tool for data custodians and systems managers to maintain high quality data throughput from a large infrastructure.

Calibration Instruments	Sensors need to be calibrated in order for the measurements performed to be reliable. Sometimes comparison of multiple instruments in the same part of a process can be used as an ind icator that calibration is required. Sometimes smart instruments have internal diagnostics indicating that calibration is advisable. Vendors may come with time or usage-based calibration guidelines. Without proper calibration, the data quality will suffer.
Sufficient instrumentat ion	In order for pragmatic data quality to be sufficient for a particular use case it is necessary to have sufficient instrumentation. If only 90% of the relevant measurements are being performed, then the usefulness of the data use case may perhaps only be 10% of the scenario where all the measurements are available. Completeness in terms of data quality is closely linked with collecting the right data (e.g. a set of relevant tags) with sufficient quality. In other words, having sufficient instrumentation at the sufficient level of quality/ detail.
Sufficient granularity of system flags	In order to make good use of data it is often imperative to know the exact system state of the source system. If the internal system flags of the real-time system are too coarse-grained, then it may be difficult for data consumers to distinguish between analytically different states of the system as a whole. E. g. if the system can only discern whether an internal state is true or false but not whether the true state was set by a human operator or by controller logic, then the information may not be useful for data consumers.
Structured I/O federation	Signals and data flow to the automation, control and safety systems need to be federated in a coherent way using consistent modern standards that allow for proper granularity, precise time stamping and consistent conceptualization.
I/O control module load	The frequency with which data driven properties of the plant are recalculated in the system is usually dependent on the load put on each I/O control module. Heavily loaded modules recalculates outputs less frequently. If possible, take this challenge into design consideration. Users should be aware of this since data quality threshold may be challenged.
I/O control loop quality	Control loops represent the wiring that connects an instrument I/O to the controller. Faulty or poorly tested control loops can result in fault signals rather than measured instrument data to be relayed to source system controllers. This is a potential cause of bad data quality from a data collection infrastructure. Good test practices of control loops and monitoring of fault signal statistics are two ways to combat data quality loss due to poor control loop quality.
Intrinsic instrument qualities	Each instrument has defined capabilities with respect to data generation. Both how often it is capable of recalculating its own internal state and the precision with which it measures the underlying physical property which it is measuring. A sensor can also have capabilities with respect to eliminating noise or producing internal diagnostics. Data consumers may need this information to utilize the data semantically correct.
Time synchronization	Issues in relation to time synchronization between nodes in a system are a common cause for im precision in data being collected. Even systems that follow every recommendation available (like using a satellitetime based NTP time server and configuring NTP stratums for the entire infrastructure) still has a level of granularity at which time stamps are somewhat uncertain and where sequence of events become difficult to determine. To avoid time synchronization issues the best advice is still to ensure that all systems to which instruments and sensors are connected are being synchronized using an applicable protocol (like NTP).
Sufficient hardware and server capacity	Having sufficient hardware and server capacity is important. Both in the control nodes where I/O signals and control blocks are constantly re-evaluated, but also in the processing nodes in the infrastructure to collect the data. A high load on servers, typically means less frequent re-evaluation of signals, and hence more coarse grained data.

Bandwidth	Network bandwidth is important to data quality. This is particularly an issue when dealing with installations that are dependent on satellite connections. The satellite link often becomes a bottleneck which limits the throughput of data and dictates either aggressive compression strategies, low sampling rates or batch transfer of collected data (low timeliness) when the unit is sporadically connected to high capacity networks.
Plant model synchroni zation and scaling	It is time consuming to create and maintain complex plant models covering all the equipment types and attributes with associated tags and interrelationships that typically make up such a model. Once such a model is defined, it is desirable to reuse the model and to be able to synchronize changes to this model from one subsystem to another. This is usually a challenge, not only because there needs to be an appropriate model communication mechanism in place which is mutually understood by both communicating systems, but because the 'proper' model at one abstraction level may not be ideal at another abstraction level. Hence, most plants have suboptimal or non-existing synchronization and scaling of plant models implemented in their infrastructure. Misalignments of models being a major source of errors and poor system performance. A.1.27 Meta data synchronization across layers Meta data, here understood as a fixed set of descriptive attributes
Meta data synchronization across layers	Meta data, here understood as a fixed set of descriptive attributes associated with a dynamic process value (a measurement of an equipment state), also needs to be synchronized between systems in the plant infrastructure. These are attributes such as ranges, engineering units, descriptive text. Lack of meta data synchronization and shared meta data understanding is a typical source of data deterioration in sensor system infrastructures.
Inconsistent data transfer standards and schemas	Data communication within the sensor system should seek to align with a common standard. If co mponents on separate layers in the architecture use different standards and schemas to relay the same type of information the data quality of the net throughput may be challenged. This is due to loss in format and code transformation. This is a common data deterioration cause.
Single point of truth	Any significant piece of information should have a master storage location. A single point of truth. Other components that depend on this information should obtain it or synchronize with this master location.
Monitor as close to source as possible	Data quality should be monitored as close to source as possible to avoid multiple root causes introducing data quality issues.
Identify bottlenecks and keep them monitored	It is important to know which component of the sensor system represents the key bottleneck in terms of e.g. processing capability or throughput. It could be a network bandwidth issue (like a satellite link) or it could be the spare processing capacity, potential alarm storm or data update frequency of a source system. It is important to know what factors put a limit to how your system can scale and what changes can be performed in runtime if system state are close bottlenecks.
Identifier management	The asset, each sensor, equipment in the sensor system etc all have their identification. Management of these identifiers and synchronizing updates to data consumers are crucial to keep consistent semantics and usage of data.

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