Smart Maintenance

Industry 4.0 and Smart Maintenance: from Manufacturing to Subsea Production Systems

Andreas Marhaug
Norwegian University of Science and Technology (NTNU)
Department of Production and Quality Engineering
Norway
andreas.marhaug@ntnu.no

Per Schjølberg
Norwegian University of Science and Technology (NTNU)
Department of Production and Quality Engineering
Norway
per.schjolberg@ntnu.no

***Abstract*–This paper is focused on how principles from Industry 4.0 in manufacturing can be used in operation and maintenance of subsea production systems. The primary purpose and goal of the paper is to investigate the application of Smart Maintenance to achieve high level of safety, availability and profit in operation and maintenance of subsea production systems.**

The paper describes state-of-the-art in Smart Maintenance. This includes the framework for intelligent predictive maintenance, use of artificial intelligence for condition monitoring purposes and the progression of technologies for Smart Maintenance. The procedures for maintenance of Ormen Lange subsea choke modules are outlined. The paper investigates the performance of procedures for maintenance of Ormen Lange subsea choke modules, as compared to state-of-the-art in Smart Maintenance.The results are presented, as well a short conclusion. Suggestion for further work includes performing a quantitative Life Cycle Profit (LCP) analysis to investigate return on investment for further implementation of Smart Maintenance for Ormen Lange subsea choke modules.

***Keywords*–smart maintenance; predictive maintenance; Industry 4.0; operation and maintenance; subsea production systems**

I. Introduction

The global demand for energy is ever increasing, at the same time un-produced resources in currently developed fields are decreasing. As the oil and gas industry pushes towards development of fields in deeper waters and harsher environments the need for specially adapted, safe and efficient technologies are emerging.

Subsea developments have the later years been increasingly popular. Placing mechanical- and electrical equipment on the bottom of the sea pose some major challenges towards safety, operation and maintenance. This paper is focused on how principles from Industry 4.0 in manufacturing can be used in operation and maintenance of subsea production systems. This is hereby denoted as, Smart Maintenance.

The primary purpose and goal of the paper is to investigate the application of Smart Maintenance to achieve high level of safety, availability and profit in operation and maintenance of subsea production systems.

To further elaborate the purpose and goal, three objectives for the paper have been defined, the following bullet points describe those. Ormen Lange subsea choke modules will be used as a case study to fulfill the goal and objectives of the research paper.

- Give a description of state-of-the-art in Smart Maintenance
- Give a description of procedures for maintenance of Ormen Lange subsea choke modules
- Investigate the performance of procedures for maintenance of Ormen Lange subsea choke modules, as compared to state-of-the-art in Smart Maintenance

The industry partner, A/S Norske Shell, expect the paper to add value to their business by providing an alternative view on the challenges described in the case study. Ideally the paper can challenge the company’s problem solving approach related to the case study, thus the paper can provide ideas for implementing new technologies or improving work methods and procedures.

The first chapter, introduction, present the purpose, goal and objectives, of the research paper. The structure of the report is also a part of the first chapter.

Chapter two is state-of-the-art in Smart Maintenance. The chapter addresses the first of the three objectives for the research paper.

Chapter three is the case description. The Ormen Lange gas field as well as the Ormen Lange choke modules is shortly introduced.

The fourth chapter describes the procedures for maintenance of Ormen Lange subsea choke modules. The chapter addresses the second of the three objectives for the research paper.

Chapter five investigates the performance of procedures for maintenance of Ormen Lange subsea choke modules, as compared to state-of-the-art in Smart Maintenance. The chapter addresses the third and final objective for the research paper.

The sixth chapter is conclusion. Acknowledgements and references are included in the following chapters.

II. State-of-the-Art in Smart Maintenance

The following sub-chapters aim to introduce Industry 4.0, the framework of Intelligent Predictive Maintenance and Artificial Intelligence for condition monitoring purposes. A description of the progression of technologies for Smart Maintenance is included.

A. *Industry 4.0 and Intelligent Predictive Maintenance*

Industry 4.0 represents the anticipated technological evolution from embedded systems to cyber-physical systems. [1] Fig. 1 illustrate the four industrial revolutions.

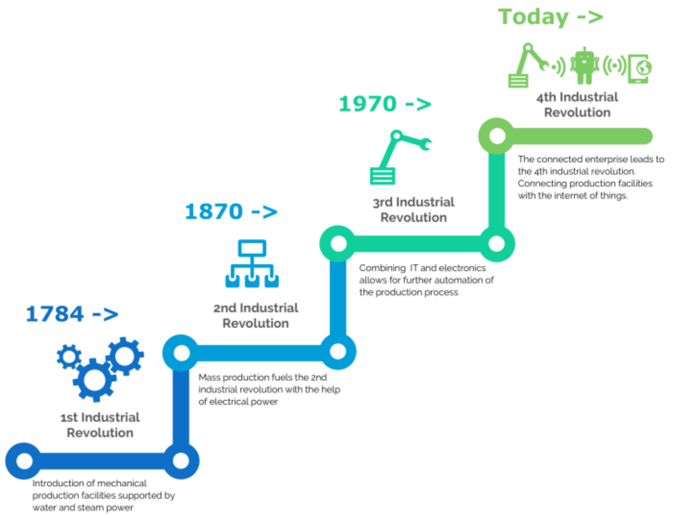

Fig. 1 The four industrial revolutions [2]

The term Industry 4.0 is often used in the context of manufacturing in Europe. Similar concepts exist for other regions and other industries; all comprises the same baseline, introduction of cyber-physical systems and machine learning.

Intelligent Predictive Maintenance (IPdM) can be said to be a sub-set of Industry 4.0. Fig. 2 present the framework of IPdM, consisting of four main components: Cyber-Physical Systems (CPS), Internet of Things (IoT), Data Mining (DM) and Internet of Services (IoS).

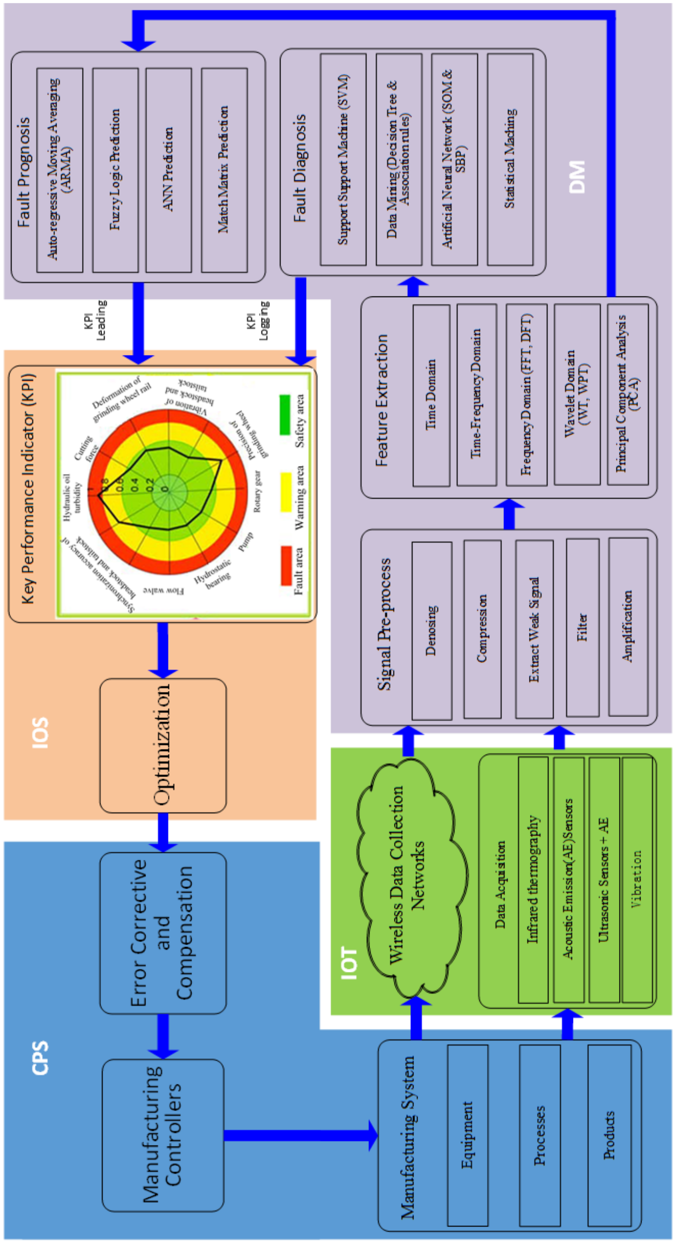

Fig. 2 The Framework of Intelligent Predictive Maintenance [3]

Cyber-Physical Systems is described as transformative technologies for managing interconnected systems between its physical assets and computational capabilities. [4] In general, CPS consist of two main components: 1) advanced connectivity that ensure real-time data acquisition from physical systems, 2) intelligent data management, analytics and computational capability. [5]

Internet of Things is about the connection of physical things to the internet, which makes it possible to access remote sensor data and control the physical object from a distance. The novelty of IoT is not in any disruptive new technologies, but in the pervasive deployment of Cyber-Physical Systems. [6]

Data Mining is the process of extracting knowledge from different sources and large amounts of data. [7] Fig. 3 illustrate the knowledge discovery process. The process is an iterative process of seven steps:

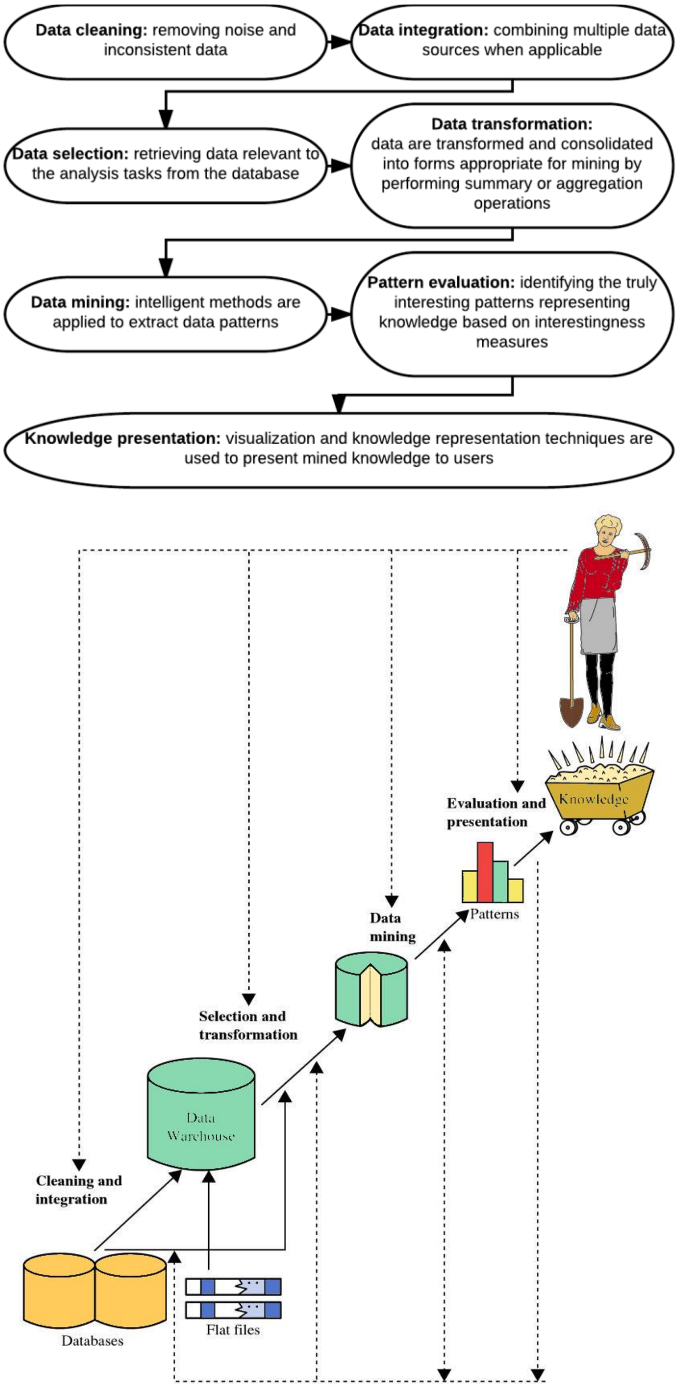

Fig. 3 Knowledge discovery process in Data Mining [7]

Internet of services is about considering computation of data and information as a service, as opposed the traditional model of considering it as a product. [8] An example of such transformation is Rolls Royce Civil Aerospace. Traditionally Rolls Royce have sold airplane engines to airplane manufactures such as Airbus and Boeing. With its newest engine-line, the company has abandoned the traditional model, in favor of selling engine operating hours to its customers. The engines is heavily instrumented, data is transferred to Rolls Royce, in-flight. Emerging issues can be analyzed whilst the aircraft is on the air, appropriate repairs, or even replacements can be planned and prepared at the destination of the aircraft; thus improving safety and efficiency of the maintenance action. The model has also proved beneficial for fuel consumption as the data can be used to optimize the running of the engine. [9]

The later years there have been developed some systems that utilize Artificial Intelligence for condition monitoring purposes. A system can be defined as an intelligent monitoring system if sensing, analyzing, knowledge learning and error correction capabilities are incorporated to the system. The system should be able to emulate as closely as possible the capabilities of a human expert operator. [10]

Expert systems that use Bayesian Case Based Reasoning (CBR) methods are one of several forms of intelligent monitoring systems designed for condition monitoring purposes. CBR is the process of solving new problems based on the solutions of similar past problems.

CBR systems keep a database of all recorded issues during the lifetime of the particular and similar systems. The information stored about the issues contain all sensor values prominent to the issue, the root cause of the issue and the measures that where implemented to fix the issue. [11] Real-time data is fed to the software that continuously checks the fit of the current situation against the recorded cases in the database.

The system can provide a list of possible prominent issues and an associated confidence level, i.e. probability that the issue is prominent based on the real-time data.

Fig. 4 illustrates an unreleased CBR software tool under development by Schlumberger. The highlighted box on the left describe measured variables and alarm status. The highlighted box on the right display the possible issues and their associated confidence level, based on the measured variables and alarm statuses.

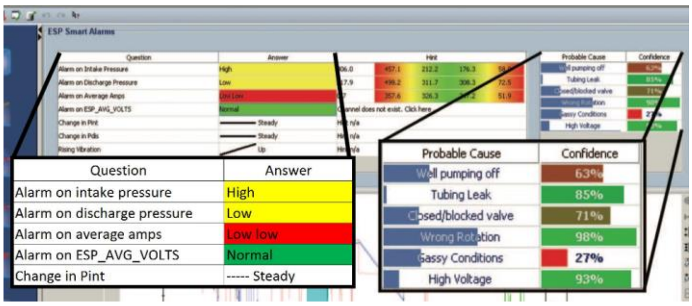

Fig. 4 Case Based Reasoning software tool screenshot [12]

A mature CBR tool is capable of identifying more probable cases, at a quicker response time and with greater accuracy than less sophisticated systems that rely more on input from engineers. Systems of this generation are yet to be commercialized in larger scale. Nevertheless, it could be claimed that there is a significant potential in development of condition monitoring that use Bayesian CBR methods.

B. Smart Maintenance Progression of Technologies

IBM Center for Applied Insights has conducted a study to identify success criteria and quantify the benefits of smart oil and gas field technologies. [13] The study maps the progression of a smart field and illustrates the characteristics of the different maturity levels, as well as the potential value creation for each maturity level. The progression of a smart oil and gas field is visualized in Fig. 5.

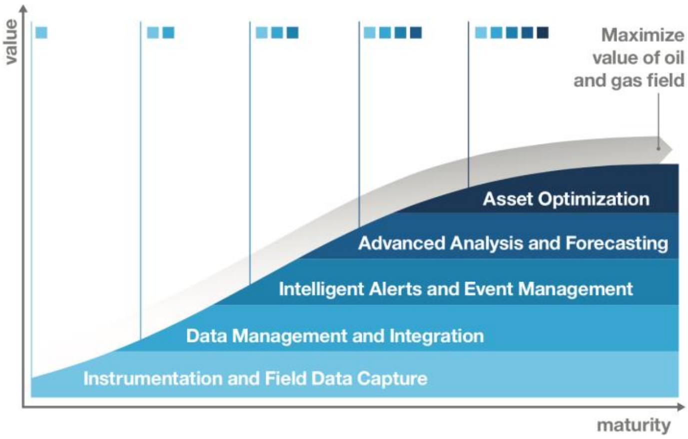

Fig. 5 The progression of a smart oil and gas field [13]

The first milestone of progression is instrumentation of critical points in the production system. This allows the user to monitor equipment and process conditions in real-time. The parameters that are to be monitored and the frequency of monitoring need to be identified through analysis, such that the monitoring can provide information to support operation, maintenance and process related decisions.

The second milestone is data management and integration. This feature is about storing the collected data efficiently, and making it readily available to all stakeholders. An important aspect, though frequently overlooked, is integration. Meaning that the system should have a holistic approach that allows for integration and collaboration between departments, suppliers and contractors. Evidence suggest that failure to implement a holistic management approach could cause key insights to be lost. [13]

Intelligent alerts and event management is the third milestone in the progression towards a smarter oil and gas field. Typically, in a smart field, many million data points are collected every day. This amount of data is too overwhelming for any human being to continuously track and make sense of. It is possible to develop algorithms that continuously process data from multiple sources and generate intelligent alerts that let the stakeholders know when there are imminent equipment or process related issues. The system can also be programmed to respond to the issue or provide a list of- and confidence for plausible root-causes.

Intelligent alerts and event management can provide a strong foundation for the smart field. To enable proactive management and decision-making the system must also provide advanced analysis and forecasting, which is the fourth milestone of progression. Predictive analytics can assess and forecast the performance of wells, facilities and exports systems; and generate models that can support higher quality decision-making.

In the culminating milestone of progression, asset optimization, information is widely shared and utilized across functions. At this stage the largest value is created for the oil and gas company and its associated partners.

Most suppliers of Subsea equipment offer condition monitoring solutions as an option for their equipment. [14] [15] [16] [17] [18] [19] [20] [21] [22]

The condition monitoring solutions offered by unlike suppliers are fundamentally very similar, with some minor differences. It can be claimed that most of these solutions is on the third level of progression on IBM's rating of progression. Most suppliers offer condition monitoring on the fourth level of progression for selected sub-systems.

III. Case Description

A. Ormen Lange Subsea-to-Beach Gas Field

Ormen Lange is Norway's second largest gas field, it is located in the Norwegian Sea, 120 kilometers offshore Kristiansund. Table 1 is some key data about the Ormen Lange reservoir.

Table 1 Ormen Lange reservoir data [23]

Water depth [m]	**Depth below seabed [m]**	**North-south stretch [m]**	**East-west stretch [m]**	**Estimated recoverable gas reserves [Sm3]**	**Estimated recoverable condensate reserves [Sm3]**
800 – 1,000	2,000	40,000	8,000	3,146,000,000	17,400,000

The red marker in Fig. 6 indicate the position of Ormen Lange.

Fig. 6 Ormen Lange's geographical position [23] [24]

The field is a subsea-to-beach development, the concept solution for Ormen Lange includes 24 wells distributed on four Subsea templates. The onshore production facilities are located at Nyhamna. The gas is exported 1200 kilometers through one of the world's longest subsea pipelines, Langeled, to Easington in south England.

Particular challenges associated with development and operation of the field is, bit is not limited to, the following bullet points. [25]

- Steep incline to shore
- Rugged seabed
- Long distance to control center
- -1.2 Celsius on the sea bed
- Formation of hydrates in multiphase flow

The concept solution utilizes a multiplex electro-hydraulic Subsea Production System (SPS), the system use a closed hydraulic circuit. Mono Ethylene Glycol (MEG) injection is used to prevent formation of hydrates.

Currently no subsea rotating equipment is utilized. In the tail production phase, it is planned to upgrade the facilities with subsea separation, compression and pumping.

B. *Ormen Lange subsea choke modules*

Ormen Lange subsea choke modules are primarily used for choking the well stream and injecting MEG to the well stream. Additionally, the choke modules contain instrumentation that collects data for production optimization and condition monitoring purposes.

The Subsea choke module is located downstream the x-mas tree, upstream the Subsea manifold. The main reason the choke module is separate from the x-mas tree is that the Process Choke Valve (PCV) is prone to wear and tear, it is likely going to need replacement during the lifetime of the field. By separating the choke module, containing the PCV; and the x-mas tree, containing the Production Master Valve (PMV) and Production Wing Valve (PWV); the PCV can be replaced without pulling the x-mas tree, thus saving substantial lifecycle costs.

Fig. 7 display a general arrangement drawing of the Ormen Lange Subsea choke module. The upper frame is removed to provide a clearer view of the internals of the choke module.

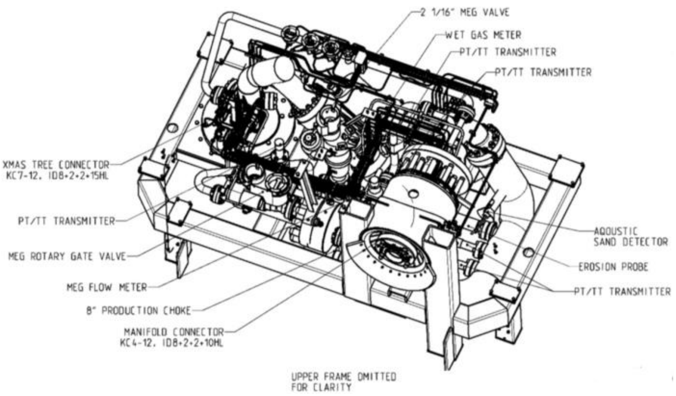

Fig. 7 Ormen Lange subsea choke module general arrangement drawing [26]

IV. Procedures for maintenance of Ormen Lange subsea choke modules

For the Ormen Lange gas field there is a Subsea Integrity Management System (SIMS) in place to define which people, processes and systems will be responsible for safeguarding the integrity of the Ormen Lange Subsea systems. The purpose of the system is to ensure availability and safe operation in line with Shell operational, societal and environmental objectives. [27]

Shell Subsea Operations Team is responsible for the integrity of Subsea systems. The team consists of discipline engineers who are responsible for the following integrity activity areas.

- Control systems
- Pipelines and umbilicals
- Structures and manifolds
- Offloading system
- Inspection, Maintenance and Repair (IMR)

The following sub-chapters is a description of the work processes of Shell and suppliers for ensuring integrity of the Subsea systems relevant to the case study through commissioning, monitoring, inspection and diagnostics. Some of the described work processes is available as written procedures, some is not defined as procedures but is performed in practical applications.

A. *Commissioning*

Commissioning of equipment for Ormen Lange is performed in accordance with procedures developed by the supplier of the equipment in question. Shell supervise the commission and require documentation that all failure scenarios are covered.

On a system level, and for the well Shell develop and perform commissioning. The reason for this is that systems normally consist of equipment from two or more unlike suppliers, as a result it is challenging putting suppliers on charge of the commission on a system level.

B. *Monitoring*

On Ormen Lange, use of condition monitoring technology provided by equipment manufacturers is limited. [28]

Shell keeps a database of all data collected by Subsea instrumentation. Tools available to all relevant engineers enable trending and comparison of the data. The discipline engineers of the Shell Subsea Operations Team perform analysis of data relevant to their respective discipline upon any operation of the Subsea equipment. This is done to detect smaller abnormalities and imminent issues. If a system or sub-system have failed, alarms imbedded in the control system detect the failure and alert operators. [29]

Relevant monitoring activities include but are not limited to hydraulic fluid consumption monitoring, valve signature analysis, circuit resistance monitoring, single- and multiple parameter trending.

C. *Inspection*

All inspection programs on Ormen Lange are prioritized in accordance with the risk-based principle. Risk Based Inspection (RBI) analysis is performed to determine the inspection program for each Subsea component. [30]

The methodology for risk based inspection developed and used by A/S Norske Shell considers three measures for determining the inspection interval for different subsea equipment. The three measures are: 1) probability of failure, 2) consequence of failure, 3) confidence in the component's ability to withstand threats.

The threats that are considered include:

- External corrosion
- External damage from dropped objects
- External damage from fishing
- Scour
- Overstress
- Hooking
- Fluid leaks
- Product leaks
- Hose or polymer failures

A flowchart that describes the methodology for risk based inspection developed and used by A/S Norske Shell is presented in Fig. 8.

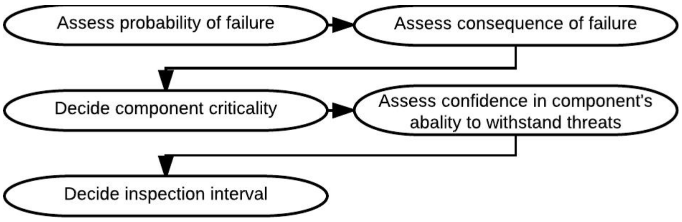

Fig. 8 Methodology for Risk Based Inspection developed and used by A/S Norske Shell [30]

D. Diagnostics

Diagnostics of imminent issues is performed using expert opinion and ROV inspection as the main tools. [29]

Data from condition monitoring and/or alarm system is assessed by Shell engineers to attach a probable diagnosis and prognosis to a pending issue. Commonly the supplier of the actual equipment under investigation will get involved to increase to accuracy of the diagnosis. The reason for this is that the equipment supplier commonly have greater in-depth knowledge about the equipment than the operator.

If the plausible diagnosis entails that the issue should be observable externally or by minor disassembly, ROV inspections is used to confirm or disconfirm the plausible diagnosis.

V. Performance of procedures for maintenance of Ormen Lange subsea modules

To investigate if further investments in Smart Maintenance should be considered for the Ormen Lange Subsea choke modules; the performance of the procedures for maintenance, as compared to state-of-the-art within Smart Maintenance should be assessed.

The following sub-chapters feature an assessment of the maturity of Ormen Lange as a smart field. As well as, a discussion on the performance of Shell procedures for maintenance of the Ormen Lange Subsea choke modules, as compared to state-of-the-art within Smart Maintenance.

The smart field concept includes different aspects of the production value chain. [31] Within the operation and maintenance part of the value chain there is no definite answer to Ormen Lange's level of maturity in relation to IBM's visualization of the progression of a smart oil and gas field, presented in Fig. 5.

Arguments could be made that Ormen Lange currently is somewhere between the second and third milestone of progression of a smarter oil and gas field. The reasoning behind this argument follows.

The second milestone of progression, data management and integration, is apparently completely fulfilled. Shell keeps a database of all data collected by Subsea instrumentation. Tools available to all relevant engineers enable trending and comparison of the data.

For the third milestone, intelligent alerts and event management, the Ormen Lange operation and maintenance system do not have all characteristics described by IBM. The alarm system is capable of automatically alerting the operator of an occurred failure. However, the condition monitoring system do rely heavily upon experienced engineers and expert judgement to identify, diagnose and prognose an imminent failure.

A seemingly logical progression for the Ormen Lange gas field is continue implementation of the five milestones towards a smarter oil and gas field described by IBM. In the culminating milestone there should be focus on integration between relatively similar fields in Shell's global portfolio. By doing so it is possible to share experiences related to operation and maintenance, share smart solutions and minimize risk for making the same costly mistakes on several locations.

Despite that Ormen Lange, by IBM's definition, is only half way to becoming a mature smart field, the availability of the choke module and the other Subsea equipment and Subsea systems have proved beyond satisfactory. Ormen Lange have thus far achieved an availability greater than 99%. [32]

A diversity of arguments to why Ormen Lange achieve near perfect availability, despite limited use of the most sophisticated Smart Maintenance technology, can be made.

There is no Subsea rotating equipment on the Ormen Lange gas field. In addition the field characteristics do not necessitate choke adjustments in normal operation of the field. As a result any operation of Subsea equipment is limited to scheduled function tests and potential emergency situations.

Condition monitoring systems that trend data to predict remaining useful life, i.e. advanced analysis and forecasting, can be worthwhile for continuously operated equipment. For periodically operated equipment such analysis is much more demanding, if even plausible. Other technologies offered by Subsea equipment manufacturers, such as coefficient of variation estimation and choke erosion modeling, is also less useful for the Ormen Lange process choke valve as the well stream is not being choked in normal operation.

The Subsea part of Ormen Lange feature a highly redundant design. Meaning that no single failure will cause production stop from any well. In addition, the sparing philosophy is based on a detailed spare part analysis. Any long lead items should be sufficiently stocked, enabling reasonable response time upon a single failure.

Because of this, the dominant maintenance policy for Ormen Lange Subsea components is run-to-failure. Condition monitoring us used, but unless there is imminent safety or environmental concern, an indication of a single failure will rarely provoke a reaction until the failure actually happen. Only when a single failure have occurred, thus the system is operating on single redundancy, action is taken. [29]

It should also be noted the A/S Norske Shell have attended sales meetings and considered condition monitoring solutions provided by equipment suppliers. The system was not considered worthwhile, due to the redundancy in design and maintenance policy. Still, such technology might be reconsidered with the future plans for Subsea separation, compression and pumping. [29]

Based on the above, it is difficult to argue that further investments Smart Maintenance will prove profit-making for the current configuration of Ormen Lange.

Because Shell have decided to not implement condition monitoring solutions provided by equipment suppliers, Shell discipline engineers have a hands-on role in the operation and maintenance of the Subsea production system. As a result, Shell have in-house, in-depth understanding of the Subsea equipment and systems that are part of Ormen Lange. This can enable A/S Norske Shell to make information-driven decisions and acts to achieve continuous improvement and continue the high availability for future operation of Ormen Lange.

VI. Conclusion

Industry 4.0 represents the anticipated technological evolution from embedded systems to cyber-physical systems in manufacturing and other industries. It can be claimed that Intelligent Predictive Maintenance is a sub-set of Industry 4.0. The framework of Intelligent Predictive Maintenance, consist of four main components: Cyber-Physical Systems, Internet of Things, Data Mining and Internet of Services. Artificial Intelligence can be used for condition monitoring purposes. The progression of Smart Maintenance technologies can be described in five milestones.

Major oil and gas companies have invested in smart fields. Subsea condition monitoring technology is commercially available from the largest equipment manufacturers. Progression of a smart oil and gas field is detailed. As well, developments using artificial intelligence, is described. It could be claimed that some of the described technologies could be adapted for Subsea applications.

The procedures for maintenance of Ormen Lange subsea choke modules consist of original equipment manufacturer written procedures, Shell written procedures and non-documented work processes performed by Shell engineers. It is possible to describe the procedures using the data and information provided by the industry partner.

For Ormen Lange subsea choke modules, use of commercially available Smart Maintenance technologies provided by original equipment manufacturers is limited. Still, Ormen Lange has thus far achieved availability greater than 99%. It is difficult to argue that investments in further implementation of Smart Maintenance will prove profit-making for the current configuration of Ormen Lange.

Based on the results presented in this research paper, the following suggestions for further work are made.

- Perform a quantitative Life Cycle Profit (LCP) analysis to investigate return on investment for further implementation of Smart Maintenance for Ormen Lange subsea choke modules
- Investigate the use and performance of Smart Maintenance for similar fields to Ormen Lange

Acknowledgment

The authors would like to show appreciation to A/S Norske Shell, represented by Jan André Furnes and Terje Meldby Hansen. Hansen and Furnes have been helpful in providing technical documentation, internal procedures and reports from the industry partner, A/S Norske Shell. The industry partner have also contributed by allowing the authors to take field trips to their offices and equipment storage facilities. Executing the study, as presented, would not have been possible without the help of A/S Norske Shell, and the dedicated engineers from Shell's offices in Kristiansund.

References

[1] Germany Trade & Invest, 2014. [Online]. Available: http://www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Brochures/Industries/industrie4.0-smart-manufacturing-for-the-future-en.pdf. [Accessed 20 May 2016].

[2] ROBOYO, [Online]. Available: https://www.roboyo.de/cms/wp-content/uploads/2016/02/industrialrevol_en.png. [Accessed 20 June 2016].

[3] K. Wang, Y. Wang , J. O. Strandhagen and T. Yu, "Intelligent Predictive Maintenance - Industry 4.0," in *Advanced manufacturing and automation*, WIT Press, 2016.

[4] R. Baheti and H. Gill, "Cyber-Physical Systems," in *Impact Control Technology*, 2011.

[5] J. Lee, B. Bagheri and H.-A. Kao, "A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems," *Manufacturing letters 3,* pp. 18-23, 2015.

[6] H. Kopetz, "Internet of things," in *Real-time systems*, Springer, 2011, pp. 307-323.

[7] J. Han, J. Pei and M. Kamber, Data Mining: Concepts and Techniques, Elsevier, 2011.

[8] R. Moreno-Vozmediano, R. S. Montero and I. M. Llorente, "Key Challenges in Cloud Computing: Enabling the Future Internet of Services," *IEEE Internet Computing,* pp. 18-25, July - August 2013.

[9] Harvard Business School, "Rolls Royce: Internet of Things in Aviation," 2015. [Online]. Available: https://digit.hbs.org/submission/rolls-royce-internet-of-things-in-aviation/. [Accessed June 02 2016].

[10] M. A. Elbestawi and M. Dumitrescu, "Tool Condition Monitoring in Machining - Neural Networks," *IFIP International Federation for Information Processing,* 2006.

[11] K. Kobbacy, "Artificial Intelligence in Maintenance," in *Complex System Maintenance Handbook*, London, Springer London, 2008.

[12] G. Deans, R. MacKenzie and Schlumberger, "Enabling Subsea Surveillance: Embracing ‘True Production Control’ with an Open Architecture Subsea Monitoring and Control System," Schlumberger, 2006.

[13] IBM, "The value of smarter oil and gas fields," 2011. [Online]. Available: http://www.ibm.com/smarterplanet/global/files/us__en_us__oil__che03002usen.pdf. [Accessed 8 June 2015].

[14] OneSubsea, "Remote Surveillance and Diagnostic System," 2014. [Online]. Available: http://www.onesubsea.com/~/media/Files/onesubsea/data_sheets/subsea_services/friend_ds.pdf. [Accessed 30 January 2015].

[15] T. Berge and FMC Technologies, *Condition and Performance Monitoring [university lecture]*, NTNU, 2014.

[16] K. Eriksson, K. Antonakoupolos and A. Solutions, "Subsea Processing Systems: Optimising the Maintenance, Maximizing the Production," in *Offshore Technology Conference*, Kuala Lumpur, 2014.

[17] K. Eriksson and A. Solutions, "Control system and condition monitoring for a subsea gas compressor pilot," *Sage Publications Measurement and Control,* 2011.

[18] GE Oil & Gas, "Smart Facilities - Facility Monitoring & Applications," 2015. [Online]. Available: http://www.geoilandgas.com/subsea-offshore/subsea-production-control-systems/smart-facilities-facility-monitoring-applications. [Accessed 4 February 2015].

[19] Oil and Gas Monitor, "Naxys graphic," 2015. [Online]. Available: http://www.oilgasmonitor.com/wp-content/uploads/2013/02/NAXYS-GE-Graphic1.jpg. [Accessed 19 February 2015].

[20] J. Abrahamsen, G. H. Lie, T. B. Bertmand, S. A. Haugen and Hydro, "Ormen Lange Subsea Condition and Leakage Monitoring," in *Offshore Europe* , Aberdeen, 2007.

[21] Naxys, "Wide Area Leak Detection - Acoustic Leak Detector," 2014. [Online]. Available: http://www.naxys.no/page/342/Leak_Detection. [Accessed 19 February 2015].

[22] FMC Technologies, "Condition and Performance Monitoring," 2014. [Online]. Available: http://www.fmctechnologies.com/SubseaSystems/Technologies/AdvancingTechnologies/ProductionMonitoringOpt/CPM.aspx. [Accessed 30 January 2015].

[23] NPD, "factpages," 2014. [Online]. Available: http://factpages.npd.no/factpages/. [Accessed 9 October 2014].

[24] Google Maps, "Ormen Lange," 2015. [Online]. Available: https://www.google.com/maps/place/63%C2%B029'48.3%22N+5%C2%B023'11.5%22E/@59.6283692,-0.3355077,6z/data=!4m2!3m1!1s0x0:0x0!6m1!1e1. [Accessed 26 May 2015].

[25] Shell and J. Furnes, *Subsea Competence and support in 2020 perspective,* 2014.

[26] FMC Technologies, *Choke module, general arrangement*, 2007.

[27] Shell, *Subsea Integrity Management System (SIMS) Draugen and Ormen Lange,* 2014.

[28] Shell and A. M. Røsdal, *Ormen Lange and Langeled NTNU presentation,* TRD, 2008.

[29] Shell and S. Lindstad, *Unformal discussion about Ormen Lange Condition Monitoring*, KSU, 2015.

[30] Shell, *Framework Inspection Program for Subsea Structures (RBI Results),* 2013.

[31] NTNU and K. Stoltz, "Better resource utilization," 2007. [Online]. Available: https://www.ntnu.edu/research/research_excellence/io. [Accessed 27 April 2015].

[32] Shell and J. Furnes, *Informal discussion about Ormen Lange availability,* KSU, 2014.