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Abstract

In recent years, the offshore wind industry has contributed to the world-wide expansion of renewable energy. Wind energy is widely viewed as one of the key renewable energy sources that make up the new energy mix that, together with other renewable sources, will relieve the worlds dependency on fossil fuels. Offshore wind has seen rapid technological development, with the ever-larger wind turbines most noticeable resulting in increased annual energy output per turbine. Despite this, the industry experiences challenges throughout the value chain and is still largely dependent on state subsidies to make projects economically viable. However, the recent tenders in northern Europe (DK, NL) have shown that the costs are rapidly decreasing, heading towards a level where subsidies are no longer needed. The grid parity levels that have been expected to be seen within 2030 are within reach. The prices in the latest tender for Kriegers Flak in DK and Borselle in the Netherlands has been, surprisingly, much lower than expected. However, to reach price levels where wind parks can be financed purely from marked prices will take some effort. The cost of an offshore wind farm needs to be reduced, components need to be more reliable, and availability must improve to increase the annual energy production. By digitalizing the industry, an increased level of predictivity and prescriptiveness could ensure opportunistic maintenance and largely avoid unscheduled maintenance events.

This thesis investigates how new digital technologies and digitalization can help further evolve the offshore wind industry using the Industry 4.0 concept as a basis, and explores how technologies within this concept can contribute to an offshore wind farm that overcomes some of these challenges. The study focuses on an offshore wind farm from a systems perspective, including respective modules, and where the Industry 4.0 technologies can be applied. Following this is the establishment of a systematic digitalization framework and a proposal on how to cope with increased volumes of data, connectivity and complexity.

The findings indicate that several of the technologies are already in use today, while others need better understanding or further development for them to have a significant impact on offshore wind systems. With an increased use of digital technologies, an offshore wind farm is seen to experience an increased level of autonomy and complexity. In order to truly utilize the capabilities of a digitally transformed system, the establishment of a decision and visualization layer (a distributed knowledge system) to facilitate for sharing and communication will be discussed and presented. Given a successful implementation of technologies and considering the human aspect of digitalization, this system is seen to potentially cope and manage the large volumes and variety of data. The system is envisioned to be able to extract the value of data and providing information, knowledge and a sound decision support for manpower throughout the value chain of offshore wind farms.

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Abbreviations and acronyms

AEP	Annual Energy Production
AIS	Automatic Identification Systems
AM	Additive Manufacturing
API	Application Programming Interface
BICC	Business Intelligence Competence Centre
CFD	Computational Fluid Dynamics
CIS	Customer Information System
CMS	Condition Monitoring System
CPS	Cyber Physical System
CTV	Crew Transfer Vessel
DAC	Disturbance Accommodating Controller
DBMS	Database Management System
DFIG	Doubly Fed Induction Generator
DMS	Distribution Management System
EAM	Enterprise Asset Management
EERA-DTOC	European Energy Research Alliance - Design Tool for Offshore Clusters
EMS	Energy Management System
EPC	Engineering Procurement Construction
EWEA	The European Wind Energy Association
GIS	Geographic Information System
GW	Giga Watt
GWEC	Global Wind Energy Council
H2M	Human to Machine
HMI	Human Machine Interface
HTS	High Temperature Super (conducting)
HVAC	High Voltage Alternate Current
HVDV	High Voltage Direct Current
IEC	International Electrotechnical Commission
I/CAD	Intergraph Computer Aided Dispatch
ICT	Information Communication Technology
IoT/IIoT	Internet of Things /Industrial Internet of Things
IRENA	The International Renewable Energy Agency
ISO	International Organisation for Standardization
IT	Information Technology
KIC	Knowledge Innovation Community
kWh	kilo Watt hour

LCC	Line Commutated Converter
LCOE	Levelised Cost of Energy
LES	Large Eddy Simulations
LIDAR	Light Detection and Ranging
M2H	Machine to Human
M2M	Machine to Machine
MCDM	Multi Criteria Decision Making
MRAC	Model Reference Accommodating Controller
MW	Mega Watt
NCS	Norwegian Continental Shelf
NES	New Energy Solutions
NOK	Norwegian Krone
NORCOWE	Norwegian Centre for Offshore Wind Energy
NOWITECH	Norwegian Research Centre for Offshore Wind Technology
O&M	Operation and Maintenance
OMS	Operation Maintenance Service
OMS	Outage Management System
OPEX	Operation Expenses
OT	Operation Technology
PAS	Publicly Available Specification
PDC	Proportional Derivative Controller
PLC	Programmable Logic Controller
PMSG	Permanent Magnet Synchronous Generator
PWh	Peta Watt hour
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SCIG	Squirrel-Cage Induction Generator
SCS	Smart Connected System
SDAC	Stochastic Disturbance Accommodating Controller
SHM	Structural Health Monitoring
SOV	Service Operation Vessels
SQL	Structured Query Language
TWh	Terra Watt hour
NoSQL	Non/ non-relational/not only Structured Query Language
VHF	Very High Frequency
VSC	Voltage Source Converter
WRSG	Wound Rotor Synchronous Generator

Section 1: Offshore wind status and challenges

1 Introduction

Offshore wind is gaining momentum with the installed and operated capacity increasing nearly every year since 2001, the forecasted capacity growth is exponential, shown in figure 1 and 2 (IRENA, 2016) and levelised cost of energy (LCOE) is dropping faster than expected (Kraemer, 2016). Hirtenstein (2017) sees UK offshore wind as the cheapest future large-scale energy, which reached its cost target of below 100 pound a megawatt-hour in 2016 – 4 years early, and with a LCOE of 97 pounds, offshore wind was made cheaper than nuclear power. A maturing technology together with bidding auctions are reducing these costs for offshore wind projects.

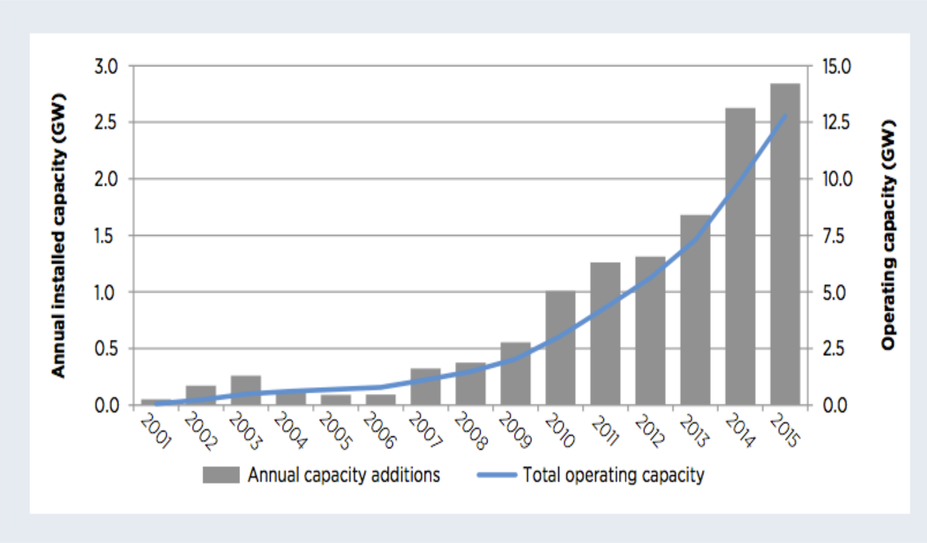


Figure 1 Global annual installed and operating capacity for offshore wind farms 2001-2015 (IRENA, 2016)

There are several different reports giving different scenarios for future offshore wind, KIC InnoEnergy, IRENA, Global Wind Energy Council and EWEA, all of them remain positive, expecting the industry to further increase and have a major impact as contributor to the global energy mix. Offshore wind has already established itself offshore Europe, and its share of the energy mix is bound to increase with the offshore wind investments going up 40% in 2016 (GWEC, 2016). UK is the world leader, with a wind farm tally of 27 and a capacity of 5,1GW. Germany has targeted their offshore wind capacity to be 15 GW by 2030, and in Denmark the capacity is planned to double by 2021 from 1,271 MW today. Netherlands broke new records, making it the 2nd largest market in 2016, whilst China passed Denmark with respect to offshore capacity, largely driven by limited capacity for new onshore development. Japan has a strong project pipeline, and due to their coastline, there is also a large focus on floating solutions.

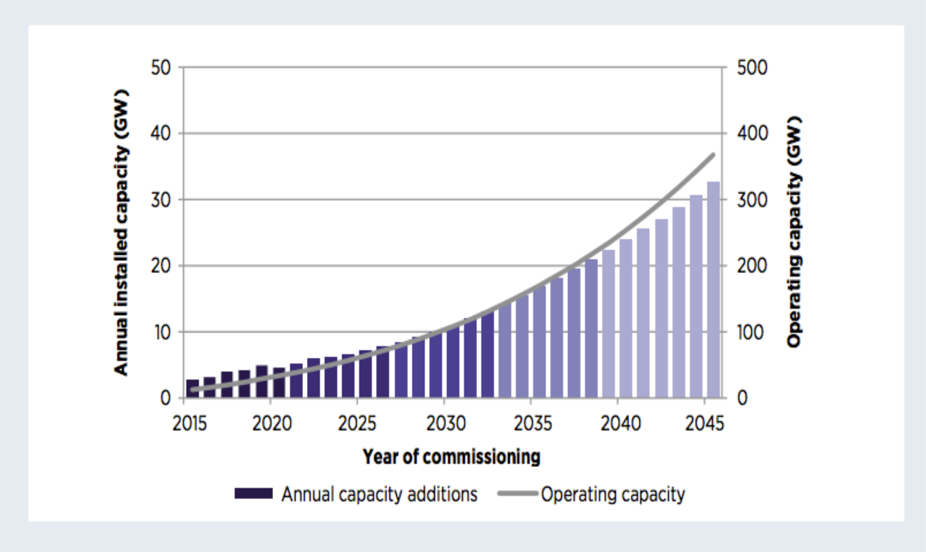


Figure 2 Forecasted global annual and operating capacity of offshore wind, 2016-2045 (IRENA, 2016)

Other countries in Asia are also showing their attention to offshore wind, with projects in South Korea moving forward and Taiwan looking to follow their president´s reiteration of the target to source 20% of electricity from renewables by 2025, targeting an offshore wind capacity at 3GW. In addition to this are India and Vietnam regarded as upcoming markets by the Global Wind Energy Council (2016). The offshore wind industry are also seeing development in the USA where the first offshore wind farm was commissioned late 2016 and the vision for offshore wind contribution to the total US electricity demand is expected to increase from 2% in 2030 to 7% in 2050 (GWEC, 2016). Below is an overview of the global offshore wind potential in PWh (petawatt-hour) presented by Sullivan, et al. (2012).

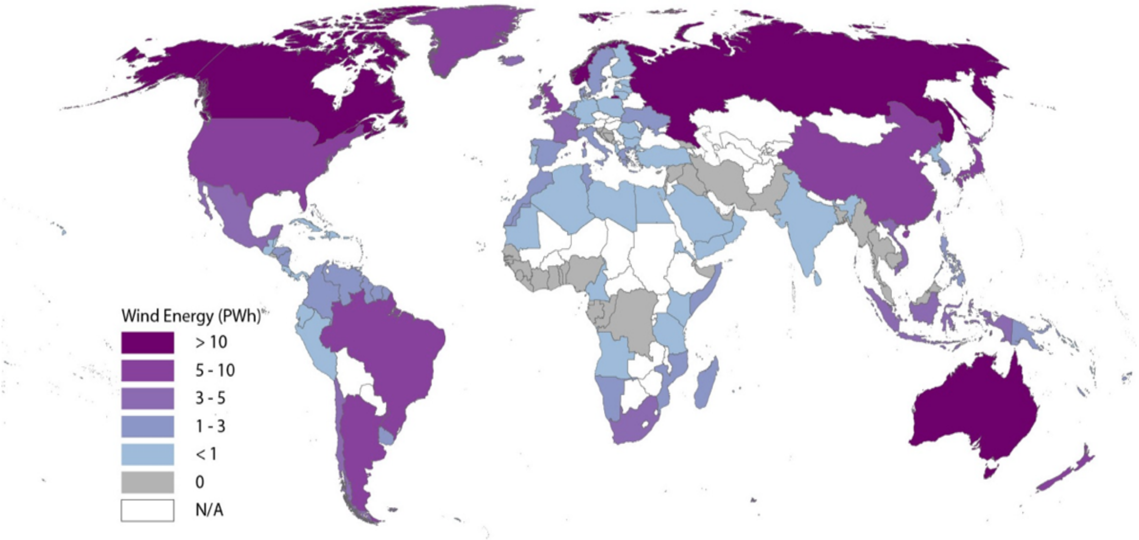


Figure 3 Global offshore wind potential (Sullivan, et al., 2012)

Norway offshore wind projects are of a small scale such as Statoil’s Hywind and Gwind´s Spinwind pilots. The onshore wind installations in Norway produced 2,1TWh in 2016, from a capacity of 873MW (NVE, 2017). However, offshore wind in Norway is seen to have a great potential; with respect to the country´s annual mean wind speed at 80 meters’ height shown below. However, the offshore wind sector is developing rather slowly. First and foremost, Norway is seen to be able to contribute with technology and knowledge regarding development of offshore wind farms, and there are plans for establishing a demo wind farm (Aarvig, 2017). According to Frøysa & Tande (2015), several reasons exists for why there should be a demo farm in Norway. The international market of offshore wind and its expected growth and that it is a renewable energy source. There are strong research and industrial environments in Norway with experience from offshore oil & gas, NOWITECH and NORCOWE are two research environments with international recognition with proven strong results and Statoil’s Hywind project. All should enable Norway to take part in innovations and preparing Norwegian industry to become competitive in a growing market.

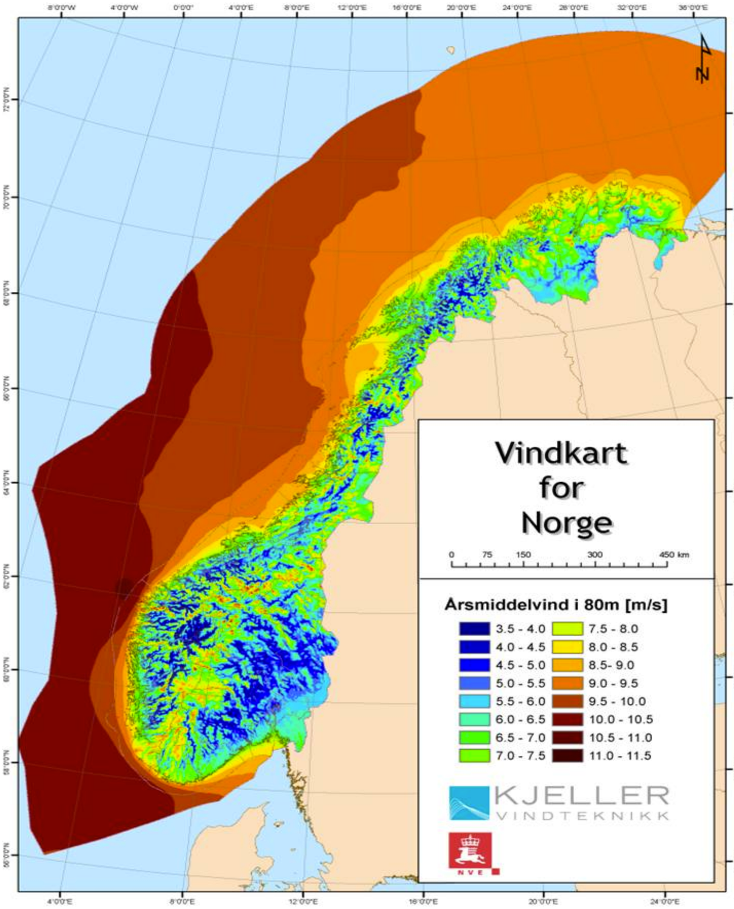


Figure 4 Annual Mean Wind Speed at 80 meters (Fornybar, 2017)

With this said, an offshore wind turbine is still more expensive than an onshore wind turbine and research on the Norwegian Continental Shelf (NCS) has proven bottom fixed wind turbines to not be suitable as their depth limitation is at about 40 meters (Midling, 2015). This makes floating wind solutions an option to consider on the NCS, but these concepts are still only at the development and trial stage with Statoil’s Hywind Scotland being in the forefront. Still, arguments are being made that, with the agreement at COP21 and the decreasing price per kWh dropping fast in projects such as at Borssele in the Netherlands and Kriegers flak in Denmark, offshore wind could be a part of Norway´s contribution in reaching the governments targeted emission cuts (Nielsen, 2017). Creating a strategy for development of full scale offshore demo sites in Norway are central in the newly launched Offshore 2025 project. Their target being to map industrial repercussions from the development of one or more full scale offshore demo sites and show what capacities there are in Norwegian industry (NORWEA, 2016).

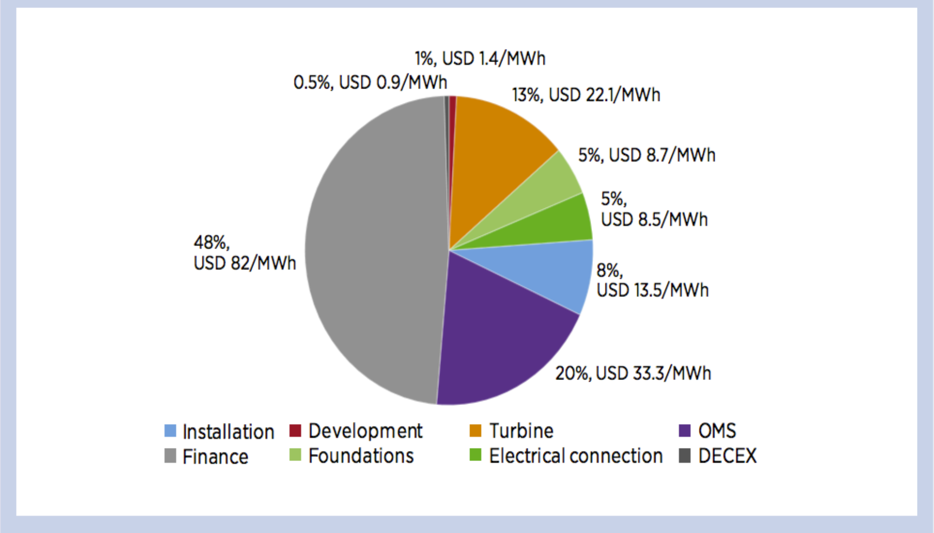


Figure 5 Contribution of each element to cost of energy for typical project commissioned end-2015 (IRENA, 2016)

O&M costs of the offshore wind farms have a central role for the global predictions to materialise. The operations, maintenance and service cost contribution was at 20% of the total cost of energy for a typical project at end 2015, down from 32% in 2001, shown in figure above (IRENA, 2016). Still, it has been estimated that the cumulative O&M costs could represent 75%-90% of a turbine´s investment cost. Given the limited value-adding margins of wind energy farms, such observations drive the wind energy industry to develop solutions to ensure that the assets can effectively be operated and managed over a period with a limited cost exposure (El-Thalji & Liyanage, 2010).

Although the offshore wind industry is maturing, it is still a relatively immature industry compared to for example offshore oil and gas. There are also a variety of challenges of different proportions that, when all added up, have a substantial impact on the economy and thus the return on investment for an offshore wind farm project in all life cycle stages. Some of the offshore wind O&M activities are listed by Hassan (2013), such as onshore logistics, back office, administration and operations, offshore logistics, export cable and grid connection, turbine maintenance, array cable maintenance and foundation maintenance. These activities are depicted in the figure below.

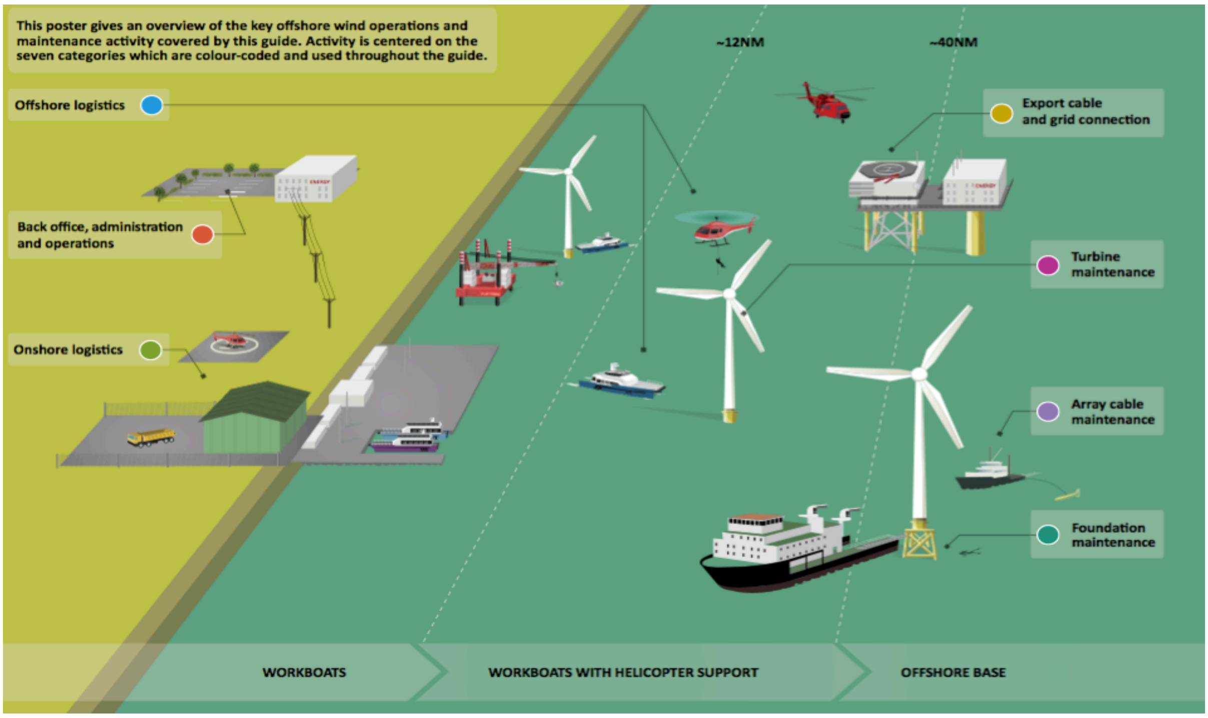


Figure 6 O&M activities (Hassan, 2013)

1.1 Challenges

Offshore wind park development is a complex task and process that consist of numerous operations under challenging conditions. There are different challenges facing the development, management and decision making of offshore wind farms such as, risks related to technology and supply chain, vessel availability and capability, grid bottlenecks, harsh weather conditions, power prices and political decisions (DNV GL, 2014). According to BIS Group (2016), companies are starting to face growing technical and economic challenges in O&M represented mostly by reliability, accessibility and logistics issues and vessels deployment costs, due to extreme environmental conditions, vibrations, operating parameters and limited equipment lifetime. With offshore wind farms being installed further from shore in deep ocean, this make transportation and logistics challenging and expensive (Cassidy, 2017), and components that are most prone to failure are the electrical systems, generators and gearboxes (Scottish Enterprise, 2011). DNV GL (2014) points out that understanding the risks and dependencies between different parts of the value chain are important for success. To visualize this, DNV GL (2014) provide a graph, shown below, that depicts the fact that expected return on investment may vary throughout the project and that the uncertainty in the return on investment is greater in the beginning of the project, where key decisions are made.

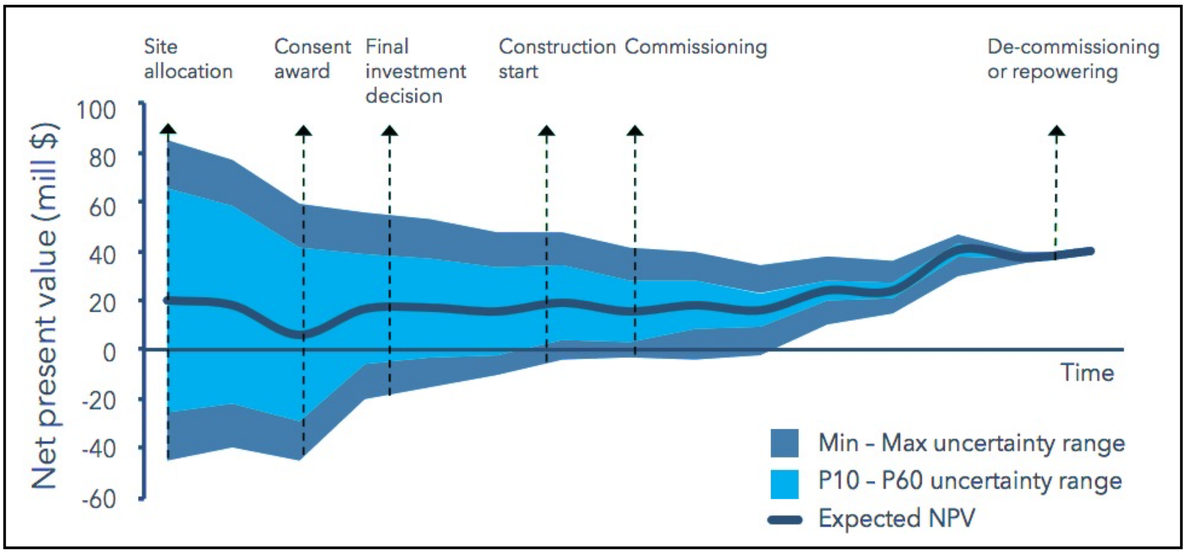


Figure 7 Net present value vs. Time (DNV GL, 2014)

According to (El-Thalji & Liyanage, 2012), is there a need for performance-accountable asset units in the offshore wind sector, and achieving performance-based targets can be influenced due to:

- Difficulties to decide clear targets in large scale systems because of the nature of performance control variables and fuzzy impact
- Difficulties in measuring the performance of the process against the actual functional characteristics because of inherent uncertainties
- Lack of comprehensive techniques and methods for the companies involved to visualize real needs w.r.t predictable performance patterns

In their review, El-Thalji & Liyanage (2010) identified different physical and technical challenges related to different segments of a wind farm lifecycle. Within design and installation, the challenges are related to design for integrity, structural & mechanical design, aerodynamic design, electrical design and quality control, testing and installation. For offshore conditions, there are specific challenges related to sites and to season. Within onshore operations, there are challenges related to

- Cost-effective maintenance
- data acquisition, analytical and decision support system
- diagnostics, prognostics and maintenance optimization system
- logistics challenges, technologies and practices (El-Thalji & Liyanage, 2010)

The main challenge within offshore support system is making sure of a safe and efficient access and within system integrity and interface aspects, where the root causes for failure are identified as technical (design, installation and quality) and operational (El-Thalji & Liyanage, 2010). There is also a focus on data and communication interfaces, where the short-term perspective focuses on the safety of personnel and on the facilitation of remote control access of turbines control system to investigate, rectify and re-set trips where possible (El-Thalji & Liyanage, 2010). And in the medium-term perspective, the focus lies more on further develop and innovate O&M strategies utilizing the advancements within SCADA and condition monitoring technology. Hameed, et al. (2011) argue that no dedicated RAMS database is available for offshore wind turbines. In this regard, they identified challenges in the reliability and maintainability data collection for offshore wind turbines and separates between specific and general challenges. Where specific challenges address technological development and improvement, novel concepts, qualification of new technologies and optimizing O&M strategies. General challenges address issues like management of database and enhancement of data quality.

Keseric (2017) states quite simply that Statoil want the least possible downtime on their wind turbines, least amounts of failures and errors, and that the need for personnel having to head offshore to perform work is at a minimum. Central in making this possible is being aware of failures before they happen, being able to predict failures so that when the time of maintenance arrives everything is well prepared. Being able to predict not only failures but also future demand and production is critical to establish and maintain control over the windfarm availability, production and future earnings. So, for the offshore wind industry to be a true alternative in the future energy mix, there are several challenges that need to be handled. These high-level challenges listed by Keseric (2017), in combination with the more specific challenges, especially the ones related to onshore and offshore operations and decision making, are used as a basis when further assessing the digitalization of offshore wind.

1.2 Scope

The scope of this thesis is to assess digitalization technologies relevant to an offshore wind farm, map these technologies´ relevance to the different modules of a windfarm and establish a systematic framework for digitalization of an offshore wind farm system. Establishing an overview of the state of offshore wind industry and the corresponding challenges is necessary. The terms digitalization, digitizing and digital transformation will also be explored and clarified as these are often misunderstood. Furthermore, the Industry 4.0 concept and related technologies, will be used as a basis to discuss what technologies are applicable to offshore wind and what technologies are relevant to what module within an offshore wind farm system. By doing this, the link between offshore wind, and the improvement potential that technologies could have on an offshore wind farm system, will be established and explored respectively. A smart connected system and its attributes will be explained and will work as a scope for the further establishment of a systematic framework for digitalization. This framework will to be built up from a suggested road map of offshore wind based on the Industry 4.0 technologies and a digitalization architecture exploring how the combination of technologies could enable the target of worry free energy production and near zero breakdowns. Additionally, the framework intends to open new thoughts about the existing systems description of an offshore windfarm and targets a further discussion about changes the offshore wind power asset management system and would face when reaching a digitally transformed state.

1.3 Method

The method used for this thesis was first a comprehensive literature review using books, web-articles and reports to present an overview of the offshore wind industry in general, explore digitalization, concepts related to digitalization, Industry 4.0 technologies relevant to offshore wind and digitalization architecture.

Interviews with interdisciplinary companies from various sectors such as Statoil, Draga, Visco, Verico, Arundo, and Jotne has been conducted. This was to establish an overview of what the industrial environment today sees as relevant digitalization technologies with respect to the Industry 4.0 concept in an offshore wind context, what technologies are in use, what technologies are seen to have an impact in both the short-term and long-term and what step-wise approach could be taken to digitalise offshore wind.

In consultation with Statoil, the author assessed technologies seen as relevant to a digitalization process of offshore wind and where they are seen to fit within a systems perspective. The method used has been to thoroughly go through each technology together with Dr. Nenad Keseric. His insight and knowledge on existing wind farm such as Sheringham Shoal and Dudgeon currently under installation, was used as reference and basis during the discussions where Dr. Keseric either confirmed or refuted the author´s suggestion to whether the technologies had relevance.

1.4 Limitation

One limitation of this thesis is that there has not been used a concrete technical case in the development of the digitalization road map. Thus, the results of the path taken is a more practical, general framework for a future digital wind farm and examines how technology can be combined to potentially cope with challenges the industry is facing, without any specific wind farm as reference or technical case. For the purpose of this report, the digital technologies explored have been limited to those derived from the Industry 4.0 concept and those with specific relevance to offshore wind and digital architecture, as the full range of technology was too vast to explore thoroughly. Even though the approach considers several modules of the wind farm system, areas such as smart grid, grid transfer and connection have not been included. Also, from a life cycle perspective, technical systems such as manufacturing, construction, installation and decommissioning of larger components of the wind farm system is not in scope for the purpose of this report, although it has been mentioned.

1.5 Structure

The thesis is divided into six sections. Section 1 comprises of Chapter 1-2, and lays the theoretical groundwork for the thesis. In addition to including method, limitations and structure, Chapter 1 introduces the reader to the offshore wind distribution today and its potential and challenges. Chapter 2 includes the offshore wind business landscape, state of

the art, offshore wind asset management practices, system availability and safety and the offshore wind farm system architecture and physical interface. Trends in offshore wind, together with Statoil´s wind energy engagement, is also covered in this chapter. Additionally, Chapter 1-2 covers the literature review and industrial practices of offshore wind to provide an overview of the direction the industry is heading towards.
Section 2 focuses on the central issues of increased automation and data exchange and therefore, in Chapter 3 and 4, establishes a basic level of knowledge on terms such as digitalization, Industry 4.0 and smart connected systems. Chapter 4 elaborates further on the technologies relating to Industry 4.0 and offshore wind and includes supporting information from interviewees.
In Section 3 a mapping of the technologies and their relevance to different parts of the offshore wind farm system is performed. This leads into Section 4 where a systematic framework for digitalizing of offshore wind is established and focuses on the step by step approach and the parallel developing technologies and capabilities, covered in Chapter 5 and 6 respectively. Section 5 follows up with offshore wind farm system changes and strategies for managing the change. Section 6 contain a general discussion and conclusion.

Below is an overview of the thesis structure.

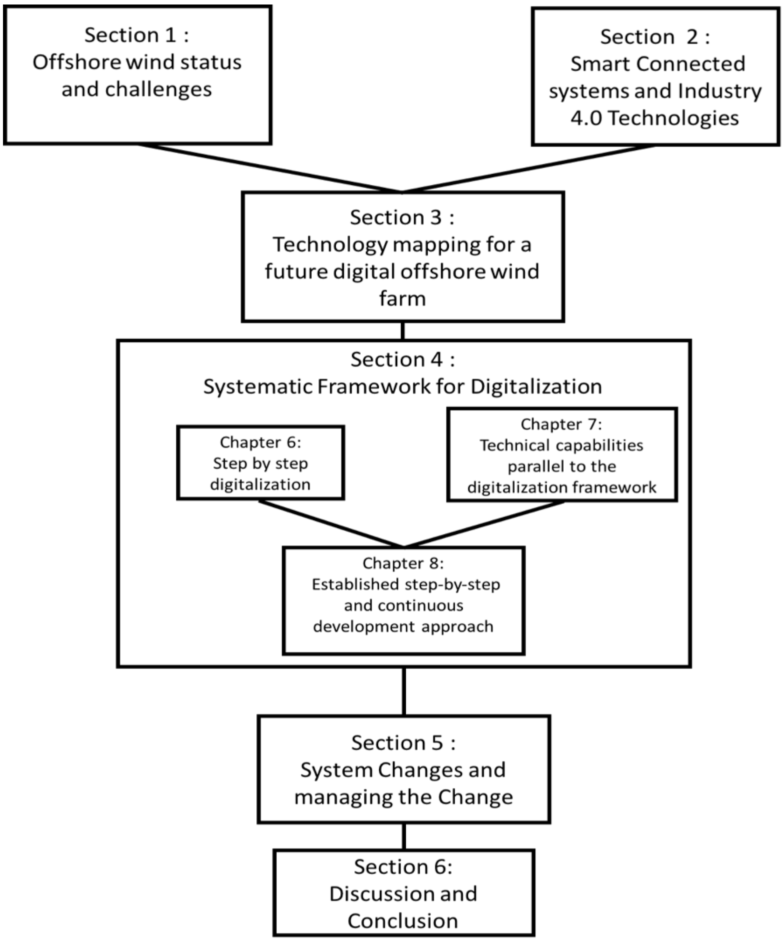
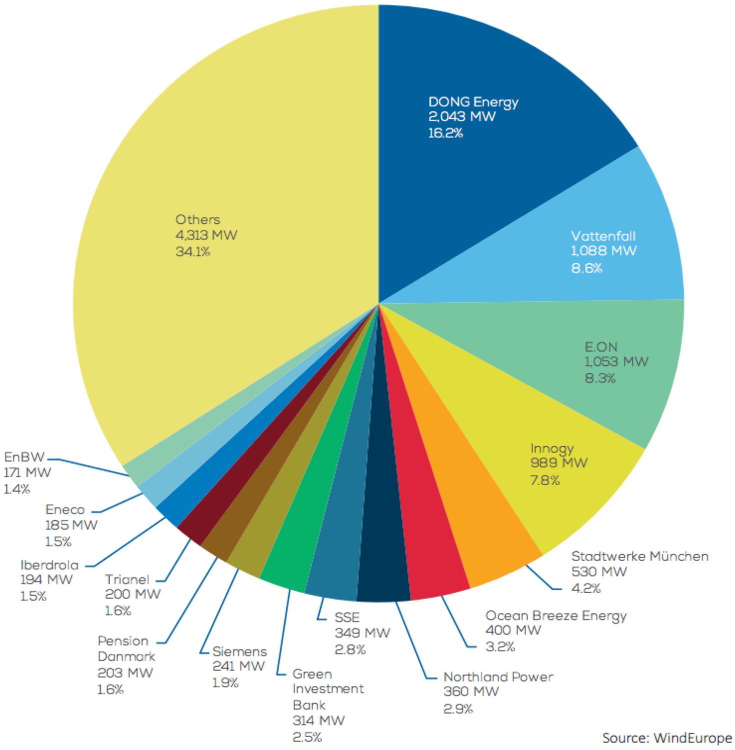


Figure 8 Thesis structure

2 Offshore wind

2.1 Business landscape, market share and stakeholders of the industry

Among offshore wind farm owners where DONG Energy biggest owner/operator in 2016 with a cumulative market share of 16,2% resulting in an installed capacity of 2043MW, followed by Vattenfall (8,6%), E.ON (8,3%) and Innogy (7,8%). There are a lot of players and adding together the companies with a share lower than 1,4%, one sees that they make up a 34,1% share of the installed capacity. This can be seen in the figure below.



Source: WindEurope

Figure 9 Owners´ share of installed Capacity (MW) (WindEurope, 2016)

There are several different offshore wind turbine manufacturers and by 2016 the top 5 manufacturers make up 98,8% of the market share in Europe with Siemens, Vestas, Senvion, Adwen and BARD. Siemens is in a league of its own with a market share of 67,8% (WindEurope, 2016). Siemens do not only provide wind turbines, they are also involved in services throughout the value chain, such as smart energy grids, power distribution and OMS. Vestas delivers services on project management, OMS, EPC including wind turbines. Senvion are focusing on development, construction and distribution of wind turbines, and provide services towards wind farm engineering, service and maintenance, transport and installation (Technavio, 2015). The complete view of manufacturers shares is depicted in Figure 9. Amongst the foundation manufacturers, the total share of installed foundations in 2016 were more evenly divided with Sif, Bladt and EEW, who all have a share of just around 20% of the market. Smulders follow somewhat close behind (12,7%) and these four companies make up almost 74% of the total installed foundations in 2016.

Out of the substructures installed in Europe, monopiles are the dominant foundation concept with a share of 80,8% (WindEurope, 2016)

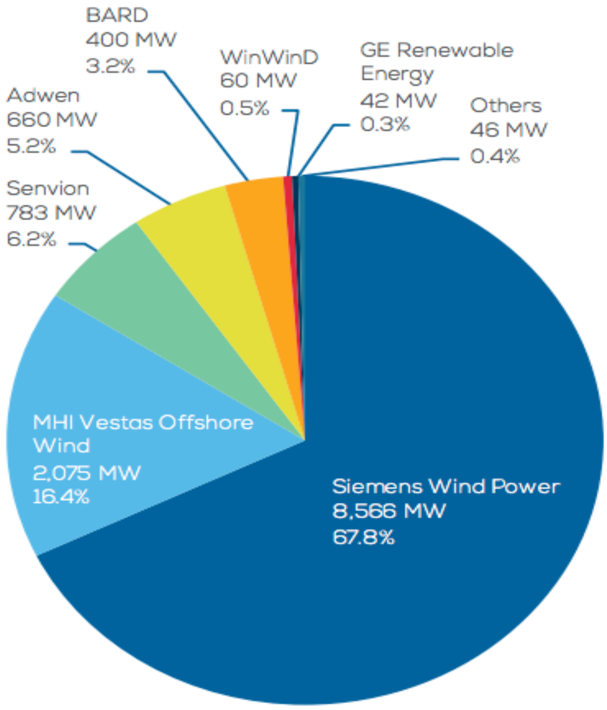


Figure 10 Wind turbine manufacturer's´ share at the end of 2016 (WindEurope, 2016)

2.2 Current state in offshore wind

2.2.1 *Site selection*

During the development of a wind farm, site selection is one of the most crucial decisions to make. A proper approach in selecting a suitable site is gathering all known information on the site options, with a blend of health and safety ~~as decision driver~~ together with feasibility and economics driving decisions. One needs to consider consenting issues, grid connections and other technical issues (Wind Energy, 2017). Van Haaren and Fthenakis (2011) categorize the factors that play a role in the site selection of wind farms as economic, planning, physical and ecological factors. And since all these are dependent, claim that using geographic information systems (GIS) poses benefits for site selection. According to Van Haaren and Fthenakis (2011), GIS provides powerful calculating capacity that can assess multiple layers of large geographic areas and display the results in usable maps. They suggest that this method can select feasible sites, assess economic value, give a preliminary impact assessment on wildlife e.g. birds' habitats and is therefore useful when used for prioritization of sites.

Lee, et al. (2010) developed a statistical model for site selection procedure for an offshore wind farm based on wind resources through using the optimization technique. Using artificial neural networks to construct wind and bathymetric maps and further, an analysis of variance to obtain accuracy and consistency of the constructed maps and perform a candidate selection through a generic algorithm. Further claiming it being possible to predict roughly a candidate site location for the installation of an offshore wind farm and to evaluate the wind resources.

Fetanat & Khorasaninejad (2015) use six criteria in their goal of finding the best site for an offshore wind farm; depths and heights, environmental issues, proximity to facilities, economic aspects, resource technical levels and culture. Using a combination of different fuzzy approaches ~~to~~ they developed a novel multi criteria decision making (MCDM) system offering a more precise and accurate analysis by integrating interdependent relationships within and among a set of criteria. According to Biswal & Shukla (2015), the complexities of selecting a site for wind farm installation necessitate the simultaneous use of several decision support tools such as high spatial resolution remotely sense data, GIS and MCDM.

2.2.2 *Wake effects*

There are several factors driving the cost of the offshore wind farm. The main driver for wind farm design being cost of energy, levelised cost of energy (LCOE). Construction of the offshore farm is a large factor impacting cost. Operating expenses (OPEX) are, to a large degree, dependent on maintenance costs; both scheduled preventive and corrective maintenance, and the related lack of availability (Giebel & Hasager, 2016). Giebel & Hasager (2016) continue explaining that the last large factor affecting the LCOE is the annual energy production (AEP), and focus further on that the determining factor of AEP are the wake effects and not purely the wind speed or wind distribution. This is because the wind distribution is given and the wind speed is not varying strongly across the offshore wind farm area.

There are different ways of calculating wake effects for example, PARK model using WAsP software, computational fluid dynamics (CFD) and large eddy simulation (LES). Increased knowledge on wake effects have also affected the wind farm layouts and turbine spacing in attempts to reduce the influence wake effects have on production, and the total wake loss. In the elongation of this, Giebel & Hasager (2016) present the EERA-DTOC tool, which is designed based on inputs from users. This tool´s aim is to support the optimisation for LCOE by comparing different variants for the farm layouts where a central part of this process is using scenarios and scenario trees.

2.2.3 *Foundations*

State-of-the-art shallow offshore wind foundations are monopiles, jackets or tripods. With respect to deep offshore, the three main types of deep offshore foundations are the spar buoy, tension leg platform and semi-submersible (EWEA, 2013). Floating foundations are proven to cope better in harsh environments, but require adaption to accommodate different dynamic characteristics and a distinct loading pattern, Commercialization of concepts are expected first after 2020, with Statoil’s Hywind Scotland 30MW windfarm scheduled to start at the end of 2017 (IRENA, 2016). IRENA (2016) further focus on the need for the concepts, both fixed and floating, to become less costly and more easily deployed to enable offshore wind to contribute significantly to the future energy mix.

2.2.4 *Generator configurations*

The paper of Yaramusu, et al. (2015) is aimed to extensively review the state of the art and emerging MW wind generator-converter configurations, wind farm configurations and grid code compliance methods. Wind energy conversion systems such as squirrel-cage induction generator (SCIG), doubly fed induction generator (DFIG), permanent magnet synchronous generator (PMSG) and wound rotor synchronous generator (WRSG) are discussed together with the most common configurations and various technical issues, such as: generator types, power converter topologies, active power control, energy conversion efficiency and grid-side reactive power compensation. Different types of converters, their features and drawbacks are included in the discussion.

2.2.5 *Wind turbine control*

In their paper, Nijiri & Söffker (2016) provide a thorough overview of state of the art control strategies used in large wind turbines, both high and low speed regions, with respect to different operational aspects with a specific focus on structural loads. Of the advanced control methods, the authors differ between classical methods, disturbance observer-based controllers, multi-variant robust control and multi-objective and model predictive approaches.

Classical methods largely involve load mitigation as it is increasingly important on the mega-scale utility turbines. Disturbance observer-based controllers considers estimation and compensation of wind speed non-linarites and other unmodeled dynamics for using suitable observers combined with a control scheme. The authors refer to controllers such as disturbance accommodating controller (DAC), stochastic disturbance accommodating controller (SDAC), proportional derivative controller (PDC), model reference accommodating controller (MRAC) and different control strategies.

Multi-variant robust control schemes such as H_2 and $H\infty$ have been applied to wind turbines to mitigate adverse effects of variability of wind speed (Nijiri & Söffker, 2016). The last multi-objective and model predictive approaches considers control solutions that cover multiple objectives such as;

- regulating output electric power and controlling rotor rotational speed
- mitigating structural loads by minimizing yawing and pithing moments on the rotor
- develop algorithm that could operate in both partial and full load regimes
- regulate generator angular speed, active and reactive power for a DFIG and so forth.

They also elaborate on different predictive models and controllers for increased insights to regulate rotational speed and minimizing load effect. Feed-forward and feedback controllers are discussed for improvement on blade root bending moment and reduce fatigue loads on wind turbines without significant compromise on power regulation (Nijiri & Söffker, 2016).

2.2.6 *Condition monitoring*

Coronado and Fischer (2015) have done a comprehensive study on condition monitoring of wind turbines and state that in contrast to pre-determined preventive maintenance, condition based maintenance has the potential to optimally utilize the technical life of components. In their report is an overview on the monitoring principles, instrumentation and data analysis techniques used in wind-turbine condition monitoring and structural health monitoring.

According to Tchakoua, et.al (2014), the state of the art maintenance strategy is the implementation of on-line continuous condition monitoring system (CMS), and the prevailing techniques are fibre-optic monitoring, vibration monitoring and oil analysis. Furthermore, the future goal in CMS is to continue to minimize the efforts required from operators using intelligent software algorithms and automated analysis. The wind industry is moving toward intelligent machine health management, where the target is to develop wind energy conversion systems capable of understanding and making decisions without human intervention (Tchakoua, et al., 2014). The authors further conclude that the wind industry is moving towards smart monitoring (a necessity of remote and E-monitoring), in-service structural health monitoring, integration and interaction of monitoring and control systems, and estimation of the remaining component life service (Tchakoua, et al., 2014).

Tian, et al. (2011) developed a condition based maintenance solution and policy addressing issues of economical opportunity to maintain multiple turbines once a team is sent to the wind farm. They suggest/propose it may be cost-effective is simultaneously replace multiple components which show relatively high risks if a turbine is stopped for maintenance.

2.2.7 *SCADA*

For data acquisition monitoring and processing, supervisory control and data acquisition (SCADA) systems is widely used in the industry. SCADA systems deploy multiple software and hardware elements that allow organizations to monitor, gather and process data, interact with and control machines and devices connected through software and record events (Inductive Automation, 2017). According to Inductive Automation (2017), basic SCADA system setups, where information from sensors or manual inputs are sent to programmable logic controllers (PLC) or remote terminal units (RTU), then sends information through the network to computers. This in turn analyses and displays the data to reduce waste and increase efficiency helping the organization save time and money. The SCADA system assess the status of the wind turbine and its subsystems using sensors such as anemometers, thermocouples and switches (Tavner, 2012). According to Tavner (2012), many large turbines with SCADA also fitted with CMSs, which monitor sensors associated with the rotating drive train such as: accelerometers, proximeters, and oil and debris particle counters.

Wu, et al. (2013) give an insight on the designs of a number of internal electric systems of an offshore wind farm (the transmission system to shore, the generator type, system frequency, transmission cable, communications medium and SCADA system, offshore substation and transformer). Wu, et al (2013) include a section on novel technologies with respect to components and writes that PMSG and DFIG generators are most common, and as the weight of the turbines is an important consideration, developing directly-driven generators is increasingly getting more popular. Further, the use of a lower AC frequency within the offshore wind farm is discussed, together with the cable system where manufacturers include ABB, NSW, Nexans, Prysmian and NKT. The importance of SCADA is mentioned and cable types relevant for this system are included. Wu, et al. (2013) discusse transformers in an offshore environment and the risks linked to them, and different technical transmission solutions such as HVAC, HVDC, LCC and VSC based converter stations. In their paper Wu, et al. (2013) champion a radial network design with enabled connections between feeders to achieve redundancy and thus higher system reliability. Tautz-Weiner & Watson (2016) did a review on using SCADA data for wind turbine condition monitoring, where using normal behaviour modelling utilizing artificial neural network or fuzzy logic gave the most positive feedback. It is important to notice that this is still in need of further research.

2.2.8 *Model and simulation*

Siemens (2017) perform 3D design risk assessment enabling them to test a product before manufacture to reduce cost and increase safety. Siemens also champion the Service Operation Vessels (SOV), which can stay offshore close to the wind farm for several weeks if necessary and contain all the technology needed for faster, safer and more efficient service. In their Remote Diagnostic Centre, Siemens (2016) have data analysts working on predicting turbine faults based on vibration anomalies. Using a combination of domain knowledge, high quality data and analytics the detection hit rate is at impressive 99 percent for drive-train damage such as main bearing damage and gear tooth cracks. Sentient Science uses software to simulate how the operating conditions affect the life of critical components in fielded wind turbines. The data could forecast future failures 18 months ahead of condition based maintenance and sensor detection (Cassidy, 2017). GE (2017) offers what they call the world´s first digital wind farm; a comprehensive hardware and software solution built on the Predix software platform. It enables collection, visualization and analysis of unit and site data. The long-run benefit promises a predictive model based on constant collection of data, allowing optimization of maintenance strategy, improved reliability and availability, and an increased annual energy output. However, for now this solution comprises only GE´s 2MW and 3MW onshore wind turbine products.

2.3 Offshore wind asset management practices

According to El-Thalji & Liyanage (2010), asset management is defined in PAS 55 as "*Systematic and coordinated activities and practices through which an organization optimally manages its physical assets and their associated performance, risks and expenditures over their lifecycles for the purpose of achieving its organizational strategic plan*" (El-Thalji & Liyanage, 2010, p. 2). ISO 55000 is the international standard for asset management and defines asset management as the coordinated activity of an organization to realize value from assets (IAM, 2017). "The goal of engineering asset management is to reveal unexpected ways of using technology to bring new and improved assets into being, that will be more competitive in the global economy" (El-Thalji & Liyanage, 2015, p. 2). Management of physical assets is key to long-term operational performance and profitability, together with the management of financial, technical, contractual and regulatory aspects of a project, according to Froese (2016). Additionally, effective and efficient asset management processes offer the basis for decision making throughout the whole asset lifecycle (Zajonic, et al., 2016). Furthermore El-Thalji & Liyanage (2010) state that decision is a contextualized form of informative (reliability centred maintenance, expert system, logistic information, technical staff reports etc.) and numeric (analytical software outputs, meteorological data etc.) contents.

Historically, asset management has been mainly focused on financials or intangibles, hence terms such as physical asset management or industrial asset management are used to differentiate from merely financial matters to also include tangible assets and people assets. Froese (2016) states that physical asset management is a system designed to minimize cost of operating, maintaining and renewing assets within constraints, while balancing the risk to an organisation. In order to balance risk one needs to fully understand the assets through:

- Performance demand
- Condition and remaining useful life
- Risk and consequence of failure
- Potential repair or refurbishments options
- Cost of risk and repair options.

The implementation of well performing asset management of offshore wind farms is challenging, largely due to many different actors with different targets throughout the lifetime of a wind farm (Zajonic, et al., 2016), and the current level of awareness within the sector is largely limited as developments remain isolated and fragmented (El-Thalji & Liyanage, 2010).

Harbor Research (2016) write that the task of optimizing the value of financial, physical and people assets require new technologies that will integrate diverse asset information in unprecedented ways to solve more complex business problems. According to Liyanage (2012), innovation and managing key in the emerging production environments, where the survival and growth do not rely on the fittest, but maybe on the smartest who develop specific capabilities to manage asset processes. In this environment, managing risks and strengthening the competitive position of an asset in the portfolio call for integrated approaches based on a clear view on the sensitive technical and operational, and other critical interfaces of the value creation process (Liyanage, 2012).

El-Thalji & Liyanage (2012) write that this is to allow a better pursuit of the critical factors by suitable means, to assess the criticality of different levels of impact and to model and trouble-shoot the critical problems. Establishing this view and context, El-Thali & Liyange (2012) state that a systems perspective will make a considerable contribution. El-Thalji & Liyanage (2010) view the definition from PAS55 as the goal and identified on six factors that define asset management in an offshore wind context:

1. Technology and their changes
2. Operations´ trends and their organizational patterns
3. Management policies and their societal expectations
4. Supportive system for logistic support, decision support, information and communication technologies support and management activities (forecasting, planning, organizing, accomplishing and controlling)
5. Operating conditions and their variability
6. Stakeholders and their human aspects behaviours and needs.

Froese (2016) writes that asset management involves balancing costs, risks and opportunities/performance to achieve organizational objectives, and that this balancing must be done considered over time. El-Thalji & Liyanage (2010) take on this approach when they conclude that to manage the complexity and changing characteristics of offshore wind power generation, asset management should cover the stages of the lifecycle of technical systems. Technical systems comprise of ten stages; planning, design, construction, manufacturing, installation, operation, performance evaluation and monitoring, maintenance and disposal operations or re-decommissioning. An overview of these systems can be seen below.

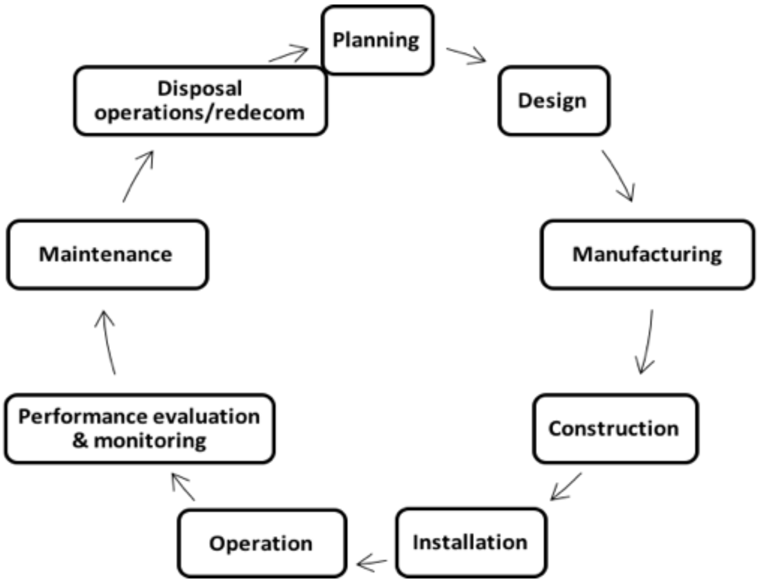


Figure 11 Ten stages of a technical system (El-Thalji & Liyanage, 2010)

2.3.1 *Interdisciplinary asset management practices and tasks*

The asset management system also included several overlapping interdisciplinary activities. El-Akruti & Dwight (2013) list this as supporting functions: procurement, technical support and development, HR management, IT/IS, finance, accounting, inventory, handling and industrial safety. Below is a representation of typical asset related activities. Within these activities there are several tasks. Some of the offshore wind asset management tasks can be, according to DNV GL (2017), cable management, structural integrity management, developing and implementing peer review ISO55001 systems, turbine performance analysis, short-term forecasting, portfolio management, SCADA data management, condition based monitoring, maintenance and performance enhancement, repair and maintenance management, technical operations management and sub-station management. K2 (2017) add on to this with tasks such as site management, contract management, risk management, compliance and reporting.

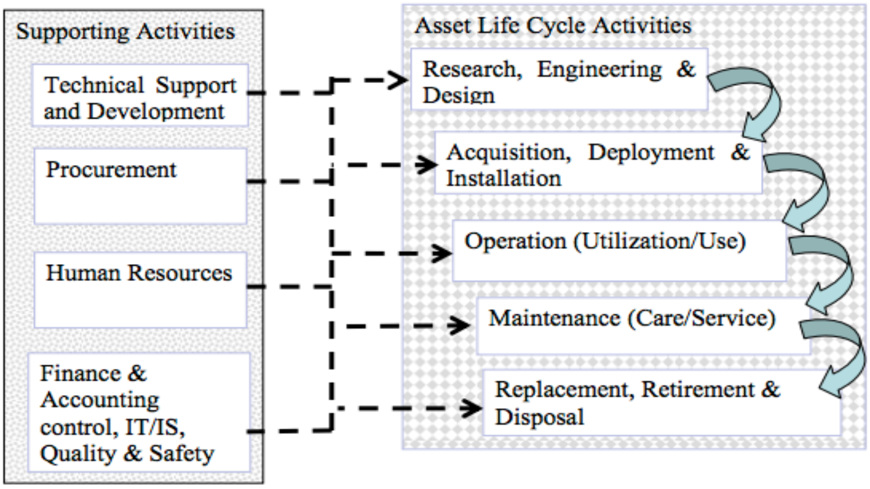


Figure 12 Typical representation of the asset-related activities (El-Akruti & Dwight, 2013)

Van der Wal, et al. (2017) emphasise the importance of the planning phase of an offshore wind project as the first phases could largely affect the offshore wind farm performance throughout the lifecycle and thus established a planning process framework. This framework was divided into initiation, concession, permitting, detailed design and financing. Their research looked at risks and uncertainties in the planning phase. Inexperience and repetitive underestimation of megaprojects resulted in ten identified risks for overruns: poor interfacing, lacking information sharing, late involvement of important parties, long application process permits, insufficient preparations, tight scheduling, poor contracting, incompetent project team, no grid connection (van der Wal, et al., 2017). All these risks could factor in on decision making.

2.3.2 *Offshore wind system availability and system safety*

Managing assets in a systematic and coordinated manner with respect to offshore wind means maintaining a high system availability that is not at the expense of system safety. Reducing downtime and minimizing number of trips for offshore maintenance personnel is a central part of the main goal of wind farm design and operation, maximizing energy production and ensuring safe operation with minimum capital and operating costs. In this regard, an understanding of the factors within wind farms that affects the system safety and availability is therefore needed. Tiusanen, et al. (2012, p. 35) state that "the optimization process during the design process aim to minimize risks, and that there is a need for appropriate and effective risk management measurers from preliminary layout design to detailed turbine design and component selection."

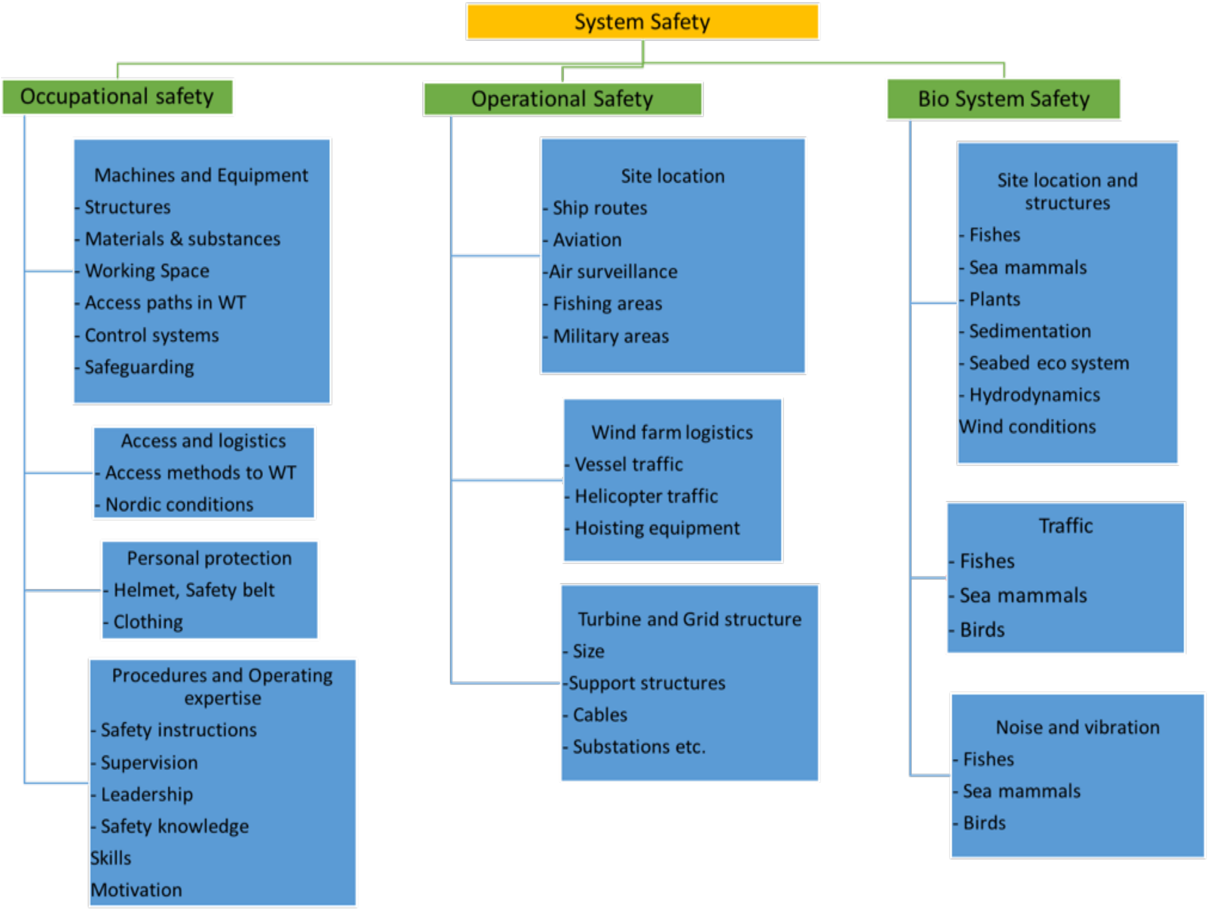


Figure 13 Factors affecting system safety in offshore wind assets in the Nordic context (Tiusanen, et al., 2012)

In their development of a RAMSI model for Nordic offshore wind energy purposes, Tiusanen, et al. (2012) present factors affecting the systems availability and safety. The safety overview is divided into sections of occupational safety, operational safety and bio system safety. Occupational risk involves manual work, not only offshore, but also in construction, installation, commissioning, testing, inspection, maintenance, repair and decommissioning phases. Operational safety risks are defined as risk affecting other operations at sea. Additionally, the potential implications on the bio systems offshore are registered as disturbances from noise, electromagnetic fields, hydrodynamic conditions, water quality and altered habitat structures (Tiusanen, et al., 2012). This overview can be seen in the figure above.

The availability overview below, is divided into sections of reliability, maintainability, inspectability and maintenance supportability. System availability is defined as "the percentage of time that an individual wind turbine or wind farm is available to generate electricity expressed as a percentage of the theoretical maximum" (Tavner, 2012, p. 13). Reliability is defined in 1999 by IEC 60050 (191) as the ability of a system to perform a required function under given conditions for a given time interval. Furthermore, the same standard defines maintainability as "the ability of a system under given conditions of use, to be retained in, or restored to, a state which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources" (Tiusanen, et al., 2012, p. 25). Tiusanen, et al. (2012, p. 26) further refers to the IEC 60050(191) standard when defining maintenance supportability performance as "the ability of a maintenance organization, under given conditions, to provide upon demand, the resources required to maintain an item, under a given maintenance policy". Further, inspectability is defined as a separate entity that reflects the ability to undergo visits and controls (Tiusanen, et al., 2012). Tiusanen, et al. (2012) emphasizes the importance of recognizing a high integrity level of software based systems, such as wind farm systems, the wind turbine and its sub system control and monitoring systems. This can only be achieved if one follow a systematic program where the RAMS-I factors are managed throughout the system lifecycle.

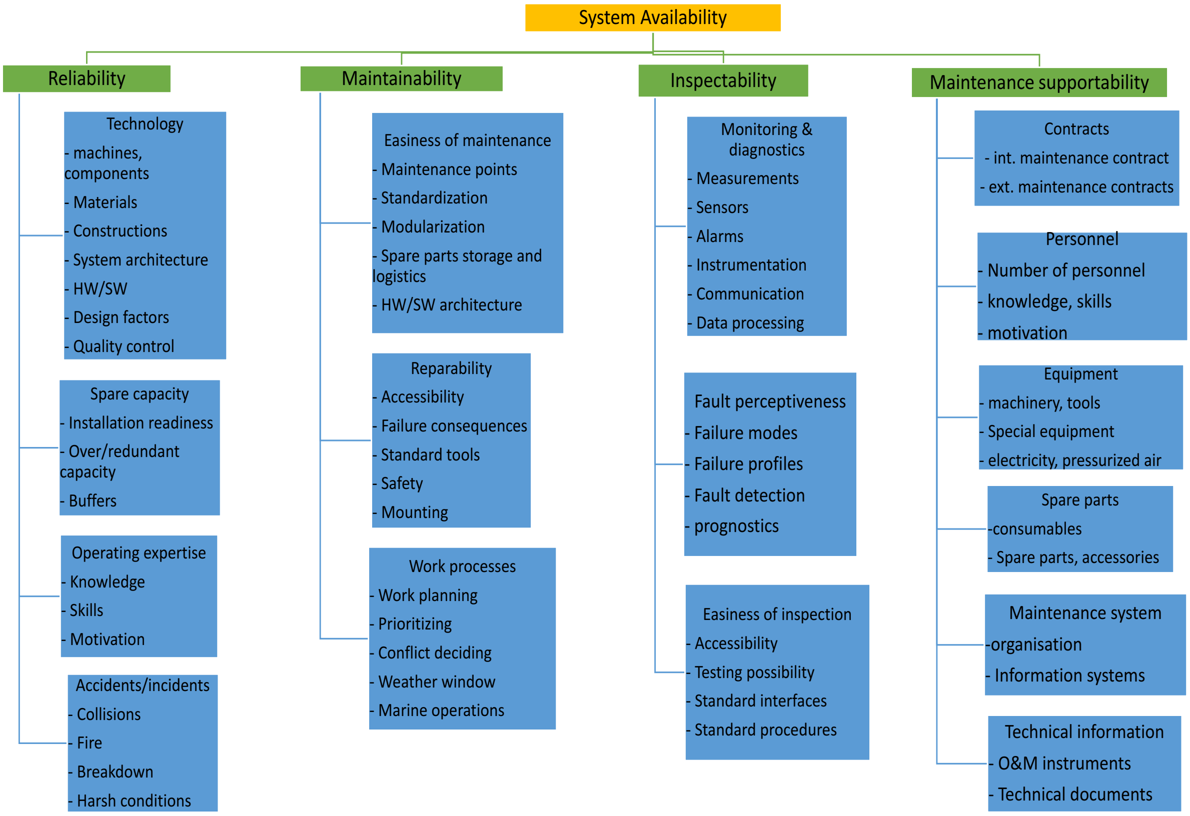


Figure 14 Factors affecting system availability in offshore wind assets in the Nordic context. (Tiusanen, et al., 2012)

2.3.3 *Asset condition and state*

Wind turbine and wind energy system´s reliability and availability are central in reaching, and hopefully exceeding, targets on production and thus income of an offshore wind farm. Structural health monitoring and condition monitoring are vital in this regard. Condition monitoring techniques and methods on wind turbines are presented by Márquez, et al. (2012). Sensory signals and signal processing methods are listed as statistical methods, time domain analysis, cepstrum analysis, fast Fourier transformation, amplitude demodulation, wavelet transformation, hidden Markov models and novel techniques. While condition monitoring can be done through techniques such as, vibration, acoustic emission, ultrasonic techniques, oil analysis, strain, electrical effects, shock pulse methods, process parameters, performance monitoring, radiographic inspection, thermography and other. Márquez, et al. (2012) state that, with good data acquisition and appropriate signal processing, faults can be detected while components are operational and appropriate actions can be planned in time to prevent damage or failure to components. For each part or component of the wind turbine there are different methods and techniques possible to make use of. Challenges or obstacles in this regard are identified by Márquez, et al. (2012) as selection of number and type of sensors, selection of effective signal processing methods, design of an effective fusion model combining sensors and signal processing methods.

In their research article, Antoniadou, et al. (2015) discussed advanced signal processing and machine learning methods for SHM and CM, an initial exploration of SCADA systems data of an offshore wind farm, and data-driven approaches for detecting abnormal behaviour of wind turbines. Antoniadou, et al. (2015) concluded that different kinds of data are needed to achieve an effective damage detection strategy, with data-driven vibration-based analysis as a potential solution. Further, the choice of an applicable and reliable sensing system for certain components is emphasized. Additionally, the potential for pattern recognitions and machine learning approaches is identified to not only be relevant to the SHM procedure but also for the manipulation of SCADA data (Antoniadou, et al., 2015).

2.3.4 *Asset databases and data integration*

Raconteur (2017) lists the techniques and methods most often used to capture asset data as: incident-monitoring systems, paper format, condition-monitoring systems, automated logging systems, mandatory fields for incident logging, handheld devices for incident logging and statistical sampling techniques. According to Asgarpour & Sorensen (2016) an initial maintenance strategy could be updated and optimized to reduce O&M costs through an O&M optimizer. In an O&M optimizer, the input data for the maintenance model are defined by all operational data such as, SCADA data, maintenance and inspection logs and condition monitoring data. Furthermore, should the output of the model be the optimal maintenance strategy to achieve the lowest O&M costs, instead of only average costs and downtime reports (Asgarpour & Sorensen, 2016). Asgarpour & Sorensen (2016) further present a framework for an ideal O&M optimizer where the main modules are a reliability model, decision model, cost model and output. The output of the O&M optimizer would be an optimal inspection, monitoring, and preventative plan.

Currently available wind turbine databases are WMEP, LWK with further databases from VTT and Elforsk (Hameed, et al., 2011). In addition to this there is a dedicated RAMS database, OREDA (Offshore Reliability Data) for the oil and gas industry, that together with WMEP provided the foundation for Hameed, et al. (2011) when they developed a dedicated RAMS database for offshore wind turbines. Hameed, et al. (2011) state that a RAMS database is necessary to enable the assessment of RAMS for critical component and to provide decision support. In the proposed RAMS database, the inputs are operational data, equipment data, failure data, maintenance data and state information. This data is combined with experience from OREDA and from onshore and offshore wind turbines. Furthermore, are some areas where the RAMS database could be employed are, but not limited to: O&M strategies, design/manufacturing, Life cycle cost, and qualification for new technologies (Hameed, et al., 2011). This can be seen in the figure below.

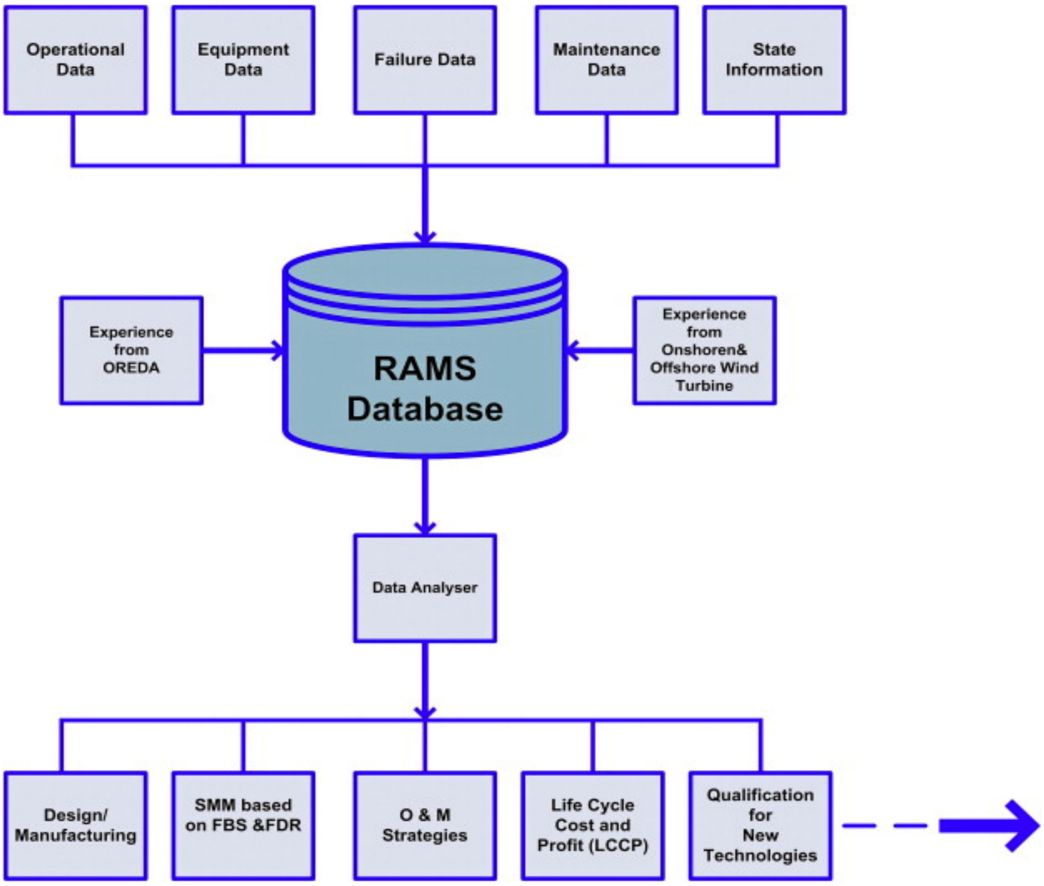


Figure 15 Schematic presentation of the proposed RAMS database (Hameed, et al., 2011)

According to Nguyen, et al. (2013), the onshore support system and its sub-systems will perform a multi-function for service technology and management development, and states that a key improvement of the O&M activities in offshore wind is the implementation of remote operations. Following are a list of optimization opportunities:

- concerted control of the entire wind farm
- system-level design and analysis approach for turbines and plants to optimize wind turbine technology, installation and O&M procedures.
- control of wear, abling risk/reliability based operation/maintenance can be scheduled at preferred time periods.
- control of power production for maximizing economic outcome (Nguyen, et al., 2013)

Following this, a unified system is essential as a way of integrating and handling data from different sources with different formats, and Nguyen, et al (2013) present a framework for data integration of offshore wind farms. A part of this development involves identifying what type of information is essential for example equipment information, discrete state information, analogue state information, control information, historical information, and descriptive information. Sharing this information and making it unambiguous for all stakeholders is vital. Nguyen, et al (2013) therefore use a semantic model to share the common understanding of domain concepts and create an offshore wind ontology to share and reuse knowledge and reasoning as the core of the model. The framework also consists of data source handling and information provisioning. The data source handling architecture comprises of three sections, communication integration, service integration and enterprise service bus. The information provisioning part is to provide efficient ways to access reliable data, mechanisms to reuse existing applications when new are introduced and ensure reusability of new applications (Nguyen, et al., 2013).

2.3.5 *Logistics and vessels*

Logistics and supply chain management of operation and maintenance is another very critical task in the offshore wind industry. Marine logistics is, beside wind turbine reliability, the most important limitation for wind turbine service, repair and replacement (Endrerud, et al., 2014). Endrerud, et al. (2014) state that in an average offshore wind park of 80 turbines there can be 2-4 failures per day needing marine logistics. In his paper Shafiee (2014) mapped maintenance logistics in offshore wind energy. Shafiee (2014) separated the issues and challenges in a threefold framework, strategic (long term), tactical (medium term) and operational (short term). In addition to this, a section of supplementary issues is mentioned that do not directly fit any of the other. Strategic issues regard decisions on wind farm design for reliability, location and capacity of on-site and off-site maintenance accommodations, selection of wind farm maintenance strategy and outsourcing of repair services. Tactical issues involve spare parts inventory management depending on the reliability and accessibility of offshore wind farms, the maintenance support organization such as vessels, crane ships and helicopters and purchasing or leasing decisions. Operational issues embrace issues such as scheduling of maintenance tasks, routing of maintenance vessels, and measuring the maintenance performance. The supplementary issues of importance to maintenance logistics are focused around RAM data availability; much of the data available in wind farm databases suffers from inaccuracy, inconsistency and incompleteness. Other factors contributing to supplementary issues are O&M costing, tools for forecasting wind and wave conditions, and information on environmental legislations (Shafiee, 2014).

Endrerud, et al. (2014) developed a multi method simulation tool to provide knowledge and to be used as a decision support tool for wind farm developers on how the offshore wind production system will work. Vessels provide services such as transport, installation and accommodation. The offshore vessels can be divided in to three sections: service, construction and maintenance, and survey, 4C Offshore (2017) provide a vessel database for subscribers. Aux-Navalia (2010) have created a comprehensive overview on different vessels and platform concepts for offshore wind. In their paper on new vessels concepts to tackle challenges within marine logistics for O&M of offshore wind farms, Endrerud, et al. (2015) show the importance of including internal logistics and operational procedures in simulations. Endrerud, et al. (2015) identified strengths and weaknesses to different vessel concepts and poses questions on marine logistics and vessels when wind farms are installed far offshore. Statoil (2017) expects that it will not be possible to use jack-up vessels for performing heavy maintenance on many of the future floating wind farm developments due to water depth limitations. In addition to this is it expected that using floating crane vessels for this type of maintenance is not economically nor practically viable due to long mobilization time, day rates and weather window.

2.4 Wind power asset management architecture

In their papers, El-Thalji & Liyanage ((2012) (2015),) describes the development process model, or the systems approach to an integrated architecture, as a six-step process. Firstly, one extracts the customer´s and stakeholder´s needs and then document specific requirements. Secondly, develop conceptual solutions, assess and select the best among them based on specific acceptance criteria. Thirdly, specifying the context and use-case scenarios, which are the elementary way in defining functional and non-functional requirements. Then from these requirements, the system functions and technical requirements are defined. Following this, the physical components are allocated and interfaces are configured with the outcome presented as functional, physical and interface architectures. Finally, architecture verification is performed where simulation appears to be the only practical way forward due to the functional, technical and operational complexity of the developed architecture (El-Thalji & Liyanage, 2012).

Following this systematic approach through the development process model, El-Thalji & Liyanage (2012) established an integrated architecture to manage offshore wind energy assets. The basic configuration for offshore wind power asset management architecture is depicted below in Figure 7 and consists of six modules or systems:

1. **Wind power asset.** This consists of all the physical assets and instruments that extract wind energy and deliver electricity to the grid such as grid connections, wind farm, wind mill and wind turbine.
2. **Onshore asset operating and control system.** This consists of remote control systems and actions. Their task is to monitor activities, data acquisition, analytical systems, expert systems, signal interpretation and risk-based decision support systems.
3. **Onshore support system**. Cover external expertise, logistics contractors and weather forecasting, equipment manufacturing and so forth.
4. **Offshore support system.** This system covers marine operations, maintenance management systems, support vessels management and logistics and O&M crew.
5. **Work process management system.** Set of activities for planning and monitoring business processes.
6. **Engineering development systems**. include actual work related matters, as well as enabling elements to further develop and operate the asset (El-Thalji & Liyanage, 2012; El-Thalji & Liyanage, 2010)

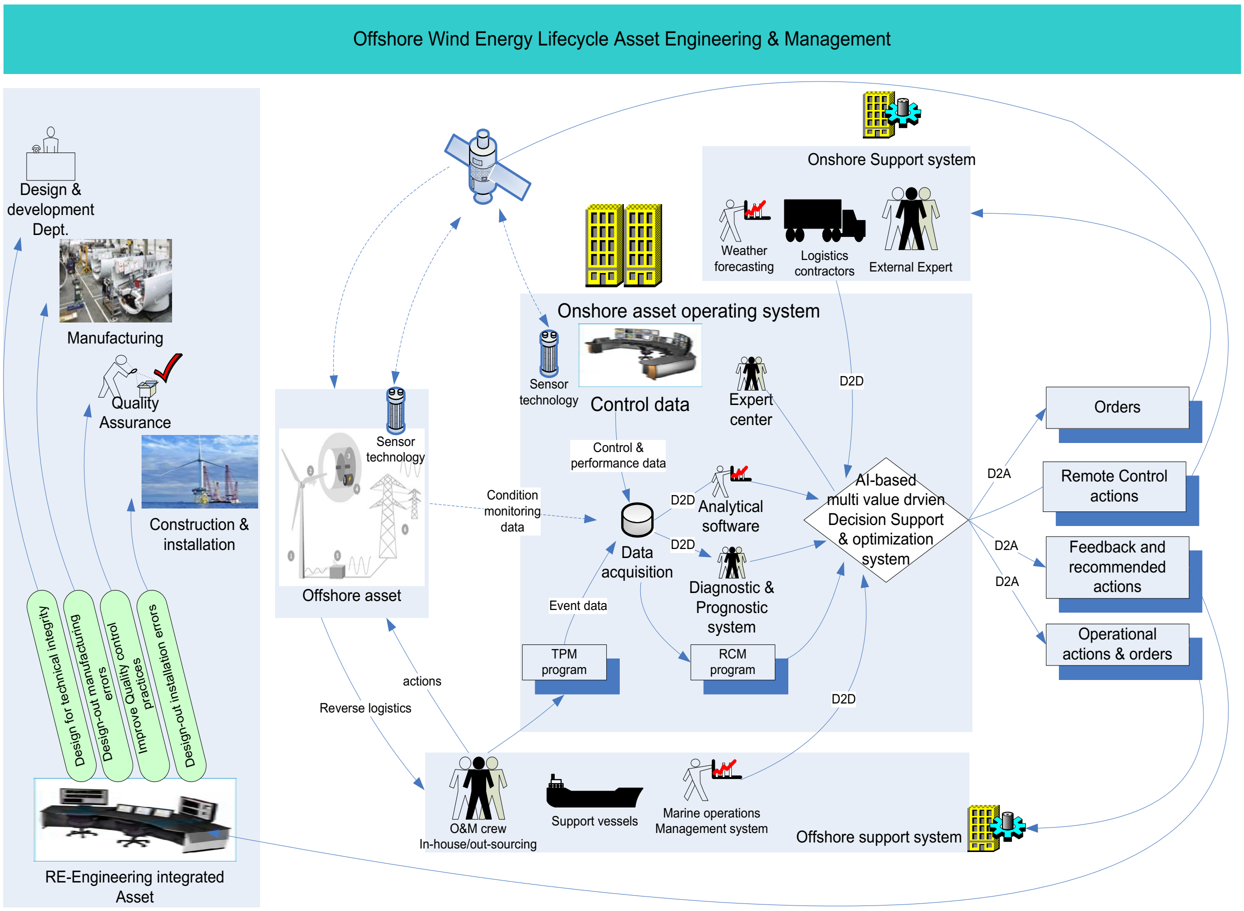


Figure 16 Basic configuration for offshore wind power asset management architecture (El-Thalji & Liyanage, 2010)

After having established the infrastructure, system requirements with functional and physical decomposition is defined. “The physical system and its decompositions are based on generic functions of asset management system, that are also supported by an additional set of specific functions to make the generic function fit into the scope of the wind energy domain.” (El-Thalji & Liyanage, 2012, p. 5). In Table 1, an overview of the identified main functions with sub-functions and the corresponding physical and interface items are displayed. The take from the table is the large amount of remote online interface items and the different systems utilized under physical items posing a challenge for proper integration amongst modules and a well-founded decision support system.

Integrated management system: Functions and physical decompositions				
	Main function	**Sub-functions**	**Physical Items**	**Interface Items**
Wind power ass	Generate	Extract energy	Aerodynamic system	
		Accelerate speed	Gearbox	
		Generate	Generator	
	Support	Bear generation system	Structure	
		Protect	Nacelle	
		Yawing	Yaw system	
		Pitching	Pitch system	
		Control	SCADA	
		Monitoring	CMS	
Onshore operating systı	Manage technical data	Manage SCADA data	SCADA analysis system	Remote control
		Manage CMS data	CMS	Remote monitoring
		Manage O&M reports	CMMS	
	Identify situation	Collect real-time data	Asset operator/maintainer	D2D
		Perform rapid analysis techniques	Control Centre	Mobile connection to asset operator
		Perform detailed analysis	Expert system	Real-time online to expert centre
		Perform prognostic analysis techniques	Intelligent diagnostic & prognostic system	
	Provide solution	Perform maintenance optimization techniques	Intelligent maintenance decision support system	
		Take decision	Asset manager	D2A
		Plan and schedule	Asset maintainer	Real-time online
Onshore suppo	Support	Technical & engineering support	External experts	Real-time online
		Provide collaborative solutions	Offshore/onshore expert centre	Real-time online
	Supply	Supply equipment	Equipment management	Real-time online
		Supply spareparts	Spare part management system	Real-time online connection to CMMS
Offshore support systı	Offshore technical support	Determine maintenance window	Weather forecasting centre	Real-time online
		Determine maintnance readiness	Emergency planning module	Remote online
	Support logistics	Determine maintenance accessibility readiness	Offshore logisitic system	Remote online
	Outsource	Service	External service contractor	Remote online
		Equipment supply	External service contractor	Remote online
Work process & (Re) Engineer	Define & assess conditions	Define & assess asset condition standards	Standards & metrics centre	International & National standards system
	Plan	Plan asset condition inspection process	Asset planning & scheduling system	Physical & remote access to asset
	Audit	Audit asset management	Asset auditing system	Physical access
	Assess risks	Assess the operation risk of asset	Asset analysis & prediction system	Real-time online to onshore/offshore asset prediction conditions
	Record, analyse and report	Short & long term findings	Computerized Asset management system	Real-time online connection to all modules
	Assess performance	Assess asset performance	Asset assessment system	Real-time online connection to all control and supportive modules

Table 1 Integrated management functions (El-Thalji & Liyanage, 2012)

2.4.1 *Management system physical interface*

With the established systems perspective for asset management within offshore wind, El-Thalji & Liyanage (2015) further explored the system pitfalls that impact complex engineering asset management within the industry. Among several findings, they identified difficulties due to the systems´ interfaces. Physical interface effects identified in El-Thalji & Liyanage´s (2015) study returned a physical interface diagram for wind power asset management system, Figure 17. Their main results and observations where:

- The main interface with the enterprise system-level is the remote control and communication due to the geographical distance between sub-systems
- The diagram highlights the information of life-cycle processes: capturing, transferring, documenting, analysing and updating. In addition to that, the input/output of sub-systems represent the information creator-user relationships
- The diagram shows individual-assessed databases which need to be integrated and responsibly shared. (El-Thalji & Liyanage, 2015)

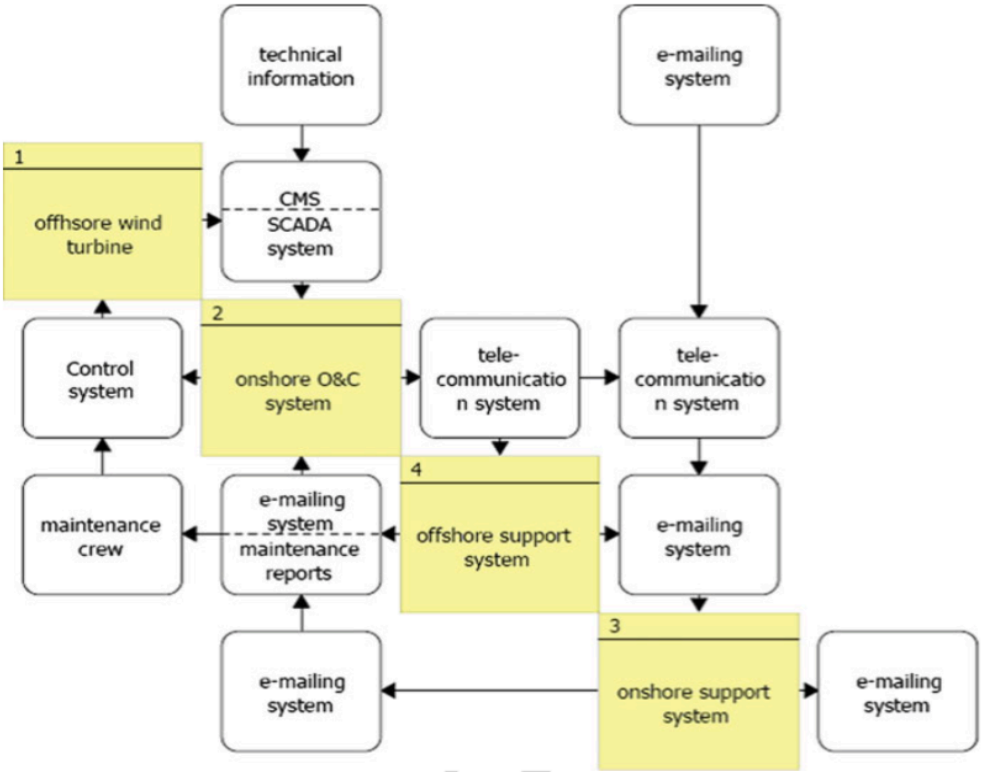


Figure 17 Physical interface diagram for wind power asset management system (El-Thalji & Liyanage, 2015)

2.5 Trends in offshore wind

The largest trends within offshore wind industry are on turbines, depth and distance. Over the past decade the rated capacity of turbines increased 62% and the average rated capacity installed in 2016 was 4,8MW. 2016 was the first year when wind turbines at a capcity of 8MW where installed (WindEurope, 2016) and Siemens are currently looking towards windturbines at a capcity above 10MW (Steel, 2015). This has its implications on the size of the windfarms with the 1,2 GW Hornsea One project as the largest to be developed in near future. The water depth and distance to shore is also increasing. The range varies from 5-20 meter depth of online wind farms at a distance to shore of below 50 km to 30-45 meters water depth for new projects at a distance to shore of over 200 km. The 2016 average was water depth at 29,2m and distance to shore at 43,5 km (WindEurope, 2016). Going further from shore implies greater water depth and with a depth limitation on monopiles at around 40-50 meters, this leads up to an era of deep-water solutions for projects far offshore.

In their paper, Valpy & English (2014) present an overview of how technology innovation is anticipated to reduce the cost of energy from European offshore wind farms. Their sections are split between innovations within wind farm development, nacelle, rotor, balance of plant, construction and commissioning and wind farm operation, maintenance and service (OMS). According to Valpy & English (2014), the three biggest innovations in OMS are: a move to holistic, condition-based maintenance, with reduced downtime and frequency of large component retrofits; improvements in the transfer of personnel from vessel to turbine and improvements in holistic wind farm control. Each will have the biggest impact on far-from-shore projects which involve greater transit distances and more severe sea conditions.

Yaramasu, et al. (2015) classified technical trends in wind energy conversion systems into mechanical technologies, electrical technologies, integration to power systems and control theory. With respect to mechanical technologies, the focus is on:

- further development on the gear box and drive train and light weight components
- further developments in the wind turbine blades sandwich technology and the importance to improve aerodynamic efficiency
- floating foundations show promising results on deeper water, whilst on shallow water there are research on several solutions such as gravity, monopile, tripod, tripile and jacket.

On trends in electrical technologies Yaramasu, et al. (2015) state that squirrel cage induction generator or synchronous generator will dominate because of increasing conversion efficiency and meeting of various grid codes without extra hardware. The industry is looking towards alternative generator configurations with a higher power density, where high temperature super conducting (HTS) synchronous generators are mentioned. New semiconductor switching devices can improve energy conversion, with new devices able to operate at higher temperatures, power densities, voltages and switching frequencies. The power electronics technology are a major source of failure and cause for downtime on wind turbines, and according to Yaramasu, et al. (2015) there will be a reliability improvement of power converters, parallel to the introduction of new converters.

Trends in integration to power systems consider changes to policies and grid code requirements and since offshore wind farms are planned in GW range and at deep sea, cost, size, reliability and efficiency of interconnection approaches become crucial. HVDC transmission will take over the current HVAC transmission and that power converters for HVDC applications will be subject to research and development (Yaramasu, et al., 2015). On trends in control theory Yaramasu, et al. (2015) write that finite control-set model predictive control (FCS-MPC) strategy eliminates the need for linear regulators and modulators. Despite the higher computational burden of introducing predictive control, modern digital signal processors can perform large amount of calculations at low cost. There is potential further development and the authors list several control solutions and schemes for power conversion where research and advancements are being made.

The view that data is an increasingly valuable asset, is being more and more recognized also within the offshore wind industry. Knight (2016) refers to Andreas Reuter´s statement that digitalization, big data and the IIoT will become much more significant than technical questions like whether a turbine has a gearbox or not. Some of the advantages when having reached the desired digital level or environment are: optimizing service schedules, control over individual turbines and their components, adapting asset output to optimize earnings, running wind farms within micro grids, integrating with industrial manufacturing processes and so forth (Knight, 2016). In more generic terms, identified trends within data management are:

- the rise of self service – businesses rapidly combining and analysing their own data in a user-friendly way
- the need for an open platform – input from different internal and external sources are needed to gain insights
- suggestive data management – modern data management tools make use of analytics to improve data management (SAS, 2016)

2.6 Statoil´s New Energy Solutions engagement

Statoil is a Norwegian-based energy company that aims to turn natural resources into energy for people and progress for society (Statoil, 2017) Statoil´s organisation engaged within the renewable energy segment of the energy mix is simply called New Energy Solutions (NES). NES expects a strong demand growth for renewables over the next few decades. While their ambitions are to grow profitably and potentially expand into a set of sources of renewable energy, their largest focus to date is to create value and growth within markets such as carbon capture and storage and offshore wind. Statoil New Energy Ventures, invests in renewable energy growth companies and currently their investments range from onshore wind energy leasing solutions (via electric vehicle charging company) to solar technology (Statoil, 2017)

Statoil has interests in four large-scale conventional wind projects off the coast of Europe: Sheringham Shoal and Dogger Bank in UK and Arkona in Germany, and are operator of the Dudgeon wind farm offshore UK that is currently under construction (Statoil, 2017). The Dudgeon wind farm, when fully installed consist of 67 turbines, each of 6MW resulting in an installed capacity of 402MW (Dudgeon Offshore Wind Farm, 2017). Statoil is pioneering this industry and currently building the world´s first floating wind farm offshore Scotland (Statoil, 2017). The Hywind Pilot Park is set to start production in 2017, and consists of 5 6MW turbines with an installed capacity of 30 MW with the objective to demonstrate the feasibility of future commercial utility-scale floating wind farms (Statoil, 2015). If proven successful this will further increase the areas and locations of potential offshore wind farm developments, and the race to build floating offshore wind farms will increasingly gather pace (Shankleman, 2017).

Statoil's engagement on floating offshore wind is not only due to their large experience of offshore technologies. Today, bottom fixed offshore wind turbines have a limitation of water depths down to approximately 40-50 meters, however floating wind can be installed at water depths from over 50 to 500 meters or more. Offshore wind is rapidly becoming subsidy free and a real alternative to conventional power. It is expected that the costs will continue to decline, which in return also will affect the costs of floating offshore wind. There is ongoing research on using storage solutions linked to offshore wind to mitigate intermittency, improve efficiency and lower costs when it comes to exporting power (Bringsværd, 2017).

2.6.1 Sheringham Shoal O&M Centre

The O&M Base related to the Sheringham Shoal is named Wind Farm Place and it is here that all O&M activities are planned and coordinated, and where the storage facility is located, just outside Wells-at-the-Sea in UK. Wind Farm Place is where the technicians transfer offshore and where all field logistics are coordinated from. The marine coordination team monitors the weather condition from three weather forecasting systems and monitors movements of personnel and vessels offshore through automatic identification systems (AIS). Vessels in field-contact is maintained through VHF Radio and vital communication lines are constantly available through advanced IT equipment (SCIRA, 2017).

To maintain turbines Siemens have acquired a five-year service contract where they employ 40 technicians totalling up to 50 people, including office based maintenance planners and administrative staff. Every year each of the 88 turbines get a full service by the Siemens team – oil changes, gearbox and generator alignment and filter replacements. Service involves a four-person team and takes four to five days to complete. Siemens also monitor the wind farm 24/7, making sure that corrective maintenance is made when due through using SCADA system (SCIRA, 2017)

2.6.2 *Dudgeon and Hywind Scotland O&M Centre*

The Dudgeon Operations Centre is situated in Great Yarmouth and when in full operative mode during 2017 there will be 70 people working full time with O&M on the wind farm at the onshore base or at the offshore site. Esvagt Njord is a purpose build vessel that can accommodate up to 40 wind turbine technicians. The Dudgeon Operations Centre also provides Hywind Scotland with technical O&M support and control room services (Dudgeon Offshore Wind, 2016).

2.6.3 *Statoil's Digital Engagement*

In 2015, Statoil launched the initiative GoDigital to address the topic of digitalization and the strategic context for Statoil. The outcome from this initiative was: a need to understand their strengths and opportunities in applying digital technologies, learn as much as possible from others, engaging the business to create commitment and understanding and set up pilots to demonstrate the potential of digitalizing. In addition to this was the initiative TSB25D launched with the intention to create knowledgeable digital ambassadors (Larsen, 2017).

Recently, Statoil announced that they intend to invest up to 2 billion NOK on digitalization towards 2020 and shall establish a digital centre of excellence to coordinate and manage the digitalization process across the company, using information from their prior initiatives. This engagement is focused around three areas; digitalization of work processes, advanced analysis of data, and robotization and remote operations (Stangeland, 2017; Ånestad, 2017). Although the major area within Statoil is oil and gas, focus points such as digital safety, sustainability, process, data-driven operations, and commercial insight is seen to also have a relevance to the offshore wind sector. It is not unreasonable to expect this sector of Statoil to also reap the benefits of this investment decision and digitalization outcome.

Operational Excellence within Statoil is a companywide program where all data and analytics is conducted as a support function to existing assets. With respect to offshore wind, Operational Excellence is involved in both the planning phase and O&M phase, where they can estimate downtime, OPEX, availability, production etc. based on existing assets and learning.

Today Statoil use several different software systems in managing their offshore wind operations. These systems do not interact optimally with each other, they are siloed in the way that if an event is registered in one system, this does not necessarily show in any of the other systems. Statoil utilize SAP for their enterprise resource planning solutions where notifications and work-orders are generated when there are faults on a wind turbine. The future target, both on Sheringham Shoal and Dudgeon, is that these notifications are sent to onshore storage where spare parts, tools, technicians and vessels are ordered in one integrated process. Today however, the solution is still very similar as described in the physical interface diagram above, with email notifications and dispersed processes. ProCoSys, project completion system, is used for life cycle information and is where all as-built information is stored. In addition to this, Statoil use the wind farm management system from Bazefield Technologies. This monitors the entire windfarm and provide Statoil with simple analytics. Bazefield Technologies (2017) provide products involving monitoring, analytics and operations management. There are several different systems in use today, and Statoil are working on a more integrated solution maybe in combination with cloud service, however it still seems difficult to break open the silos.

Section 2: Smart Connected Systems and Industry 4.0 Technologies

This section focus on establishing the theoretical foundation related to digitalization and smart connected systems. In addition to this, a review of technologies encompassed by the Industry 4.0 concept has been conducted.

3 Understanding the buzzwords

Digitalization is a buzzword with a vague meaning to most people. Depending on the industry and situation, it could encompass different concepts and technologies. For the offshore wind industry to further develop and establish themselves as a renewable energy, with a truly competitive argument compared to other energy solutions, it need to embrace the rapid technological climate of today. The challenges to offshore wind are large and many; digitalizing in the right manner could be the breakthrough to offshore wind that one has been waiting for. Creating a digital wind farm (a smart connected system) where all the modules of an offshore wind farm system contribute to each other, combining different data sources and utilizing new software solutions, is the future state the industry seems to be striving for. This chapter focus on establishing an understanding of different terms such as digitizing, digitalizing and digital transformation. In addition to this, the concepts of Industry 4.0, Internet of Things, Industrial Internet of Things, smart connected products and smart connected systems are explained.

3.1 Data

"Writing" was the world´s first data-processing system invented by the Sumerians some 5000 years ago. About at the same time, this also happened in Egypt, with China and Central America following some thousands of years later. What enabled the languages of the Sumer, Egyptians, Chinese and Incas to flourish was their ability to develop good techniques of archiving, cataloguing and retrieving written records. In the event of Arabic numerals, the basis of modern mathematical notation became established, with the mathematical script now being the world´s leading language, and have more recently given rise to the computerized binary script (Harari, 2016).

The digitization of operations began in the 1960s and 70s with basic transactional systems. Good techniques for archiving, cataloguing and retrieving data were continuously being improved and this accelerated with the introduction of PCs, e-mail, and online systems in the 1980s and 90s (Westerman, et al., 2014). With the increase in computer storage, processing power and wireless connectivity in the aftermath of the third industrial revolution, (focus on automation of single machines and processes) we expanded our capabilities and leaped forward in the 2000s with mobile phones, ubiquitous internet and cheap global communications (Westerman, et al., 2014; PWC, 2016). Now it is poised to accelerate even faster through technologies such as advanced analytics (Seehusen, 2016;

GE, 2017; IBM, 2017), IoT, smart sensors, 3-D printing, voice and translation technologies and flexible robotics (Westerman, et al., 2014).

To understand what digitalization is, it´s equally important to know what it is not. The terms digital transformation and digitization are often incorrectly used interchangeably (i-SCOOP, 2017). Having an idea of what digitalization is will only get you so far, and being able to separate the terms is vital when understanding and explaining what digitalization is and what possibilities it creates. People would probably tell you that digitalization has something to do with data, processing, computers and the Internet. What they might not tell you is: to be able to digitalize, we must have digitized first.

3.2 Digitization

The binary language of 0´s and 1´s developed by Leibniz in late 1600s (Walter, 2014) created the basis of machine language and are key to our ability to further digitally transform society and industry. The computerized binary script has enabled the creation of a digital version of analogue/physical things such as paper documents, microfilm images, photographs, sounds and more (i-SCOOP, 2017). This process of converting data from analogue to digital is digitization. Oxford English Dictionary explains digitization as “the action or process of digitizing, the conversion of analogue data into digital form” (Peters, 2016). According to i-SCOOP (2017), digitizing also includes the perspective of processes, and defines digitization as conversion from analogue to digital (or digital representation of a physical item) with the goal to digitize and automate processes and workflow. McAfee (2010) takes on a broader approach and define digitization as “the transformation of business activities by the introduction and use of information technology”. Kagermann (2015) are in line with McAfee´s view and defines digitization as “the networking of people and things and the convergence of the real and virtual worlds that is enabled by information and communication technology (ICT)”.

3.3 Digitalization

Digitalization is, according to Peters (2016), defined by Oxford English Dictionary as the adoption or increase in use of digital or computer technology by an organization, industry, country etc. Furthermore, allows digitalization us to use our automated processes and digital technology and use gathered data to improve our business outcomes. Further, by gathering data and using the derived information in real time, enables informed decision-making ability throughout the business (Peters, 2016). Digitalization according to EY (2015) means that companies are digitalizing their horizontal and vertical value chains. The vertical value chain includes operations where the company´s functions such as marketing, sales, purchasing, product development, manufacturing and distribution are linked and integrated via a digital information flow. The horizontal value chain involves the suppliers and customers (EY, 2015).

i-SCOOP (2017) explains that, depending on different perspectives, digitalization can be understood or defined in three different ways. Firstly, business define digitalization as

> *"enabling, improving and/or transforming business operations and/or business functions and or business models/processes and/or activities, by leveraging digital technologies and a broader use and context of digitized data, turned into actionable, knowledge with a specific benefit in mind."* (i-SCOOP, 2017)

Secondly, digitalization could mean something different to a specific area or environment of the business, such as the digital workplace. Meaning that the workforce is operating differently with digital tools and systems enabling them to work in a more digital way, and this requires more than just digitized data (i-SCOOP, 2017). This seems also to be the view of Mäenpää & Korhonen (2015) who explain that there are different active players with different views and definitions; the "pure digitals" (to which digitalization provides an existence) and more conservative companies (to which digitalization is a means that may open new opportunities). The former will promote digitalization and the latter may have their primary focus elsewhere, other than on the digitalization process (Mäenpää & Korhonen, 2015). Thirdly, digitalization can have a meaning that stretches beyond business which refers to the ongoing adaption of digital technologies across all social and human activities (i-SCOOP, 2017).

Sannes (2016) define "*digitalisering*" as the transformation from IT being a support tool in the business to it being a part of the business´ DNA. Meaning that the business model, organization and processes are designed with respect to exploit todays and tomorrows technology. Sannes (2016) also write that some would claim that digitalization is merely using digital technology, while others believe it to mean digitizing manual processes.

When asked the question: "*How are you using digitalization to cut costs?*", by Wind Power Monthly (2016) during WindEnergy Hamburg 2016, Edward Wagner, CDO of Sentient Science responded:

> *"Digitalization is about getting information from the assets that we have, and using that information to drive the cost of energy downwards. Once you have digital information you can do supply chain integration, you can lower the cost of financing, you can improve O&M, but you have to be able to use the data to your advantage. This is a data driven application, we think only by having that data, simulating, doing what-if studies, and making sure you get it right before you actually climb that turbine to do work. Make sure you do it in a digital environment so you make sure you get it right before you do it".* (WindPowerMonthly, 2016)

While Michael Lewis, E.ON Climate & Renewables GmbH responded:

> *"For us digitalization is all about getting the right data so that we understand how our turbines are performing, how we can improve that performance, both in the short run and in the long run. And digitalization will allow us to have the right data, in the right time, in the right format so we can drive improvements in costs and performance"* (WindPowerMonthly, 2016).

From the comments, digitalization is about getting the right data and information and then analysing this information to get an advantage. This approach is wider and relies on further technological development than the definitions above where digitalization is largely defined as a change of business, increased use or adaption of technology or an increased connectivity among products. Digitalization is - whether using a broad or a narrow definition - dependent on both information technology and operation technology.

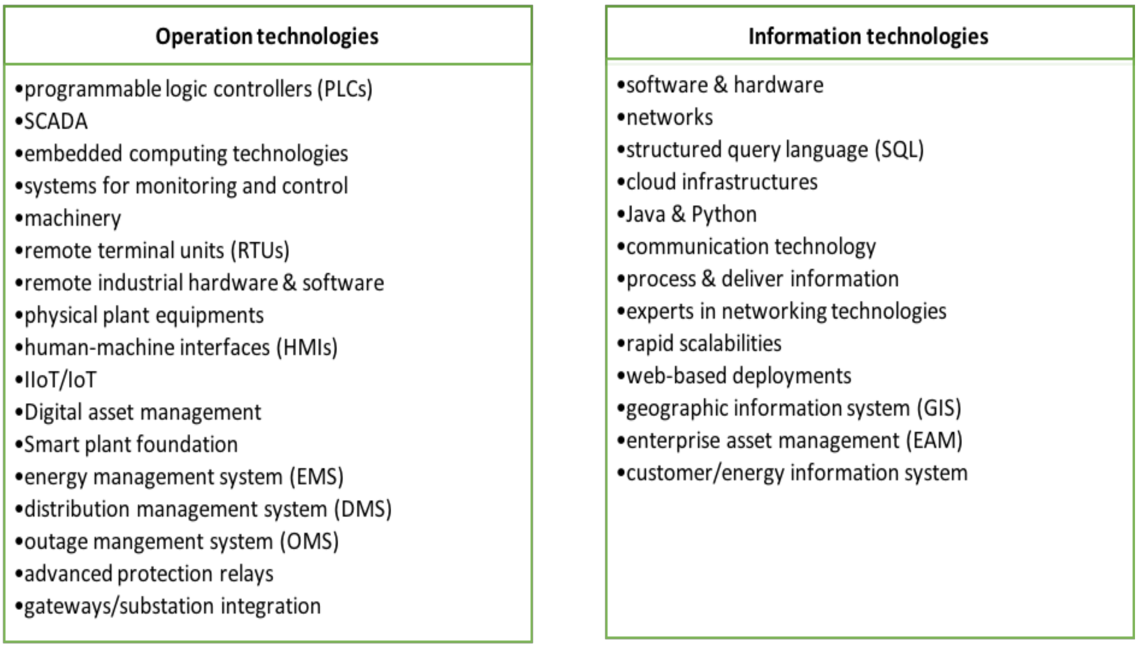
3.3.1 *Information Technology*

According to Nature (2017), information technology is the design and implementation of computer networks for data processing and communication. This includes designing the hardware for processing information and connecting separate components, and developing software that can efficiently and faultlessly analyse and distribute this data (Nature, 2017). Atos (2012) explain information technology as combining all necessary technologies for information processing. Carbo (2013) list some applications of IT, such as geographic info system (GIS), Enterprise asset management (EAM) and customer/energy information system (CIS). Carbo´s (2013) IT world focuses on that the data history goes back more than one year and comprises of business real-time, model of asset structure, business content data. Inductive Automation (2016) list software & hardware, networks, SQL (structured query language), cloud infrastructures, Java & Python (programming software), communication technologies, store process & deliver information, experts in networking technologies, rapid scalabilities and web-based deployments as information technology.

3.3.2 *Operational Technology*

Gartner (2017) defines operational technology (OT) as hardware and software that detects or causes change through the direct monitoring and control of physical devices, processes and events in the enterprise. Atos (2012) explains OT as supporting physical value creation and manufacturing processes and that it comprises the devices, sensors and software necessary to control and monitor plant and equipment. Atos (2012) further defines OT as acting in real time on physical operational systems and lists OT elements such as SCADA, meters, sensors and motors. IBM (2017) states that OT is an independent world of physical, equipment-oriented technology developed, implemented and supported separately from IT groups. IBM (2017) further explains OT as including the application of analytics for streaming real-time data, both structured and unstructured, to make faster and better decisions.

OT is about translating volumes of data into models to increase predictivity through using tools such as next generation optimization, supply chain, visualization, pattern recognition, cognitive computing and competitive intelligence (IBM, 2017). OT is also about using this data, information and intelligence throughout the enterprise to improve operability, reliability and performance of plant and personnel while lowering costs (IBM, 2017). IBM (2017) lists SmartPlant Foundation, Internet of Things, Industrial Internet and Digital Asset Management as some operational technologies that are creating value for operations. Other OTs listed by Carbo (2013) are energy management systems (EMS), distribution management systems (DMS), outage management systems (OMS), advanced protection relays and gateways/substation integration. Carbo´s (2013) OT world focus on data history that goes back less than one year and comprises of real-time process control, tag IDs, and time series data. Inductive Automation (2016) lists SCADA software, PLCs, Embedded computing technologies, systems for monitoring and controlling, machinery, RTUs, remote industrial hardware and software, physical plant equipment and HMIs as operational technology. These information and operation technologies are listed below to provide an overview.



Operation technologies	Information technologies
•programmable logic controllers (PLCs)	•software & hardware
•SCADA	•networks
•embedded computing technologies	•structured query language (SQL)
•systems for monitoring and control	•cloud infrastructures
•machinery	•Java & Python
•remote terminal units (RTUs)	•communication technology
•remote industrial hardware & software	•process & deliver information
•physical plant equipments	•experts in networking technologies
•human-machine interfaces (HMIs)	•rapid scalabilities
•IIoT/IoT	•web-based deployments
•Digital asset management	•geographic information system (GIS)
•Smart plant foundation	•enterprise asset management (EAM)
•energy management system (EMS)	•customer/energy information system
•distribution management system (DMS)	
•outage mangement system (OMS)	
•advanced protection relays	
•gateways/substation integration	

Table 2 Operation & Information Technology

3.4 Digital transformation

In addition to digitization and digitalization is the term digital transformation. Collin (2015) combines two of the terms and describes digitalization and digital transformation as a fast-moving, global megatrend that is fundamentally changing existing value chains across industries and public sectors. Collin (2015) links the following terms to digital transformation: Big Data, Internet of Things, Industrial Internet, Industry 4.0, Machine-to-machine and Mobile Apps. Capgemini (2011) defines digital transformation as the use of technology to radically improve performance or reach of enterprises. Due to the large variety of interpretations on the meaning of the different terms (i-SCOOP, 2017; Peters, 2016; Kreiss & Brennen, 2014; Collin, 2015; Kagermann, 2015; McAfee, 2010) it can be challenging to be able to separate digitization, digitalization and digital transformation as well as to be consistent when using them. The interchangeable use of terms is also observable in the wind industry, for instance, where Siemens (2017) utilize *digitalization* and GE (2017) coined the term *Digital Industrial Transformation,* two terms that are understood to have somewhat the same meaning with respect to the companies´ services within the wind energy sector.

The take from the wide range of different interpretations and definitions is that there´s no surprise that an interchangeable use of the terms is made. One person might write digitization and the other digitalization but both understand it principally to be the same, while a third person might call it digital transformation. Avoiding this interchangeable use of the terms is a challenge and one might argue that using them interchangeably will do no harm. However, the author believes that there is a vital distinction between the terms and that the reason of interchangeable use is largely due to confusion. Below is a simple suggestion, based on the above, of how the three terms could be better understood.

Digitizing is understood as the conversion of analogue data to digital form. *Digitalization* is understood as the increased use of digital technology in an organization, it is the utilization of software to get the most out of your hardware (both are in line with the definition from Oxford English Dictionary provided by Peters (2016)). *Digital transformation* is understood as the continuously forward-moving future state a company would want as the desired outcome or state (Younker, 1993) through the process of first digitizing and then digitalizing. This future state, that some companies have already reached, are described by Westerman, Bonnet and McAfee (2014) as Digital Masters. Digital Masters are companies that find themselves in a state where they excel at both digital and leading capabilities and knowingly uses digital technologies to drive significantly higher levels of profits, productivity and performance (Westerman, et al., 2014). This also follows Capgemini (2011) definition, using technology to radically improve performance and reach.

3.5 Internet of Things, Industrial Internet of Things and Industry 4.0

Even though Industry 4.0, Internet of Things and Industrial Internet of Things are terms easier to separate than digitizing and digitalizing, these terms are also interchangeably used. “This emergence of machine-to-machine interactions, human-to-machine interactions, robust data and analytics capabilities, and cheaper more ubiquitous sensors are variously called Industry 4.0, Industrial Internet, digitization, digitalization and IoT” (Alvarez, et al., 2016, p. 5). Below is an attempt to differentiate between Industry 4.0, Internet of Things and Industrial Internet of things.

3.5.1 *The Industry 4.0 concept*

Industry 4.0, Smart manufacturing (Porter & Heppelmann, 2015) or Industrie 4.0 started as German industry´s vision for the future of manufacturing, where smart factories use information and communications technologies to digitalize their processes to gain higher profits from improved quality, increased efficiency and lower costs (Zaske, 2015, p. 1). Industry 4.0 is the future expectation of an advanced digitalization within factories, the fourth industrial revolution, following the first industrial revolution (mechanization), the second industrial revolution (intensive use of electrical energy), and the third industrial revolution (widespread digitization) (Lasi, et al., 2014). According to Roblek et.al (2016), one cannot only limit the Industry 4.0 thinking or approach to robotics and the automation of production, because Industry 4.0 is a digitalization of business processes involving the whole value chain. PWC (2016) also take on a view on Industry 4.0 that stretches beyond manufacturing, and believes it focuses on the end-to-end digitalization of all physical assets and integration into digital ecosystems with value chain partners. This comprehensive approach is also seen by Brynjolfsson & McAfee (2014), who believe that we are at an inflection point in the history of our economies and societies because of digitization and digitalization and that the key building blocks are in place for digital technologies to be as important and transformational as the steam engine which triggered the first machine age. However, Brynjolfsson & McAfee (2014) refer to this current time-period and future vision, not as the Industry 4.0, but as the second machine age.

Amongst different actors there are different views on what the Industry 4.0 concept includes. According to Rüßmann, et al. (2015), Industry 4.0 is powered by nine foundational technologies which they call The Nine Pillars of Technological Advancement: The Industrial Internet of Things, Big data and analytics, simulation, autonomous robots, augmented reality, additive manufacturing (AM), horizontal and vertical system integration, the cloud and cybersecurity. PWC´s (2016) Industry 4.0 framework, in addition to the ones listed by Rüßmann, et al. (2015) contains mobile devices, smart sensors, multilevel customer interaction/profiling, location detection technologies and advanced human-machine interfaces. Some of these, however, such as augmented reality and advanced human-machine interface are, arguably, closely connected.

3.5.2 *Internet of Things*

Internet of Things (IoT) is defined by Meola (2016) as a network of internet-connected objects able to collect and exchange data using embedded sensors. Gartner (2017) defines IoT as the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment. McKinsey (2015) define the IoT as sensors and actuators by networks to computing systems, and these systems can monitor or manage the health and actions of connected objects and machines. IBM (2017) explain IoT as a future Internet, and that the connected things will have self-configuring capabilities based on standard communication protocols, bringing real-time dynamics to otherwise static systems. According to BI Intelligence (2016) and Gartner (2013), the IoT will grow to 24-26 billion units installed in 2020. Existing IoT platforms include, amongst other, the GE Predix, IBM's Watson, Cisco IoT Cloud Connect (Meola, 2016) and Siemens' MindSphere (Siemens, 2017). According to Iansiti & Lakhani (2014), IoT enables large collecting of data, increased connectedness and cyber physical systems and extends digitization, digitalization and connectivity to previously analogue tasks, processes and machine and service operations.

According to Iansiti and Lakhani (2014), there are three fundamental properties to why IoT has the transforming effect on businesses. Firstly, unlike analogue signals, digital signals can be transmitted perfectly, without error. Secondly, digital signals can be repeated indefinitely. Thirdly, once the investment in network infrastructure has been made, it can be communicated to the incremental consumer at zero marginal cost: And a digital task performed at zero marginal cost will immediately supersede any traditional analogue task completed at significant marginal cost (Iansiti & Lakhani, 2014).

3.5.3 *Industrial Internet or Industrial Internet of Things*

To separate the industrial and consumer level of IoT, GE coined the term Industrial Internet in 2012 (GE Digital, 2017). GE's (2017) perspective on Industrial Internet of Things (IIoT) or the Industrial Internet is to think of it as connecting machines and devices in industries where there is more at stake or where system failures and unplanned downtime can result in life-threatening or high risk situations. IBM´s (2017) view is that there is a convergence of intelligent machines, facilities, fleets and networks with advanced analytics, predictive algorithms and automation. These connected machines can tell the operators how to optimize productivity or detect a failure before it occurs, thus connecting people to support more intelligent design, operations, maintenance and higher service quality and safety (GE Digital, 2017; IBM, 2017).

IIoT can greatly improve connectivity, efficiency, scalability, time savings, and cost savings for industrial organizations through predictive maintenance, improved safety and operational efficiencies, according to Inductive Automation (2017). In addition, Inductive Automation (2017) supports the view from GE and IBM in stating that IIoT allows industrial organizations to break open silos and connect all their people, data, and processes from the factory floor to the executive offices.

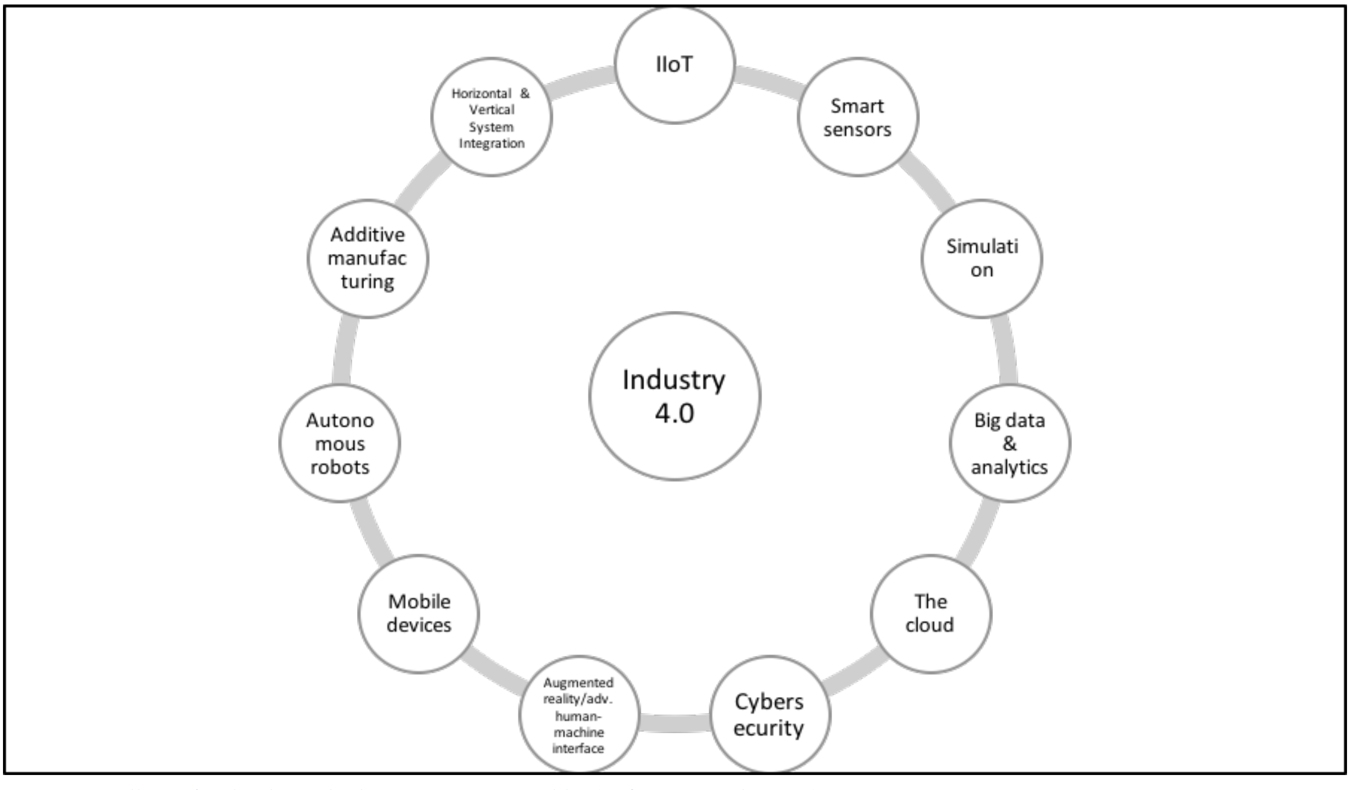


Figure 18 Pillars of technological advancement, inspired by (Rüßmann, et al., 2015)

Porter & Heppelmann (2015) state that the Internet of Things, or smart connected products, and its effects are not confined to manufacturing, but are spreading to other industries. EY (2015) chooses to combine the Industrial Internet and Industry 4.0 and explain that this current phase of industrial development turns products "smart" with the help of sensors collecting data continually, coupled with interconnectivity. Accenture (2017) has named the fourth industrial revolution Industry X.0, and are communicating that the core of Industry X.0 is highly intelligent connected systems that create a fully digital value chain. All this is enabled through the IIoT.

The take from these different views is that Industry 4.0, in a wide context, is facilitated through the expansion of the Industrial Internet of Things. Whilst at the same time IIoT is incorporated into the concept of Industry 4.0. Depending on the interpretation of what Industry 4.0 is and within what industry this applies, there are different additional technologies that powers the concept or capability of Industry 4.0. The figure above depicts the technologies of the ones listed and thought to have the largest impact on offshore wind from a systems perspective.

3.6 Smart, connected products, wind turbines, -farms and -energy systems.

Smart connected products are made possible by vast improvements in processing power and device miniaturization and by the network benefits of ubiquitous wireless connectivity, Porter & Heppelmann (2014) explain why they use "smart connected products" above the phrase Internet of Things:

> *The internet, whether involving people or things, is simply a mechanism for transmitting information. What makes smart connected products fundamentally different is not the internet, but the changing nature of the "things". It is the expanded capabilities of smart, connected products and the data they generate that are ushering in a new era of competition."* (Porter & Heppelmann, 2014)

Porter & Heppelmann (2014) further explains that smart components amplify the capabilities and value of the physical components, while connectivity amplifies the capabilities and value of the smart components and enables some of them to exist outside the physical product itself. By physical, Porter & Heppelmann (2014) means components that comprise the products mechanical or electrical parts. In a wind turbine, for example, these include the electrical generator, turbine blades and gearbox. Smart components comprise sensors, microprocessors, data storage, controls, software and an embedded operating system and enhanced user interface (Porter & Heppelmann, 2014). In a wind turbine, for example, smart components include blade sensors, vibration sensors, other embedded sensors and adaptive turbine control system due to data processing algorithms recognizing changing conditions (Crawford, 2013). Connectivity components comprise the ports, antennae and protocols, such as MQTT (Message Queueing Telemetry Transport) (Inductive Automation, 2016), enabling wired or wireless connection with the product.

Porter & Heppelmann (2014) further divide the connectivity components into one-to-one, one-to-many and many-to-many connections. Especially one-to-many and many-to-many connection is interesting with respect to wind industry. Many-to-many connection involves multiple products connected to many other products and to external sources. The increasing capabilities of smart connected products will expand industry boundaries beyond product systems to system systems (Porter & Heppelmann, 2014). The author sees this to be relevant also within offshore wind systems.

By following the view of the offshore wind farm system architecture from Section 1:2.4, the wind power asset module is here used as basis for explaining. Firstly, turning wind turbines smart, and connecting them with each other, could return a set of smart connected products. This can be described as a product system. Secondly, by connecting the other modules of the offshore wind farm system (i.e. offshore support system and onshore support system and so forth) with the wind power asset module, could return a system of systems or a smart connected system. The attributes of a smart connected system can be seen below.

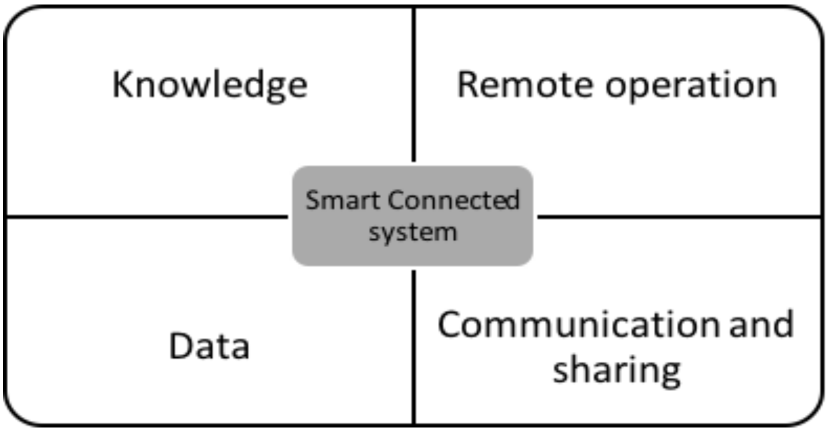


Figure 19 Main elements of a smart connected system

According to Harbor Research (2016), “Smart Systems” should automatically be understood as real-time networked information and computation. Laney (2016) state that the drivers of a smart connected system is sensors, connectivity, and people and processes. Sensors generates data on position, vibration, machine vision, electricity or magnetism, acceleration, load etc. (Laney, 2016). Connectivity enables communication, sharing and remote control through local area network, personal area network, Wi-Fi, Ethernet, 4G and so forth (Laney, 2016). People and processes utilizes the new created and established knowledge through remote monitoring/maintenance, analytics & Cloud/API, control and automation, mobile devices and so forth (Laney, 2016). Data could be in a set of different formats, and it can either be raw data or analysed data. When using the data to enlighten different situations or gain insight, knowledge is created. Knowledge also incorporates past experiences, lessons learned and external experts. Additionally, knowledge includes educated personnel, best practices and both practical and theoretical understanding. Types of communication include humans to humans, humans to machines, machines to humans, and machines to machines in the most practical solution possible. Sharing is understood as the agreement on access to relevant data and knowledge between systems and throughout the value chain. Remote operation is the ability to monitor, control, perform changes and make decisions in a safe environment at a different location than the performing machines or systems.

According to The National Institute of Standards and Technology (2017), smart systems or cyber physical systems (CPS) are co-engineered, interacting networks of physical and computational components. CPS are further defined by Baheti & Gill (2015) as transformative technologies for managing interconnected systems between its physical assets and computational capabilities. Below is a further elaboration on the cyber physical system architecture.

3.6.1 *Cyber-physical system architecture*

According to Lee, et.al (2015), CPS can be developed for managing Big Data and leverage the interconnectivity of machines to reach the goal of intelligent, resilient and self-adaptable machines. Lee, et.al´s (2015) approach is toward manufacturing and claim that integrating production, logistics and services in the current climate, could transform todays factories to an Industry 4.0 factory context. Creating CPS in industry is still at the initial stages of development, and according to Lee, et.al (2015) should there be defined a structure and methodology to operate as guideline for implementation of a CPS.
The result of this is the 5C architecture described below, a step-by-step guideline for developing and deploying a CPS where the two main functional components are:

1. advanced connectivity that ensures real-time data acquisition from the physical world and information feedback from the cyber space.
2. Intelligent data management, analytics and computational capability that constructs cyber space.

3.6.1.1 Smart connection

As seen in the figure below, smart connection is the lowest level on the 5C architecture. Lee, et.al (2015, p. 19) state that acquiring accurate and reliable data from machines and their components is the first step of a CPS application. At this stage one should first consider the important factors of various types of data and then land upon a way to manage data acquisition and transfer together with selecting the proper sensors. Key words at this level are tether-free communication and sensor network and condition based monitoring.

3.6.1.2 Data-to Information Conversion

Level two is about using the data and turning it to something useful. According to Lee, et.al (2015), focus is on developing specific algorithms for prognostics and health management applications and that the second level of the architecture brings self-awareness to machines. Key words, smart analysis for component machine health and multi-dimensional data correlation, degradation and performance prediction, prognostics and health management.

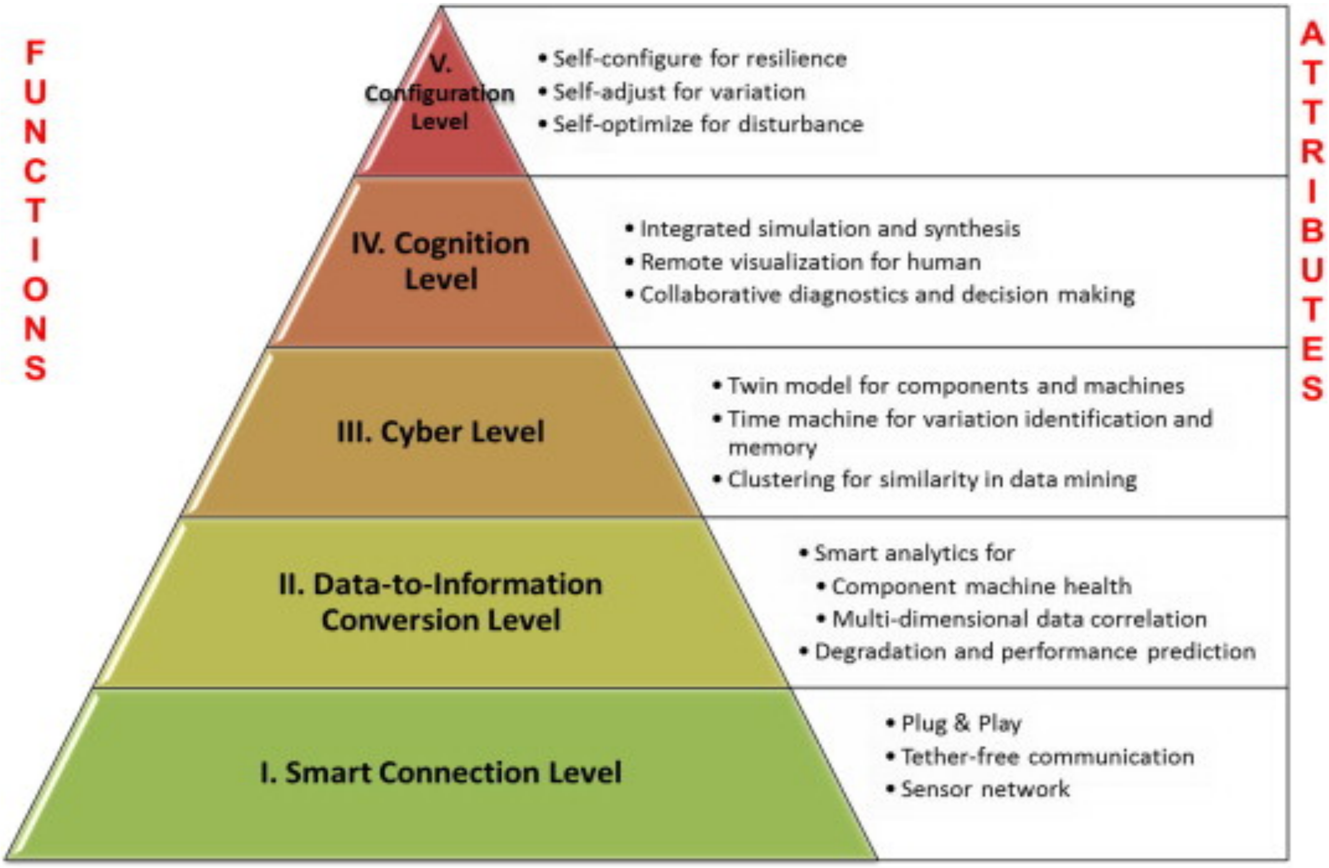


Figure 20 5C architecture for implementation of Cyber-Physical System (Lee, et al., 2015)

3.6.1.3 Cyber

At this level, a network between machines or turbines or the different modules on an offshore wind farm is established and the cyber level acts as the information hub where all information is being pushed. Having large amounts of information gathered, there need to be further analysis on how to extract additional information on the connected products. By enabling the products with self-comparison ability one make them smart. In addition, future behaviour can be predicted by using historical information (Lee, et al., 2015). Key words are twin models (digital twin) for components, machines and systems, time machine for variation verification and memory, clustering for similarity in data mining and CPS

3.6.1.4 Cognition

At the cognition level, comparative information and individual status information is available. According to Lee, et.al (2015) is a thorough knowledge of the monitored system together with solid info-graphics necessary to transfer acquired knowledge to the users for them to take the correct decisions. Key words, integrated simulation and synthesis, remote visualization for human and collaborative diagnostics, smart decision making and decision support system.

3.6.1.5 Configuration

"The configuration level is the feedback from cyber space to physical space and acts as supervisory control to make machines self-configure and self-adaptive. This stage acts as resilience control system to apply the corrective and predictive decisions, which has been made in cognition level, to the monitored system" (Lee, et al., 2015, p. 20). Key words at this stage is self-configure for resilience, self-adjust for variation, self-optimize for disturbance and resilient control system.

4 Industry 4.0 Technology review

Below is a review of the technologies that comprises the Industry 4.0 concept and are influencing or could influence the offshore wind industry. Industry 4.0 and its technologies was discussed and listed in 3.5.3. IoT and IIoT are concepts within Industry 4.0 that are already covered in 3.5.2 and 3.5.3. Important to mention is that even though the following technologies are different, they are closely intertwined. For example, will one not have Big Data if it was not for the smart sensors, and if the cloud is to be utilized, cybersecurity is naturally involved. Simulation, augmented reality and autonomous robots are also technologies that, when first discuss one of them, it is hard not to also include the other.

4.1 Big Data, Smart Data and Analytics

Historically, data was generated primarily by internal operations and through transactions by order processing, interactions with suppliers, sales, customer service and so forth (Porter & Heppelmann, 2015). In addition, Porter & Heppelmann (2015) state that now this is supplemented with data from the products themselves, generating real-time readings that are unprecedented in variety and volume. Originally, Big Data provided companies with opportunities for storing large amounts of information and this could again be used to establish patterns, and optimize products and services (Llorente & Cuenca, 2017). A new world of Big Data, defined as "the ability to process and analyse huge amounts of data" (Maniyka, et al., 2013, p. 43), is generated through the convergence of the IoT and analytics (Alvarez, et al., 2016). Llorente & Cuenca (2017) explain Big Data as a phenomenon that consists of finding correlations between large amounts of data, and that emerged alongside the Internet of Things. Even though we are now at a time where technological evolutions have facilitated for analysing these large amounts of data, it is still difficult getting value from them (Iafrate, 2015). According to offshoreWIND (2017), Big Data offers large benefits within visualization of real time data, development of decision support tools based on disparate data sources, and data mining to aid planning and find performance inefficiencies to improve real time operations. More specifically, within offshore wind could Big Bata have an impact on wind turbine monitoring, control systems, supply chain management and marine operations/logistics.

According to Iafrate (2015) is Big Data characterized by the four V´s, Volume, Variety, Velocity and Value (Smart data). As mentioned in 3.5.2, the IoT is expanding and the growth of connected units are increasing rapidly, this in turn result in an exponential accumulation of data, where 90% of today´s data has been created in just the last two years (IBM, 2017). With the enormous volumes of data available, collating the data can be incredibly difficult. In order to find out which data have value, it is necessary to read, sort and reduce the data by sending it through storage, filtering, organization and analysis (Iafrate, 2015). On top of this, the data often exists in different forms and formats around the organization, there is a large variety in the data available, with 90% of generated data unstructured, according to IBM (2017).

How this variety has been handled is by Iafrate (2015) explained through decision-support databases, transaction- and decision data models. The transaction data model or normalized data model, enables transaction activities to run efficiently (response time and parallel actions), but makes implementing business intelligence solutions and operational reporting difficult. To partly mitigate this issue, operational data store was put in place in order to facilitate for an operational reporting database and with business intelligence tools enabling metadata to be implemented. Metadata is data on data and allowed analysts to create reports without any knowledge of the physical data model (Iafrate, 2015). The decision data model focuses on analysis, modelling and data mining, which most of the time require a large volume of historic information. This historic information, with joints and relations between entities, together with volume, had a large impact on query times and made use of relational data models difficult.

To cope with this, denormalized data models where implemented, with a simpler "star" structure, where source data was organized in the same entity, a fact table. With analytical dimensions split into customer dimension, employee dimension, product dimension and time dimension (Iafrate, 2015), this is depicted below. This model made access to data easier, however with a level of data redundancy resulting in larger volumes to process.

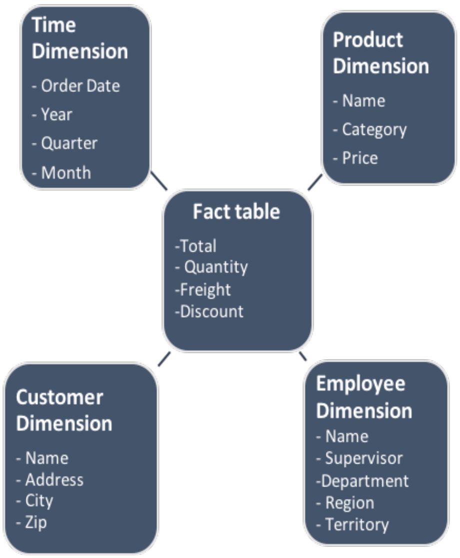


Figure 21 "Star" data model (Iafrate, 2015)

In the latter years, there have been large amounts of unstructured data, messages, blogs, social networks, films, photos, and according to Iafrate (2015) will these data have to be processed in a way to be included in the decision-making process of businesses. All the data diversity make up the variety vector of big data, and this type of data doesn´t easily fit into fields on a spreadsheet of a database application (Gewirtz, 2016). A further development of this, taking on a data centric approach is further explained below.

The internet never sleeps, and data is generated all the time, for instance weather stations and wind turbines provide continuous flows of data. Velocity, is by Gewirtz (2016) defined as the measure of how fast the data is coming in, and the more the IoT takes off, the more connected sensors will be out and transmitting data at a near constant rate. The estimated rate of global Internet traffic by 2018 is 50000 GB/s (IBM, 2017). As this number of connected units grow, so does the flow of data, velocity.

The fourth V of Big Data according to Iafrate (2015) is value, and Big Data must be viewed as an additional source of information that will enrich businesses´ decision-making processes. According to Biehn (2017), we are creating models that answers sophisticated queries, delivers counterintuitive insights and create unique learnings. These models should point us to actions we can take that improve business outcomes, and without high-performance analytics and data scientists to make sense of it all, you run the risk of simply creating big costs without creating the value that translates into business advantage (Biehn, 2017). Big data is the ability to achieve greater value through insights from superior analytics (IBM, 2017). Smart data and analytics are given some more attention below.

The traditional three V´s of Big Data are Volume, Velocity and Variety. Value, making sure we capture the Smart Data has been mentioned, in addition to this, Veracity and Viability have also been added by various actors to complement the traditional three. IBM (2017) include veracity in their V´s, to focus on the certainty of data. Veracity is about data quality, but also about data understandability (Saporito, 2014). Viability is described by van Rijmenam (2016) as carefully selecting those attributes in the data that are most likely to predict outcomes that matter most to the organization. As many Big Data scientists believe that 5% of the attributes in the data are responsible for 95% of the benefits, paying attention to the most important attributes can be very rewarding (van Rijmenam, 2016).

4.1.1 *Smart data and Analytics*

Smart data is by Iafrate (2015) defined as the way in which different data sources are brought together, correlated, analysed etc., to be able to feed decision-making and action processes. According to Heuring (2015) are the term Big Data, and how it’s generally understood, inadequate when it comes to the bits and bytes from industrial facilities, buildings, and energy systems and concludes that Big Data should evolve into smart data. Smart data is therefore seen as the valuable and useable data extracted from Big Data using analytics.

To correctly evaluate the data, one must understand the mass of data, knowing how the various devices´ and facilities´ function, and what sensors and measuring technology we need to obtain the relevant data (Heuring, 2015). Heuring (2015), in addition to Iafrate (2015), focuses on that it’s the valuable (or smart) content of the data that is the decisive criterion, not the volume or amount of data. Smart data will not only enable us to find out what is happening in our facilities at any given moment, but also why it is happening (Heuring, 2015). Heuring (2015) exemplifies this using wind power plants and Siemens´ remote-maintenance centres as an example. In these systems, sensors measure mechanical vibrations, which are compared with a database containing the measurement values of more than 6000 wind turbines. In the event of a deviation or anomaly, a service team can take an immediate action and make corrections before breakdown (Heuring, 2015). In addition to this, anticipatory maintenance and real-time remote diagnosis are some examples of how smart data will change companies´ business models (Heuring, 2015).

Analytics are often divided between descriptive, diagnostic, predictive and prescriptive tools. Descriptive is focusing on what happened, diagnostic analytics are concerning why it happened and both these are possible to perform at an early stage, with a low level of digitalization. In Arundo, predictive and prescriptive analytics are regarded as advanced analytics. Predictive analytics is defined as what is likely to happen, and can be further divided into fault prediction and anomaly detection. Fault prediction can be done when there is access to historical data and failure data, with fault modes and time of fault. With this you will be able to develop a fault prediction model. For anomaly detection one have an opposite approach, depending on normal data, where the model learns what is normal and register any anomalies from this, not needing fault logs. Prescriptive analytics are to take this even further and is dedicated to finding what is the best course of action. "Often defined as part of the next generation of analytics, prescriptive analytics combines descriptive analytics to elucidate what happened in the past with the forecasting capabilities of predictive analytics to prescribe the next best steps to take" (Tucci, 2017, p. 4). A further development from this is systems, that can not only predict and prescribe but also adopt and operate autonomously, that can learn and change future behaviour accordingly.

According to Iafrate (2015), Smart Data should be viewed as a set of technologies and processes, as well as the structures associated with it, that enable all value to be taken from the data, and calls this Business Intelligence Competency Centres (BICC). Further, Iafrate (2015) explains that the characteristics that follows Smart Data are:

- **Formal integration into business processes:** Iafrate (2015) argues that decision-making must be as close as possible to its implementation, that the monitoring and optimization indicators of the activity are aligned to the operational decision-making and action processes.
- **Stronger relationship with transaction solutions:** The digitalization and the following IoT has integrated the communication between the operational activities space (transactions) and the analytical space (decision-making) and Iafrate (2015) argues that this relationship has required the duration of the decision-making cycle (capturing and transforming data, storage and analysis, publication) to be drastically reduced.
- **Mobility and temporality of information:** New mobile devices, interconnectivity and wireless communication amongst these and people is never interrupted, thus information has had to adapt to these new formats. Additionally, the temporality of data processing processes has been aligned with the temporality of business processes, for which the information is destined (Iafrate, 2015). Temporality can be defined as "any time" (Iafrate, 2015) or as the state of existing within or having some relationship with time (Oxford Dictionaries, 2017). This way of working has

required the information systems to evolve for the information to be processes in “real-time”.

4.1.2 *Data centric approach, Data lake*

The ever-increasing volume and variety of structured and unstructured data requires a flexible computing architecture or system capable of addressing the growing needs for the workloads this data scale demands (Agerwala, 2014). According to Harbor Research (2016), scalability, interoperability and seamless integration of real-time or event-driven data are the functions one should want the most in the era of ubiquitous computing. Agerwala (2014) continues focusing on that the cost of moving data around becomes prohibitive and that it is more reasonable to move data less by running workloads where the data lives, employing distributed intelligence to bring computation to the data. That a data centric approach and systems will be the future systems of insights. Data centric design is explained by IBM (2017) as moving much of the processing to the places where the data is stored, whether that’s within a single computing system, in a network of computers, or far away in sensors tracking the weather or monitoring an energy pipeline. Data centric refers to an architecture where data is the primary and permanent asset, and applications come and go. Harbor Research (2016) writes that what is needed is to go from simple device monitoring to a model where device data is gathered into new applications to achieve true system intelligence. In the data centric architecture, the data model precedes the implementation of any given application and will be around and valid long after it is gone (McComb, 2016). Following a data centric approach, a database management system is helpful in providing a centralized view of the data, accessible by several users, from multiple locations and in a controlled manner (Rouse, 2015). Below is a figure elegantly explaining the DBMS connection to the database, applications and users.

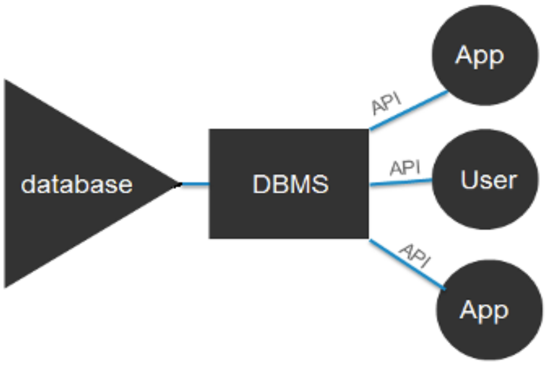


Figure 22 DBMS Connection (Rouse, 2015)

There are several different DBMS models, considering that one wants to get control over both structured and unstructured data, a NoSQL DMBS is one alternative. The building blocks for this approach are scale-out Big Data and NoSQL solutions to unify operational and informational data stores, small and efficient micro-services instead of monoliths, and smart data centres (Anadiotis, 2017). According to Agerwala (2014), true data centric systems will be realized when we can consolidate modelling, simulation, analytics, Big Data, machine learning and cognitive computing as “Systems of Insight.”. They will provide these capabilities faster with more flexibility and lower energy costs, effectively ushering in a new category of computers. Machine learning is described as the ability of a computer to automatically refine its methods and improve its results as it gets more data (Brynjolfsson & McAfee, 2014).

One way of depicting this the data centric approach as a part of a grander scheme is using the overview presented below. Data from smart connected products in combination with additional data sources is generating some insights. Whether some of the data processing or edge analytics are performed in sensors, or if all the raw data are gathered in a “data lake” is not necessarily the main issue. It is to handle the data volume and variety and being able to harmonize the data models. When this aggregated data, processed or raw, is stored in a data lake one will be able to fully study the data, perform business intelligence and gain deeper insights with a new set of data analytics tools (Porter & Heppelmann, 2015). Vital in this regard is the concept of data virtualization. Data virtualization is explained by Techopedia (2017) as the process of aggregating data from different sources of information to develop a single, logical and virtual view of information so that it can be access by front-end solutions such as applications, dashboards and portals without having to know the

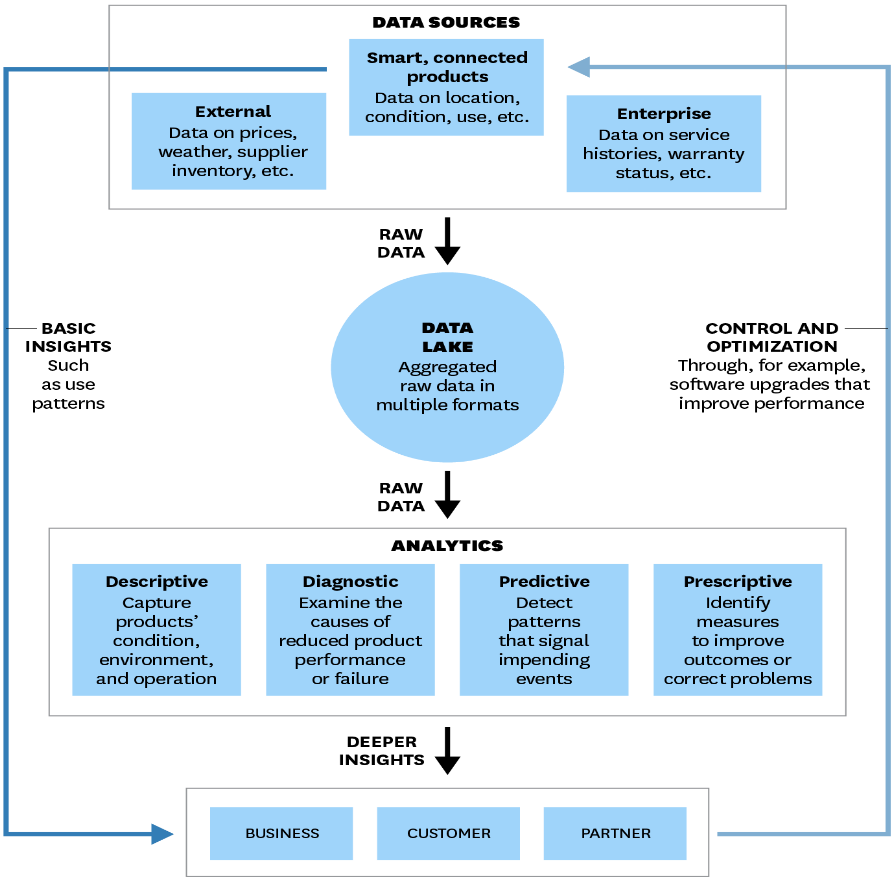


Figure 23 Creating New Value with Data (Porter & Heppelmann, 2015)

data´s exact storage location. Following this, data virtualization software can be used to perform data and business integration, service-oriented data services and enterprise search.

4.2 Smart sensors

Smart sensors and sensors embedded in components are not new, it is essentially sensors that are intelligent enough to understand that something is wrong and that have analytical possibilities. In a future Industry 4.0 context, a further development of sensor technologies involves monitoring degradation and remaining useful life prediction of the components, according to Lee et. al (2015). With edge analytics, performed on either the sensors or edge devices, one can gather data even with lost connectivity. In addition to this, intelligence driven on the edge have limited bandwidth, resulting in that one need to be able to send the right data, and therefore having to reduce the data to what is relevant. With the edge analytics established, it is facilitated to enable communication between turbines and wind farms through fleet learning.

4.3 Simulation/Optimization

Historically, simulation have been used during the engineering phase with 3-D models (Rüßmann, et al., 2015). Simulation/Optimization involves statistics where one uses legacy data and lessons learned to simulate different scenarios with given parameters and are closely linked to big data and analytics. Simulation will be increasingly used in plant operations where it will leverage real-time data to mirror the physical world in a virtual model (Rüßmann, et al., 2015, p. 5). Being able to visualize data and information can be a powerful tool for better communication, cooperation and decision making because our eyes are a very powerful sensor. It is stressed that simulation and optimizing are terms often interchangeably used, but the output from a simulation and optimization are different. Optimizing a process will eventually give you a recommendation of what the best practice is, or best solution. A simulation will only give you an output based on the given constrains. Shoreline provides integrated simulation solutions for offshore wind and have developed software (MAINTSYS & SIMSTALL) so operators can best decide their O&M strategy and estimate precisely when the wind farm is installed and up and running. MAINTSYS is a simulation solution to analyse operation and maintenance and marine logistics. Using SIMSTALL one can simulate port operations, logistics, installation, completion, commissioning and testing (Shoreline, 2017). These outputs however, are better or more accurate, when an experienced person is adding the constraints, returning different benchmarks based on the number of cases you simulate. A thorough and accurate simulation create the ability to make better decisions on, for example, the best installation or logistics programme.

Reporting on future wind power production have been deemed difficult and may result in large fees if the levels reported are wrong. Powel and Trønderenergi have partnered up, making a software that combines actual weather measurement data, prognostic data and historic data resulting in forecasting that are more accurate than regular meteorologists. This adds up to about 350 parameters and resulting in reducing production uncertainty with 45% and costs related to imbalance with over 50% (Sprenger, 2017).

4.4 Additive manufacturing

Additive manufacturing (AM) or 3D printing has up to now mostly been used for prototypes and to produce individual components. With Industry 4.0, additive manufacturing will be widely used to produce small batches of customized products that offer construction advantages, such as complex, lightweight designs. “High-performance, decentralized AM systems will reduce transport distances and stock on hand” (Rüßmann, et al., 2015, p. 7). For instance, Norsk Titanium have a very exciting project going where they have developed a method for AM of aerospace-grade titanium structures, and they are currently also developing solutions for wind turbines (Norsk Titanium, 2017). The wind-industry are currently looking to AM for wind turbine blade moulds and other components, for in that way to speed up innovation due to reduced costs and amount of time required for blade manufacture (Zayas & Johnson, 2016). It is due to the increased possibilities of rapid prototyping, simplifying complex parts, trying out different materials, weight reduction and rapid repair that Dodd (2017) claims it to be a game changer for the wind industry. It is not hard to imagine that AM and predictive maintenance is a good combination, given there are AM facilities close to a wind farm.

4.5 The Cloud

Cloud computing means storing, accessing and delivering, applications, programs, photos, videos and more over the internet instead of your computer´s hard-drive or data-centre (Griffith, 2016; Meola, 2016). Cloud-based software is already well developed, however Rüßmann, et al. (2015, p. 6) focus on Industry 4.0 and implementing this in industrial environments will require increased data sharing across sites and company boundaries. Rüßmann, et al. (2015) continue foreseeing that with improved technologies, machine data and functionality will increasingly be deployed to the cloud. This enables a more data-driven approach, and even systems that monitor and control processes may become cloud based. Cloud deployment possibilities include scalability, elasticity and service based internet technologies (Antvogel, 2017).

One example of how cloud technology can be used is the Kognifai cloud platform by Kongsberg, a platform ecosystem of relevant services and capabilities that can be used alone or in combination, and that can increase wind farm control using performance and condition monitoring and production forecasting (Kongsberg, 2017). It seems that Arundo also have this view when explaining that cloud service enables data management from several different sources and thus opens up for global analytics, with a two-way commuication. Analyzed data or analyses in the cloud can be pushed to the edge, for example to the wind power asset, creating a learning environment between your hardwares.

Meola (2016) uses the IBM breakdown of cloud computing:

- **Software as a service (SaaS):** Cloud-based applications run on computers off site. Other people or companies own and operate these devices, which connect to users' computers.
- **Platform as a service (PaaS):** Here, the cloud houses everything necessary to build and deliver cloud-based applications. This removes the need to purchase and maintain hardware, software, hosting, and more.
- **Infrastructure as a service (IaaS):** provides companies with servers, storage, networking, and data centers on a per-use basis.
- Public/private/hybrid Cloud: Provide quick access to users over a network but differences in ownership, user access publicity and so forth.

4.6 Mobile devices

Mobile devices, such as smartphones, tablets and laptops have had a great journey the last 10 years, and we are now seeing that their increased capacities are proven beneficial for different industries. Devices can be brought up to the wind turbine nacelle and used as a tool when performing maintenance, giving information on components condition, vibration analysis and so forth. With cloud services available, all relevant personnel can get access to information on the wind farm whether it is production, distribution, prediction, condition, diagnostics or logistics. At no concern, whether the location is on a turbine, support vessel, platform, supply base or control centre. Intergraph (2017), provide what they call I/CAD Mobile Applications. It is explained as field personnel being able to update event details, access databases and send and receive messages, and this use could increase productivity and safety. Intergraph (2017) also offer SmartPlant for Enterprise for Owner Operators, applications that provide preconfigured work processes covering the complete plant life cycle and interoperability with maintenance and other operations systems.

4.7 Cybersecurity

With the increased connectivity amongst devices, products, turbines and modules, cybersecurity-threats increase drastically. To manage this threat, there need to be secure and reliable communication, and in addition to this, sophisticated identity and access management of products and users (Rüßmann, et al., 2015, p. 6). As an example, the Kognifai platform takes care of cybersecurity, identity, encryption and data governance (Kongsberg, 2017). Verico makes a point regarding data handling and cybersecurity, that there is a hosting issue if it becomes necessary to share and move data. If there is a company that need a service that cannot be performed in-house, it need to be security graded that all outside partners are committed to handle the data with absolute care. In Verico, they see a trend where the different stakeholders are less conservative regarding this.

4.8 Autonomous robots

Robots and drones are increasingly getting more autonomous, flexible and cooperative, and eventually will they interact with one another and work safely together with humans and learn from them (Rüßmann, et al., 2015, p. 5). Siemens are working on self-optimizing wind turbines, where machine learning, neural networks and artificial intelligence are at the core of this development (Siemens, 2014) An artificial neural network is a computational model based on the structure and functions of biological neural networks (Techopedia, 2017). And artificial intelligence is an area of computer science that emphasizes the creation of intelligent machines that work and react like humans (Techopedia, 2017).

Draga mentioned that for electrical power today, a power management system is utilized for synchronization, load sharing and optimizing efficiency, this might be done in a similar way on wind farms today. An offshore wind farm with connected turbines, enables these turbines to access operational data combined with weather data, learning from this, detect regular patterns and optimize their own operations (Siemens, 2014). Robots are not necessary only applicable to wind turbines in a wind farm system, Rolls-Royce and Stena Line are looking toward autonomous ships and vessels by first creating an intelligent awareness system. This system will get its data and information from a range of sensors, global databases, electronic maps, satellites, LIDAR and cameras to establish decision support for crew and eventually be fully autonomous (Stensvold, 2017). Furthermore, is it a focus on increased autonomy of position and manoeuvring, ship automation and bridge solutions (Stensvold, 2016). Performing inspection using autonomous drones is also viewed as a potential area where the wind industry can benefit, cutting inspection time down to minutes (Dvorak, 2017).

4.9 Horizontal & Vertical System Integration

The link in terms of sharing and cooperation between operators, suppliers and service providers are often limited to the bare necessities. The same goes for departments within a company, such as engineering, production and service. System integration can be defined as an engineering or IT process concerned with joining different subsystems or components as one large system and system integration can be used to add value through new functions provided by connecting functions of different systems (Techopedia, 2017). Today, there is a lack of integration between the levels of an organisation and throughout the engineering itself. According to Rüßmann, et al. (2015, p. 6) will companies, departments, functions and capabilities become much more cohesive, as cross-company and universal data-integration networks evolve, and enable truly automated value chains. This however, seems only possible if there is an underlying trust, such as a contract agreement, and that the technological foundation facilitates for open sharing and cooperation.

4.10 Augmented reality and human-machine interface

Gartner (2017) defines augmented reality as the real-time use of information in the form of text, graphics, audio and other virtual enhancements integrated with real-world objects. Augmented reality enables a blend of the real and virtual world, enabling graphics that overlay real world objects, such as wires or fluids inside a turbine. One example of this is where workers get information on instructions of how to replace a specific component as they are looking at the actual system needing repair (Rüßmann, et al., 2015). This is basically a step further than doing the same with a mobile device in a wind turbine. Rüßmann, et al (2015) also mentions virtual training, where one create a realistic data-based 3D environment with augmented-reality glasses to train plant personnel in different scenarions.

With augmented reality, operators will experience an increased level of interaction with machines through cyber-representation and also being able to change parameters and retrieve operational data and maintenance instructions. This is seemingly an elongation from simulation, the largest difference being real-time data and the immersive effect of having this information in your sight instead of on a screen. Microsoft HoloLens enable a mulitmonitor experience and makes it possible to swiftly change from a regular working environment to getting a full view on for instance a turbine to learn, train or control the turbine and to explore 3D in 3D (Microsoft, 2017). GE uses this technology in combination with a digital twin to demonstrate than one not necessarily need to be on site to get the smart data on the companies' products to make intelligent decisions (GE Digital, 2016). With respect to offshore wind industry, not having to go offshore to make inspection, gather information or map conditions except from when highly critical is an interesting path to consider. Utilizing this technology in the correct way could mean that you are better prepared and have made sure that you will have gone through your work tasks prior to heading offshore. Another example is the Rolls-Royce (2017) Unified Bridge, a human-machine interface within ship operation where the goal is to lower the operator´s cognitive load, make the workflow more efficient and to reduce the risk of accidents on crew, vessels or installations. Interviewees from Draga made an interesting distinction between simulation and augmented reality, where simulation is mainly on moving items such as Shoreline´s (2017) solutions and augmented reality is real-time without necessarily being on location.

Section 3: Technology mapping for a future digital offshore wind farm

5 Evaluation based on the Industry 4.0 technologies

The Industry 4.0 concept with its corresponding technologies could potentially have a game changing effect. To manage the digitalizing change, having an overview of where in a system a set of technologies combined could make a difference is necessary. Different Industry 4.0 technologies is seen to have a changing impact and relevance to different modules of an offshore wind farm system. In this chapter, an evaluation and mapping of these technologies relevance have been performed in collaboration with Statoil. The modules where describes in Section 1:2.4 and are: the wind power asset, onshore asset operating and control system, onshore support system, offshore support system and work process management & continuous improvement system. Figure 24 shows the result of mapping each of the technologies and where in a wind farm system they are believed to have greatest impact. Together with Statoil it was agreed on how the relevance of technologies to modules should be based. For instance, Big Data and analytics have a relevance to all modules in one way or the other, however it is where the Big Data are most likely to be gathered and where the analytics are performed that has the "real" relevance.

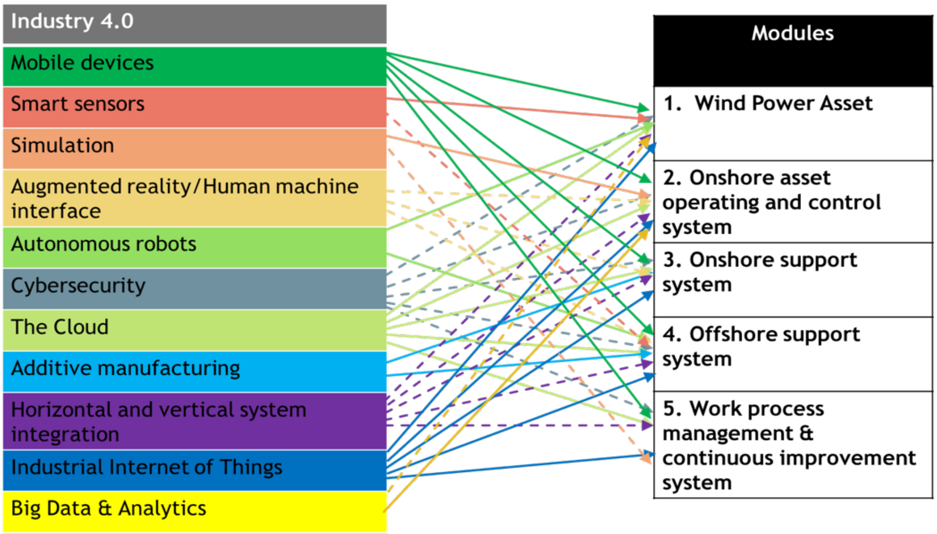


Figure 24 Industry 4.0 technologies and its relevance to the modules of an offshore wind system.

The following sections contain the discussion around mapping the technologies, supported with examples and scenarios where they are seen to have a positive impact. For the sake of simplicity and overview, the discussions have been divided into sections. There are different ways of doing this and it was chosen to, as far as possible, gather technologies seen to have a connection between them. With the result that smart sensors and Big Data & analytics are discussed in the same sub-chapter. Thoughts and views from discussions with interviewees from Statoil, Draga, Visco, Verico, Arundo and Jotne are included.

5.1 Mobile devices and Horizontal and Vertical Integration

Today still, some of maintenance operations are registered on sheets of paper. According to Statoil is there an ongoing process of getting the wind farm management system to also function on mobile devices, such as smartphones and tablets. However, integrating logistics, maintenance work, service providers and operators is no easy task. Often, during the first years of operation, maintenance work is performed by turbine manufacturer, they might have a different system than that of the operator, thus sharing of information is hard and integration between systems proves to be difficult. Making such a simple task as getting notifications on an application and automatically generating a work order challenging. Still, mobile devices, due to the share distance between control centre and power generating assets, is highly relevant for all modules because once there is a solution between the different stakeholders the benefits seem obvious.

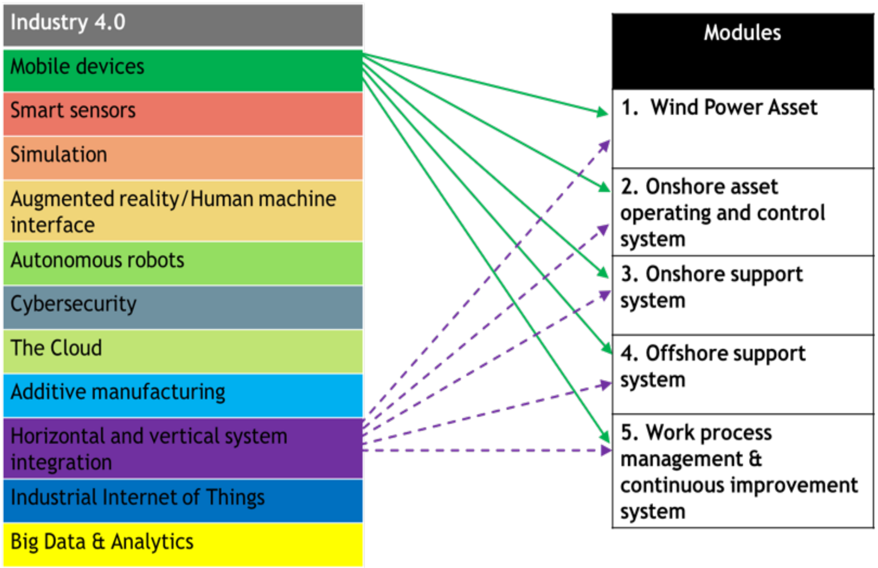


Figure 25 Mobile devices and Horizontal and Vertical Integration relevance

Firstly, as a mere communication tool the mobile devices are a given. Secondly, as an information carrier, assisting management and personnel in decision making through instant, correct and updated knowledge on the assets. One evident use case is that a failure is reported automatically and the notification is immediately transferred to the onshore control centre, offshore personnel, onshore personnel and relevant vessels. Work orders are generated, the personnel will know what and where the failure is and how to perform the maintenance. Following this, will onshore personnel start preparing for any tools or components needed and the vessels will be sent to location.

Arguably, horizontal and vertical system integration is not a technology. Its importance to digitalization however, is difficult not to emphasize enough. Statoil states that horizontal and vertical integration today is difficult, largely due to juridical differences, differences in core functions from operator, service provider, turbine provider and other stakeholders. But the potential to improve this is large and is regarded as very reasonable to complete in the future. A complete horizontal and vertical integration would have relevance throughout the offshore wind system, this can be seen in the figure above. With the different stakeholders having their own digital agenda and an ever-increasing batch of applications, there need to be a platform to share data. Not necessarily change or share the ownership of the data, but facilitate for the access to relevant data and enabling parties throughout the value chain to share data to its advantage.

5.2 Smart sensors and Big Data & Analytics

Smart sensors are relevant at the edges of the system, hence the wind power asset and the offshore support system are the modules where this would be applicable. Here the smart sensors will make the vital contribution of gathering data, and potentially analytics, before transferred to the data lake. Sensors are today embedded in several components of the wind power assets, and there is an increasing number of sensors getting installed, largely due to decreasing cost and increased computing power on sensors. Sensors used today may often have larger capabilities than what they are set to do. A temperature sensor might only give 0 and 1 (indicating that the temperature is either above or below a set threshold) as output and not the exact temperature. This affect the regarded quality on the data it generates and result in weaker intelligence on the state of the component. There is also the issue whether the sensor data are accurate, that the sensor is working properly, leading up to the question of introducing increased redundancy on sensors to obtain data value and data veracity.

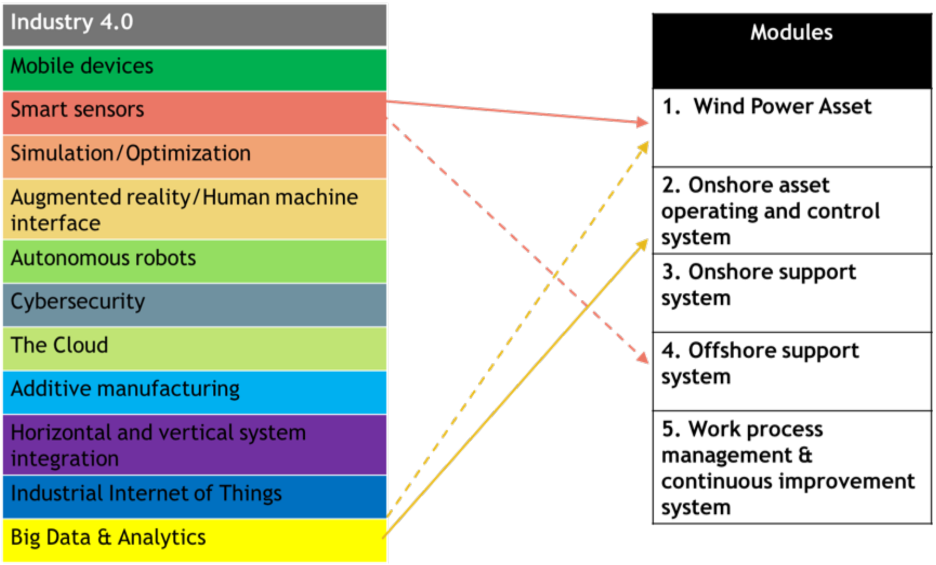


Figure 26 Smart sensor and Big Data & Analytics relevance

On the offshore support system, an increased implementation of sensors on the support vessels is one of the firsts steps that, in the long-term, could result in a higher level of autonomy of the vessels. Thus, creating a safer environment when approaching and accessing the wind turbines. However, as described in previous chapter, this solution is also dependent on several other technologies. For a floating wind turbine, the vessel approach and boarding situation is more vital than for the bottom fixed turbines due to the action of wind and waves. Statoil is participating in a research project where they look towards using sensors to monitor the vessels, getting more data on movements and performance and log this data to then have more relevant input for future simulations.

Big Data & Analytics is seen to have its real relevance at module 2, onshore asset operating and control centre. This is dependent on a view taken after the service contract with the turbine manufacturer is expired, because today Siemens have a centralized analytics centre in Denmark where they perform their predictive analyses and so forth. The interviewee from Statoil explains that there is a goal in developing a failure database, not only from a single asset but from all similar assets, both turbines and farms, thus creating a foundation for more experience, knowledge and sound analytics. This initiative is meeting its obstacles today due to the turbine operators not willing to share more data than necessary. The dotted line in the figure above indicates that data processing and analytics can be performed on the wind power asset itself using intelligent sensors and edge connectors, not necessarily replacing the onshore operating and control centre, but controlling the variety and volume of the data generated. This technology exists today and is seen to be highly relevant in a not too distant future.

5.3 Simulation/Optimization, Augmented reality and IIoT

In Statoil, simulation and optimization is somewhat divided into two parts, the operative, with technicians close or on site, and the operational excellence centre off site. Therefore, simulation and optimization is seen to have its relevance within module 2 and 5. Within the onshore asset operating and control system it is seen to have its relevance for simulation and optimization that will have a direct impact on the day to day operations at the offshore wind farm. But due to the function of Statoil´s Operational Excellence program the author argues that there is also a relevance at a higher organizational level, at the process management & continuous improvement module. This module could utilize near real time and historical data for decision support reaching farther than day-to-day operations. Such as planning of new wind farms and long term operational and maintenance plans or different work programs that would be communicated to the onshore asset operating and control system.

As already discussed in Section 2:3.5, IIoT is of such an importance to the digitalization process that people struggle separating the term from Industry 4.0 and digitalization. Therefore, it is almost self-explanatory that IIoT is relevant throughout the offshore wind farm system and needs to be covering the entire system for it to have its full effect. Toward establishing a smart connected system, there need to be an interconnectivity amongst smart machines, devices and components and the respective modules and personnel. IIoT defines this interconnectivity which is, in essence, a to-way communication between humans and machines (H2M, and M2H and M2M), depending on whether it is data generation, data processing, data interpretation or decision making. The different technologies of Industry 4.0 listed are closely linked. This is the case especially for IIoT which is the result of a combination of technologies: the cloud, smart sensors, mobile devices, Big Data and the underlying software tying it together. Nevertheless, it would be wrong to exclude it from the Industry 4.0 concept. As one of the interviewees simply puts it when discussing IIoT´s relevance; "it needs to be there, across the whole system".

Augmented reality in offshore wind today is mainly confined to presentations, training, courses and to a certain degree installation and maintenance purposes. For a new wind farm planned, augmented reality glasses can provide a 3D view in actual 3D of the wind farm and thus give a sound overview for potential investors. Using augmented reality technology as described in the previous chapter proved to have a few interesting points for Statoil, but is believed to may need a period of maturing before it is implemented in offshore wind. Nevertheless, it was a common understanding that when the technology to a larger extent is applicable to offshore wind its relevance is seen to be within the control and support systems of the wind farm, modules 2, 3 and 4 shown in the figure below. Statoil commented that, in reality, there are one or maybe two service technicians among all the technicians that have vast experience and knowledge when it comes to maintenance work and that this knowledge should be shared. It was suggested that one could establish a knowledge or skill database where technicians with a more limited skillset or experience could get transferred a way of performing the task, or the solution to the problem. Thus, reducing the need to ship more offshore crew and thereby reduce time and cost.

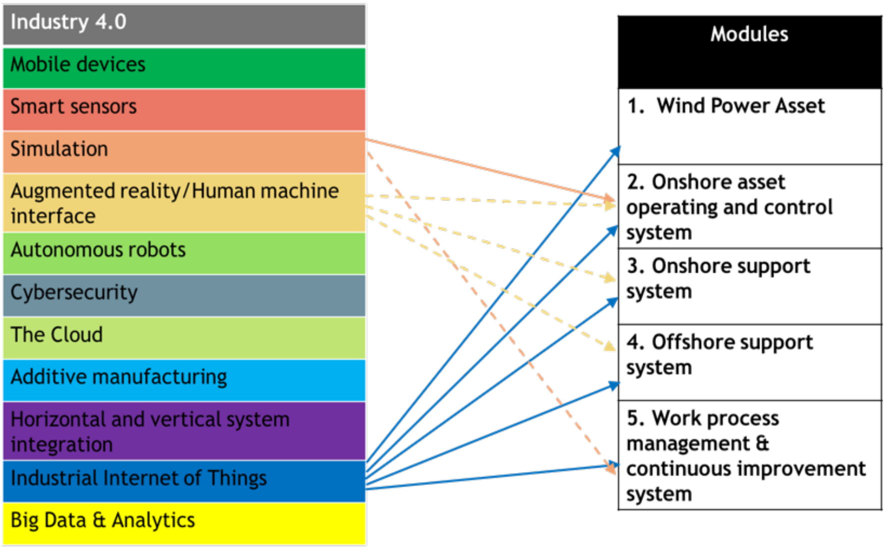


Figure 27 Simulation/Optimization, Augmented reality and IIoT relevance

5.4 Autonomous robots, Additive manufacturing

Self-configuring, self-adjusting and self-optimizing wind turbines is an idea that is relevant for offshore wind because one look to a future state with high availability and a low intensity in visits of wind turbines. Module 1, the wind power asset, therefore stands out as the module with the most obvious relevance to autonomy. However, achieving this is dependent on further technological development of existing technologies and methods such as sensors, IIoT, analytics, manufacturing and so forth. The same goes for module 4, the offshore support system, where autonomous vessels and drones for access and inspection are under development. Robots performing work inside the nacelle of the wind turbine has been considered, together with autonomous drones doing inspection and maintenance in one operation.

Additive manufacturing is a similar case as autonomous robots where a further development is needed. Ideally could one have components 3-D manufactured instead of having a low-volume storage. Either having the 3-D printer installed onshore or offshore on a vessel or platform. This however, is largely dependent on predictive and prescriptive analytics and that the production method is approved and reliable. Statoil mentioned an idea that combine autonomous robots and additive manufacturing where robots that inspect the wind turbine blades also could fix the blade during the same operation with a built-in 3D printer. But acknowledge that this is far ahead and not realistic in today's technological environment. Nevertheless, it is technology that, if it develops in the proper direction, could have a significant effect on an offshore wind system especially within modules 1 and 4 seen in the figure below.

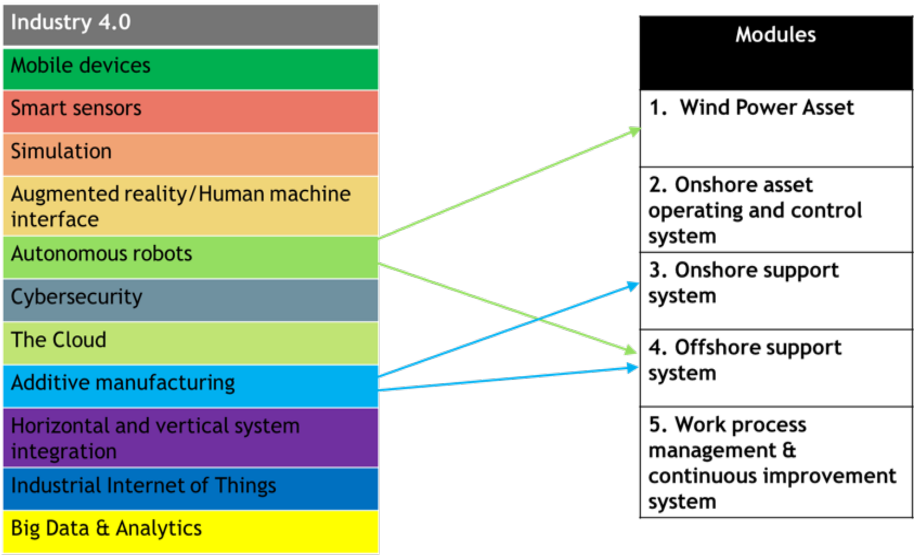


Figure 28 Autonomous robots and Additive manufacturing relevance

5.5 The Cloud and Cybersecurity

Statoil regard cybersecurity as a matter of course, that it should be a default, that security is taken care of throughout the different services provided and used. Based on this comment, regarding cybersecurity as highly relevant in a digitally transformed company is obvious. The dotted lines in the figure below indicates this obviousness, cybersecurity shall be included, it shall be reliable and it shall provide the level of security required to ensure that operations, sharing information and decision making are safe and protected.
Cloud and IIoT are closely linked, where the IIoT generates Big Data through connectivity and sensors, cloud computing facilitates for the data to travel to its destination (Meola, 2016). Therefore, if IIoT is seen to have a relevance to offshore wind, then the cloud or cloud computing should have the same relevance.

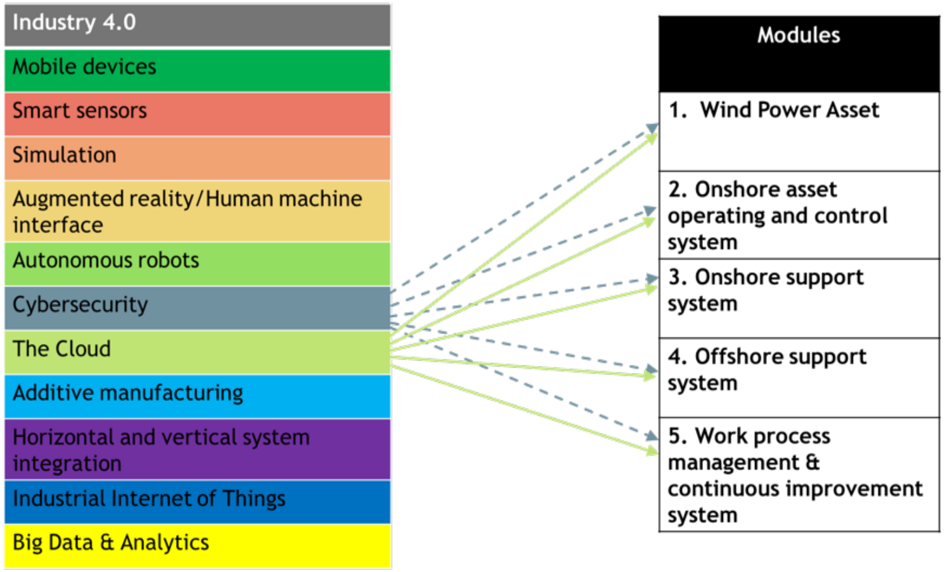


Figure 29 The Cloud and cybersecurity relevance

5.6 Technology mapping summary

Having considered and mapped the technologies it is possible to identify two trends. The first is what technologies that directly have a saying in the development of a smart connected system and beyond. These technologies are identified as mobile devices, smart sensors, simulation, augmented reality, autonomous robots, the cloud, IIoT, Big Data & Analytics and horizontal and vertical system integration. At different stages and of changing importance will these technologies combined (given a correct and proper implementation and use) enable the change towards a state where data, knowledge, communication, sharing and remote operation are the main attributes of an offshore wind farm system. In addition to this is it clear that the technologies that potentially could have the greatest impact on the offshore wind farm system are the technologies where relevance was identified throughout the system. These technologies are identified as mobile devices, Big Data & Analytics, IIoT, The cloud, cybersecurity and horizontal and vertical system integration.

The other trend are the technologies that clearly have a relevance to a future digital offshore wind farm, but not necessarily directly involved in the digitalization process described above. These are cybersecurity and additive manufacturing, this is not to indicate that they are less important, it is to focus on the parallel development of these technologies that are central in the Industry 4.0 context. In addition to this must we not forget humans´ skills, competencies and influence, which need to follow the trends we are seeing of a more digitalized future. The next two chapters follow this discussion, where chapter 6 covers the systematic framework for digitalization and chapter 7 focus on the technological capabilities parallel to the digitalization framework.

Section 4: Systematic Framework for Digitalization

6 Step by step approach for digitalization.

In the following is a proposed framework for digitalization of an offshore wind farm system and how for it to be established as a smart connected system and beyond. This framework is based on the cyber-physical system architecture by Lee, et.al (2015) and the Industry 4.0 concept presented and discussed in Section 2:3 and Section 2:4. What is clear is that digitalization is a somewhat floating expression, and the documented technologies are co-dependent on each other. This chapter takes on the task of defining what need to be in place to digitalize, and defining at what stage different technologies should be implemented. It must be noted that there is a large challenge in introducing the same pace of digitalization in all technologies and across all work processes, sections or systems. The actual process is expected to be more dynamic, organic and not so rigid as the digitalization framework might suggest.

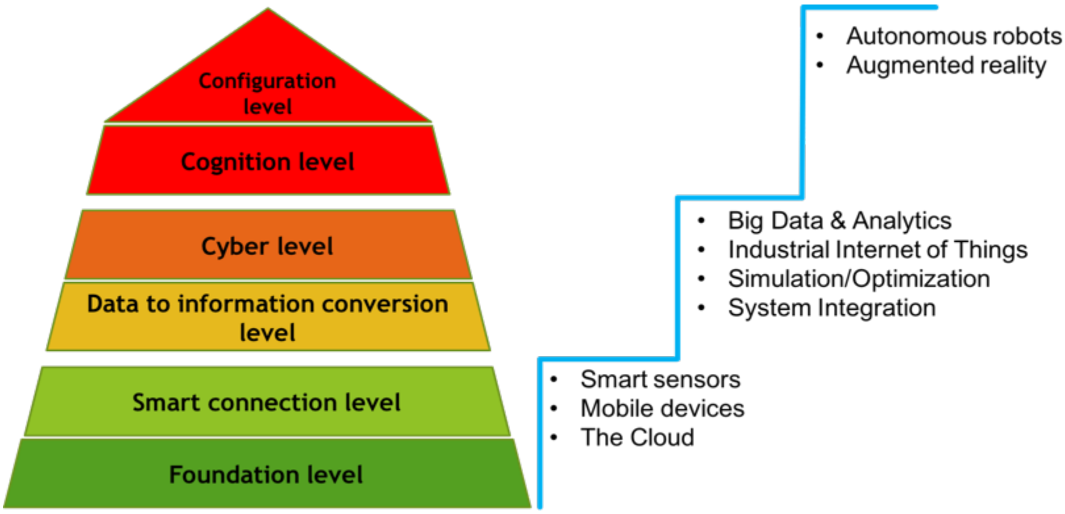


Figure 30 Digitalization architecture, adopted from Lee, et al. (Lee, et al., 2015) and step-wise approach

The largest focus is on the producing assets, the wind power asset module. Hence, the wind farm and more specifically the wind turbines are today subject to digitalization to a larger degree than the other modules of the system. It is of the author´s conviction that there also need to be a digitalization-focus on the other modules of the wind farm system to completely digitally transform the offshore wind industry and its systems. Important to mention is that the focus is on the offshore wind farm life cycle, but the discussion is mainly hovering around, and using examples from, O&M. Lessons learned from operation and maintenance could have implications on continuous improvement, for example, component replacement and the design and development of these and on the design of new wind farms such as farm layout, and decommissioning processes. What drives this discussion is the long-term target described by Statoil as best possible system availability, as low number of visits to an offshore wind farm as possibly, and eventually an autonomous wind farm system that only occasionally would need personnel performing planned work offshore. The ideal state of an offshore windfarm is seen to have near zero breakdown and worry free production. In the figure above is the digitalization architecture and step by step approach for the digitalization of an offshore wind farm.

The following parts contain an overview of the connection between a smart connected system and the adopted 5C architecture. A foundation level is seen necessary to have established for a successful implementation of digitalization and is subject to a further elaboration. A decision and virtualization layer over the smart connected system and parallel to the cognition and configuration level is also included. Together with a three-step approach and a parallel development approach combining the Industry 4.0 technologies.

6.1 Smart connected system and the adopted 5C architecture

The connection between the digitalization architecture and smart connected systems is seen below, where the foundation level are the underlying bases seen in both figures. A smart connected system is explained in Section 2:3.6 as to be equivalent to the cyber level. With data, knowledge, communication and sharing and remote operation the attributes needing to be fulfilled, these attributes works as a scope for the following discussion. The main features of a smart connected system are made smart, connected and put in a system through the process of going from the foundation level via the smart connection level, the data to information conversion level and to the cyber level.

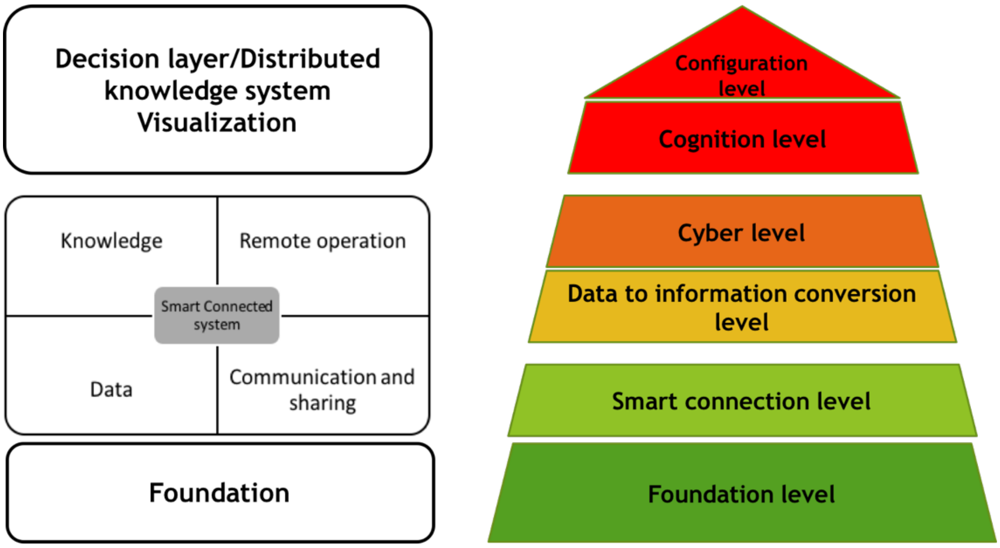


Figure 31 Smart, founded and connected system with decision and virtualization layer, and its relation to the 5C architecture adopted from Lee, et al. (Lee, et al., 2015).

Further digitalizing the offshore wind farm, while reaching the cognition and configuration level is the simultaneous development of a decision and virtualization layer to truly enable the organization´s capabilities made possible through digitalization. In the figure above this is the two red levels in the 5C architecture and the rectangular shape above the smart connected system figure. The decision and visualization layer is seen relevant for the people in the offshore wind farm to keep an overview and coordinate activities through a visualization and decision support tool. With an increased level of connectivity, the complexity of the system increases. Therefore, having such layer available parallel to the parts of the wind farm that reaches the configuration and cognition level could be of great importance.

The first level of the original 5C architecture, the smart connection level, is focused around acquiring accurate and reliable data from machines and their components. There need to be a level below this, presented as the foundation level, where the target is to establish or maintain a sound technological foundation before one is ready to step up at the smart connection level. The foundation level takes into consideration that offshore wind might not yet have the infrastructure entirely established or a wide enough overview over assets to facilitate for the increased use of digital technology and into a smart connected system.

6.2 Features of a foundation level

As mentioned above are the different parts of the offshore wind farm system at different stages of the digitalization process. Reaching the smart connection level indicates that one has established an entire overview of the organization´s assets and are prepared for a move towards digitalization Therefore, the foundation level is to focus on creating an overview to know what next steps to take in the digitalization process, in order for the organization to digitally mature faster and more controlled. The view in Verico is that data are the building blocks making up the foundation on which the rest of the building stands. Suggesting that if there is no data, not enough data or wrong data, reaching your targets is not possible. First and foremost, should one gather data on the state of assets itself. Secondly, getting information on the location, performance and maybe the largest risks associated with those assets is essential. The target should be to gather data on what you know about your assets, but also knowing what is missing. Thirdly, establishing an overview and mapping of the utilized technologies related to both IT and OT to bridge the gaps and identify improvement potential is important. Lastly, knowing what databases and data acquisition solutions are already being used in the offshore wind farm system and establish confidence in the data to be acquired.

For the smart connection level to be plug & play it is vital to have an updated hardware and operating system that can handle the forthcoming amounts of data, different applications, software and so forth. Enabling wireless communication and a solid sensor network are largely dependent on a deep understanding of bandwidth and frequency for data transfer and connectivity. One must feel confident that the data to be gathered are correct and that the architecture facilitates for all the V´s of Big Data: Volume, Variety, Velocity and Value (and Veracity and Viability). Requirements for wireless communication in industrial automation are focused on real-time characteristics and application and communication parameters. Future wireless communication systems requirements are linked to low latency, high reliability and cost efficient availability of frequency spectrum (Frotzscher, et al., 2014). According to Kumar S., et al. (2014), requirements for industrial wireless sensor networks are size, cost, interoperability, resistance to noise and co-existence, energy consumption, robustness, link reliability, scalability, predictability, data aggregation, application specific protocols and so forth. Given the requirements needed for the smart connection level, the evident convergence of IT and OT should be considered at the foundation level. Thereby establish an overview of information and operation technology already embedded in the offshore wind farm system and start leading, rather than follow, the convergence of these technologies.

The convergence of IT and OT are largely driven by IIoT (Inductive Automation, 2016), therefore being able to completely converge these technologies at the foundation level is not the target. The convergence where early predicted by Gartner (2011), which states that the relationship between IT and OT need to be challenged better. The nature of OT is changing, where platforms, software, security and communications, the underlying technology, is becoming more like IT systems. Gartner (2017) defines IT/OT integration as the end state sought by organizations, most commonly, asset intensive organizations. At this state, there is integrated process and information flow, instead of a separation of IT and OT with different areas of authority and responsibility. The convergence of IT and OT is necessary to find common ground to establish a new information driven (GE Digital, 2017) or data centric infrastructure. Once this common ground is established and IT/OT convergence is at a desired level will we be able to reap the benefits, enabling a single view of an enterprise´s complete asset information (Gilbert, 2015).

6.3 Step one, establish a foundation and a smart connection level.

The foundation level and the smart connection level serves as step one on the digitalization road map for offshore wind. For a wind farm already in operation, this step should be near completed already and might therefore be more relevant for a wind farm in the early planning phase. However, there should be room for improvements in an existing wind farm as the author don’t believe that the established systems and cultures within the offshore wind industry is neither complete nor too rigid and set. Based on the importance and elaboration of IT/OT convergence, the criteria needed for the foundation level, and the actions needed at the smart connection level the Industry 4.0 technologies seen to be implemented at step one are: smart sensors, mobile devices and the cloud. These technologies are regarded as already developed, ready for implementation or able to utilize in a new way to facilitate for the further development of the cyber physical system. This can be seen in the figure below.

At this step, the focus should be on establishing a near complete picture of relevant assets, increasing the connectivity amongst existing technologies, and develop an overview of what one want the system to do and how it should perform. In addition to lay the groundwork for data collection and storage, there should be put thought into how this data is to be presented. A picture could say more than a thousand words and our eyes are a very strong sensor, therefore it is only reasonable to try to enable visualization at an early stage. Of course, with a limited amount of relevant data on operation and maintenance, a visualization tool will at first only have overview and presentation purposes. What is needed to start making an off-line visualization model is, according to Visco, merely the blueprints of the assets in question from the design phase.

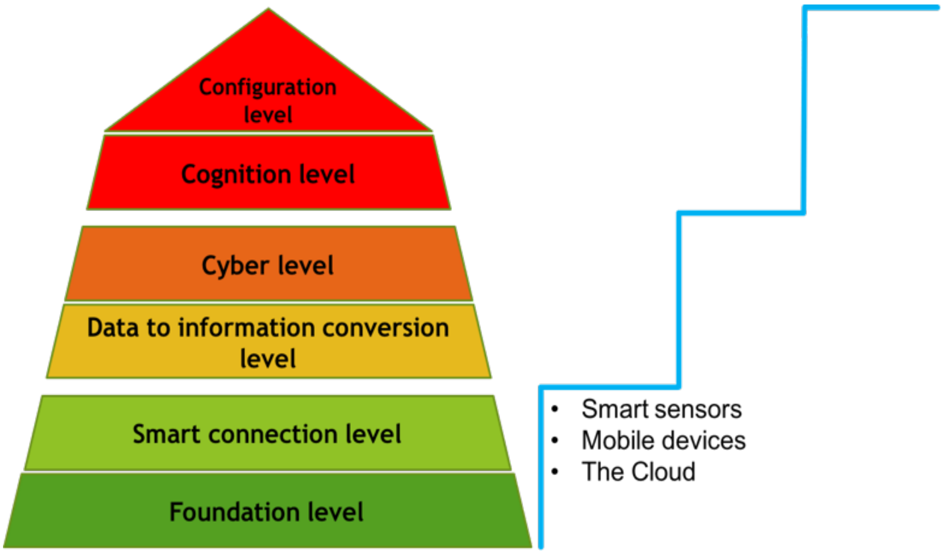


Figure 32 Digitalization architecture adopted from Lee, et al. (Lee, et al., 2015) and approach, step 1

A data centric approach, where one gather data from throughout the value chain and modules of the system has already been mentioned. A consideration on how to get this done is needed. To start changing the mentality amongst stakeholders from that “the data is ours” to “the data should be shared” is vital. There need to be a realisation that the real value of data can only be extracted if one get access to the relevant data when you need it, and this can be done through an established platform to share data. A decision should also be made in the industry whether one want to standardize representation and exchange of digital product information (ISO 10303) as is Jotne´s views, if there should be an open (vendor neutral API) or a private (closed API) solution. Bandwidth and frequency challenges due to growth of connected devices and different data sources should also be considered, thus figuring out what protocols are the best fit for the case of offshore wind (Postscapes, 2017). According to Knight (2016), if this is not organized it could develop into islands of activity, controlled by a few companies without good connectivity and agreed standards. The main target should be ensuring that different intelligent platforms can communicate easily with each other.

Regular sensors that can utilized in a smart way or smart sensors are needed for the data acquisition, and their number will only increase. Sensors are already in use on the wind power asset. For a more complete set of relevant data should sensors also be considered implemented in the offshore support system, thus including the offshore logistics parts of the wind farm system. This can be expanded to the onshore support system, including the storage and handling of daily work processes. The mobile devices are a vital part of the initial communication between the different part of the system, and critical for both todays and future information sharing. These devices are important with respect to visualization, especially in the longer term when extensive amounts of data require new ways of representation and understanding. Visco focuses on what makes the cloud technology and use unmatched, that it enables distribution of heavy information onto a light or simple unit.

6.4 Step two, develop a data to information conversion and cyber level

Data to information conversion and cyber level make up step two. With the foundation and smart connection level established, the industry 4.0 technologies seen to follow at this step is Big Data & analytics, Industrial Internet of Things, simulation & optimization, and vertical & horizontal integration. These are technologies seen to be at a stage where they today have yet to fully reach their potential. People would know what they are, but not necessarily know how to properly use them or within what areas they might be relevant. Since there is a potential for further development, these technologies are therefore regarded as relevant to step two and is shown in the figure below.

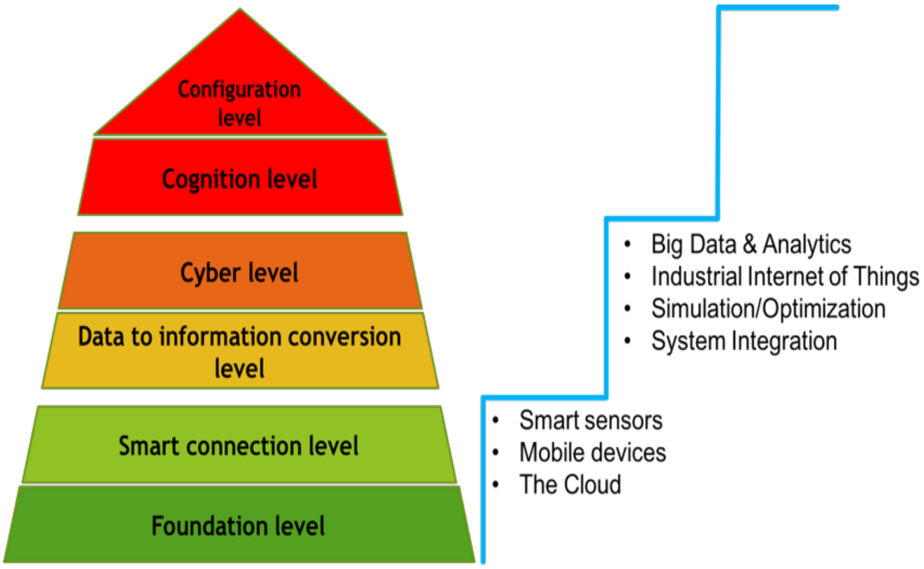


Figure 33 Digitalization architecture adopted from Lee, et al. (Lee, et al., 2015) and approach, step 2

With the ability to gather and organize data established at step one, the data to information conversion level is mainly about enable processes to use the gathered data. Such as develop algorithms to perform simulation, descriptive and diagnostic analysis, essentially converting the data into information. A level where the wind industry is at or close to already today, according to Statoil. The RAMS database as presented by Hameed, et al (2011) and the framework for data integration by Nguyen, et al (2013) are solutions that may very well be feasible at this stage. Bearing in mind that the focus need to not be on only the wind power asset of the modules or the O&M part of the technical life cycle systems.

With data converted to information, simulation and optimization of, for example turbines, the installation process and day-to-day logistics can be performed. Simulation can over time be further extended to include more details on existing simulations and on a larger portion of the wind farm system. This also counts for optimization, where with more robust data knowledge we should be able to perform optimization tasks considering a larger set of variables and creating an output that with good confidence could advice on decision making at both module 2 and 5. At this level, large volumes of data and further analytical developments create the need and possibility to extract value from the generated data so that Big Data & analytics come into its place.

At the cyber level, Lee, et.al (2015) write that one shall establish the cyber physical system. This mean one shall establish a connectivity between the data generating assets and systems, the data analysis systems and the other support systems. By combining the smart sensors, data lake, cloud, and a wireless connection the products will be connected and one will be taking the first steps into an Industrial Internet of Things. The first step of connectivity is established between one physical asset and its simulation or digital model. By combining the underlying technologies, the IIoT will enable connectivity between several physical assets and their corresponding models into cyber physical systems. As the focus is largely on the wind power assets, it is reasonable to expect the connectivity to be established there first. And following this, the support vessels and personnel of the offshore support system. Adding the mobile device technology used throughout the system and applying the IIoT concept further, the entire system should have the capability to be connected.

Through the data-centric approach, now with both historic and live-data, an increased further knowledge on the gathered data can be obtained. A more advanced level of computing and algorithms create the ability to perform analysis and monitoring on a higher level such as prognostics, performance and condition monitoring and structural health monitoring Lee, et.al (2015). From this, the connected products and systems can be turned smart. Big Data & analytics, IIoT, simulation and optimization enable the products to have self-awareness and self-comparison abilities.

A digital technology platform is the building block for a digital business and are necessary to break into digital (Gartner, 2016), utilizing the connectivity and link between the systems enabled by the cloud and IIoT. A digital representation of the main assets and the supporting system is necessary to fully utilize the different technologies explained under the Industry 4.0 concept. At the cyber level one should be able to create a digital twin, a dynamic software model of a physical system (Gartner, 2016). Being able to have a complete overview of all assets, data, processes, operations and so forth during step two might be somewhat ambitious, but if the job is done at step one it should be feasible to have established a digital model on the most critical assets. The cloud based digital twin can first be created for every turbine, effectively monitoring the turbine´s real-world operating conditions, giving us a complete view on the assets. The digital twin utilizes digital models of the assets to enhance production and optimize operations and maintenance planning for the fleet of wind farms (GE, 2017), with Big Data & Analytics, IIoT and Simulation & Optimization technologies well integrated into the wind farm system this is within reach. Artificial intelligence is at this stage seen to be possible to implement on parts of the system and neural networks learn from examples, recognize patterns and use past measurement data to make forecasts and models regarding future behaviour (Gorges, 2017).

People & processes are vital for the digital transformation. The process of establishing a digital twin should be undertaken early, possibly before the underlying technologies have been implemented and facilitated for such a development. Being able to agree internally in the organization and externally, among operators and service personnel is challenging as they all have their different agendas. Firstly, the equipment suppliers want an increased understanding of how their equipment function during operation for them to provide more attractive products and services. Secondly, the services suppliers want a better understanding on the condition of the equipment they operate for them to operate safer and more effective and efficiently. Thirdly, the operators want increased knowledge on how to reduce risk, increase efficiency, effectiveness and production (Ramsøy & Furuholmen, 2016).
These discussions should have a high grade of importance, because without having a clarity on who owns the data, have user rights and agree on shared information one risk never being able to break down the silos. One will not be able to utilize the full potential of new technology and the user experience will be poorer, which could result in a failed digitalization of offshore wind. Considering this, horizontal and vertical system integration is dependent on several factors and are as important as it is challenging. Therefore, being able to implement such a system integration at step two would be ideal. By fulfilling the demands of stakeholders, the technological requirements and combining technologies, one should be able to reach the cyber level and having developed a smart connected system.

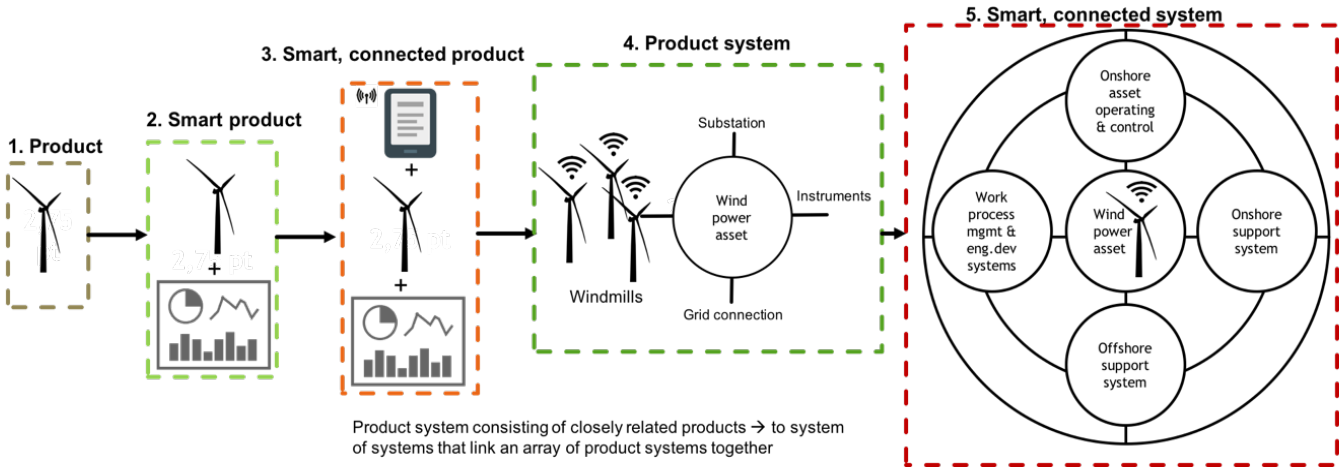


Figure 34 Smart connected offshore wind system, inspired by Porter & Heppelmann (2014)

A description of the digitalization process from a single wind turbine to a cyber physical (or smart connected) system, from the foundation level to the cyber level, can be seen in the figure above. At the end of this step, is it reasonable to expect that the entire offshore wind farm is well into the process of being a smart connected system. Sensors, connectivity and peoples & processes are enabling the systems to generate data, communication and sharing, opening for more knowledge and remote operations.

6.5 Step three, enable for increased cognition and configuration level

Having reached the cyber level, going further to step three is where the true potential of the Industry 4.0 concept is unleashed. It is during this step, you first can claim that a truly digital transformation of the organization has been made. The Industry 4.0 technologies seen to reach their full potential at this step is augmented reality and autonomous robots. This is due to their dependency on the underlying technologies expected to work properly, that strategy and leadership have been successful and that the humans are prepared and properly skilled. As mentioned earlier in this chapter, a dynamic and organic technological development and digitalization process is expected, this also counts for augmented reality and autonomous robots in isolation. Autonomous robots in the form of drones, are possible not too far into the future, however, having autonomous SOVs, wind turbines and entire wind farms are further ahead. This is what has been considered in this conclusion. Augmented reality is technology that today are experiencing a hype, and we are starting to see its potential (GE Digital, 2016) . However, establishing a killer use case for augmented reality in offshore wind is still needed today and before reaching this, augmented displays could be used to support tele operated robots and control drones.

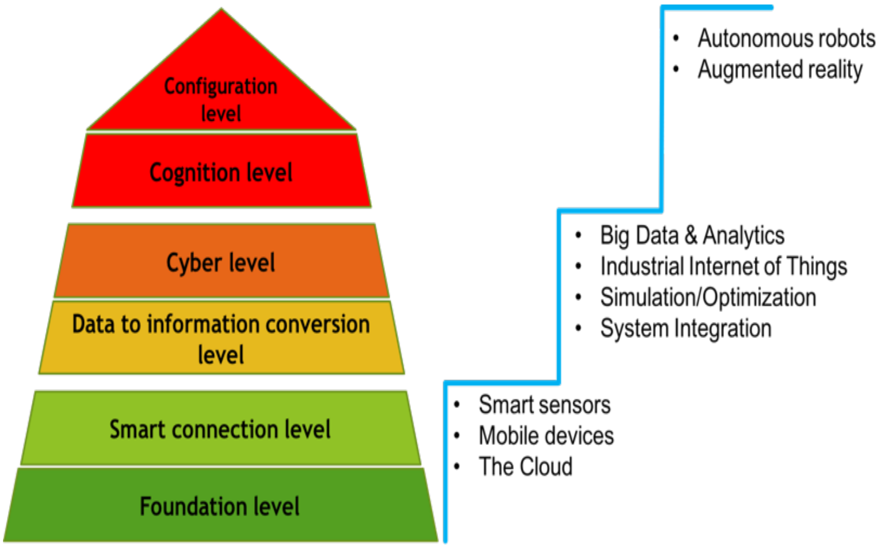


Figure 35 Digitalization architecture adopted from Lee, et al. (Lee, et al., 2015) and approach, step 3

What is clear is that for people to fully utilize the capabilities of digitalization, visualization keeps coming up. With ever increasing volumes of data being generated and analysed there need to be a new way in presenting information, easing the cognitive effort needed of the operators. With a digital twin developed, using this established connectivity to software and smart data to present truly enhancing visuals, information on status, faults, logistics, and the comings and goings throughout the system is centre of attention at Lee, et.al´s (2015) cognition level. Visco champions the creation of a virtual collaborative environment, a common operational picture, where what is visualized offshore is the same as what is shown in the control room. With the wind power asset in centre of the attention, and with the same system perspective as in the management model, visualization can be a powerful instrument for communication, cooperation and decision making. Included in the data lake or data warehouse are also the different systems utilized by the different systems of the wind farm, systems for operation, maintenance, document control, inspection and so on. These systems tell us when to perform maintenance, what your output is and so forth an historically have they been in different silos, for instance and ERP system, maintenance system, notification systems. Arguably, the modules or systems of the entire wind farm system are in practice functioning in silos as well, they live in their own worlds.

The idea is that if the digitalization process is done properly, through the architecture described by sharing and visualization of data, these silos will be broken down. The large amounts of data and intelligence driven from the edge to the data lake and turned into value, enables H2M, M2H and M2M communication. What differs from today is that at this step, the systems are aware. We should be able to use increased knowledge on improving operation and maintenance procedures, from wind turbine condition, support vessels logistics, maintenance personnel routines, onshore storage facilities and parts ordering to general coordination between the modules. At this stage, if all the steps and levels have been performed with success and the organization are at a satisfactory level, artificial intelligence will enable not only the turbines, but the entire wind farm system to learn from data and optimize their operation.

With an increasing number of turbines and farms connected, this can drive a heuristic feedback process that generate more and more learning, this is fleet learning. Klein (2017) calls this the new network effect and could have large implications on the annual production and value creation. Fleet learning are possible through the further digitalization of the industry. When Big Data & analytics are combined with IIoT, this enables increased optimization capabilities. A fleet of wind turbines, later a fleet of wind farms, connected to each other and to the other parts of the system, the machine and human cognition are improved, leveraging and extending human capabilities. With respect to M2M communication, if a wind turbine detects an anomaly or experience a change in output due to weather conditions, this can be recorded and sent to module 2 or the cloud, which distributes this learning to the other wind turbines. In the case of a wind gust for instance, the wind turbines further back in the formation could then alter their settings and be better prepared for when the gust arrive. Another situation is, as already mentioned, a wind turbine in front of several other wind turbines could alter its pitch to enable an increased output for the wind turbines in the back.

Combining all this with weather forecasts, electricity demand, grid capacity, expected production and so forth, the wind farm could essentially self-configure, self-adjust and self-optimize. Regarding M2H communication, the onshore asset operating system and the offshore support system could get “advice” from prescriptive analyses on specific wind turbines. Autonomous support vessels could suggest alteration to the maintenance procedures through pattern recognition and machine learning optimizing the logistics of transferring personnel or maintenance robots to each specific case. Additive manufacturing, as mentioned could serve an important role on these vessels or either on offshore platforms or onshore bases. One should never settle and there will always be challenges ahead that need to be identified. This poses questions for further consideration: How will the industry platform evolve from this stage? How will new technology affect the situation when one arguably is already a digitally transformed organisation? The company should try defining or envision how technology will evolve and plan on how to meet them.

7 Technical capabilities parallel to the Digitalization framework

Parallel to the digitalization framework is the human skills, competencies and experience together with the technologies cybersecurity and additive manufacturing. These are not positioned on the side-line and forgotten, but should be treated as equally important to the success of reaching digital transformation and are seen to contribute each in their own way. This is illustrated in the figure below, showing the continuous parallel development of human skills and competence, cybersecurity and additive manufacturing.

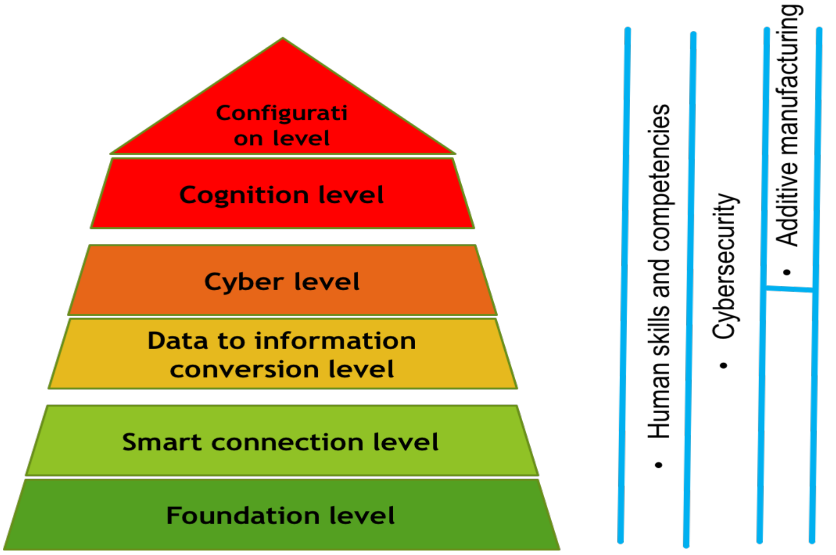


Figure 36 Digitalization architechture adopted from Lee, et al. (Lee, et al., 2015) and parallell development approach

7.1 Cybersecurity and additive manufacturing

Cybersecurity are today given much attention in media and its importance will only increase as more of the industry and the global community are turning digital. Having a high level of safety and security embedded in software related to the discussed technologies is vital. For instance, to establish the cloud technology, there need to be a confidence that the safety and integrity of the cloud solution is sustained. Further, through step two of the digitalization approach, increased connectivity amongst assets and the system may create isolated cybersecurity solutions between the systems. This could enable loopholes to be exploited needing more resources allocated to this task preventing attacks and incidents. At the highest levels of the framework where machines can make decisions and have increased control, avoiding any entry into these cyber systems would need high priority. If the scenarios and forecasts of the increased share offshore wind will have on the total energy mix come true, experiencing a shut down or a disconnection from the grid through a cyber-attack could have severe consequences. Cybersecurity would need to be maintained and developed throughout the digitalization process, and further.

Additive manufacturing, not too closely linked to the other technologies, is seen to experience a large technological development. For the technology to experience a wider application, a supporting framework, and industrial standards is needed with priorities on terminology and general principles to create the groundwork for standards (Tranchard, 2015). Possibly, throughout the time when having reached the cyber level, additive manufacturing technology could be able to contribute, such as described in Section 3:5.4.

7.2 Human skills, competencies and influence on digitalization

Parallel to establishing the technical infrastructure for a future digital transformation, should there be a focus on the humans and their influence, skills and competencies. It is not enough to rely on that the correct combination and implementation of technologies does the trick in digitalizing an offshore wind farm. The human factor, human talent, people as change makers, role of human resources, behaviour and the human element in its entirety is getting more and more attention (Abraham, 2016; Hart, 2016; Segertåhl, 2016; Accenture, 2016). Below is an elaboration on how to approach the people throughout the digitalization process.

7.2.1 Human aspect at step one

An organization today with its culture, procedures and routines are well worked in, changing it is hard. But since the wind industry is dependent on technological and organizational change to be competitive, that might ease this process. However, humans cannot be programmed, handled, implemented or ´managed´ to change. The humans need to understand why digitalization is being done and feel inspired to be a part of it (Day, 2017). Involving the humans are vital, keeping them updated on the leadership-decisions for change and how this is done. The people with practical know-how that can participate in creating a product as best as possible should be having a high focus early in this process, involving and engaging them along the way. Day (2017) points to that there will be required a radical change in organization of companies, the importance of emotional intelligence to reduce the leadership gap, and that a leader must learn to create cultures with a can-do attitude.

At this step, one should establish a digital strategy and creating pilot projects to establish a proof of concept, thus having a leverage or founded argument when introducing the future strategy of the organization. Advisian (2017) focus on designing based on a continual cycle of empathizing with the human experience to find opportunities, and laying the focus on benefits of an object or a technology to the side, Design Thinking. This, however, must not go on compromise with the system integrity when developing or implementing software;

> *"the system integrity level cannot be validated at the end of the project by testing the system in the factory or on site. System integrity must be built into the system by means of system requirement specifications, design specifications, design verification, and testing, integration testing, system validation, etc. concurrently and with the right timing as part of the system development process."* (Tiusanen, et al., 2012, p. 37).

Getting digital transformation right the first time is hard so there need to be a great motivation behind the digital initiative and being ready to accept failure. Vital in this is using all learnings to update the strategy and develop a robust business model (Danielsen, 2017). A high level of foresightedness is crucial, one need to get hand of the right skilled people. People with “old” tasks should be considered given new positions to give them a chance to start fresh leaving old procedures and routines behind and easier establishing relations to the change process. A digitalization process is seen to be a long-term project where the digital transformation is reached first after maybe 5-15 years. Cultural change is hard, and the outmost consequence of the digitalization process is having to completely restructure the organization, from changing the structure and hierarchy itself to replace the people working there.

7.2.2 *Human aspect at step two*

According to Advisian (2017), when we develop technology to solve a problem, we should continue to monitor how our technology is used. We should know what are the experimenters doing with the technology, whether someone use the technology in an unexpected way – and whether they develop any ideas. At this step, the humans will be in the middle of a digitalization process, new systems will be introduced, while older systems would need changes or still need to be run in the wait for a better solution. Getting people to use the new technology is one thing, making them see the purpose of it, its possibilities and keeping them from falling back to old routines is another. A culture where the people of the organization are championing digitally driven improvement is vital, one need to truly engage to make it happen. Involve people in the creative process, encourage critical questions and let people establish an ownership to the digital transformation they are a part of. Important to mention and focus on is that whatever technology the people are using, it should just work, and it should be easy to use.

Dashboarding for example, business intelligence such as Microsoft Power BI, enables people to quickly do productive work because of access to clean data, visual analytics and mobility (Microsoft, 2017). Arundo focus on social and collaborative features, a Facebook of the machines, where all stakeholders agree on sharing access to data and establish a higher level of transparency. Sharing data to its advantage, and gaining access to when you need it, whether this is on an onshore or offshore module should be in focus at this step. What is described here is believed by the author to be incorporated in the term mesh, which Gartner (2016) explains as the dynamic connection of people, processes, things and services supporting intelligent digital ecosystems. At this step, with the establishment of a digital platform, humans and machines should be able to communicate through sight, sound and tactile, resulting in a big change in user experience as this evolves together with technology.

As already mentioned, the user experience is also increased through visualization, if a person want to know where the support vessels are, this is shown in a map and not by merely coordinates. If a technician want to know where the fault lies, it should be shown where on the turbine and not only the identification number or tag of the vibration sensor. The fault should be shown and visualized, if there is a crack or if there is an electrical error, not just listed. As an example of increased user experience for an operator, following the predictive analysis performed by a computer and there is a component that need changing, a set of processes should have started automatically and be available to all relevant personnel. This could be, a maintenance plan suggestion, a relevant storage inventory overview (or the 3D-printer have started production of said component), available maintenance personnel overview, vessels locations, previous lessons learned on similar work and so forth should be easily available and visible. If recurring faults are identified this should be communicated to module 5, or directly to manufacturer to initiate a component improvement program. All this information will be easier digested if it is shown and visualized and not only listed.

7.2.3 *Human aspect at step three*

A digitally transformed company will utilize a large set of technologies that, if put together and implemented in the correct way, will have a positive impact both financial, social and environmental. The machines will be able to do a lot of the work themselves and work as support functions to humans in other areas. That the machines will take over a large part of our work processes and responsibilities is a definitive. But the humans will not go away and the robots will not take over the world, at least not right now and the potential robotic takeover should not be loaded with negative undertones. The reason for this, is the same as for why the combination of man and machine have the outlook to be an utter success. This is because people and computers don´t approach the same task the same way (Brynjolfsson & McAfee, 2014). Ideation, the formation of ideas or concepts, large-frame pattern recognition, and the most complex forms of communication are the cognitive areas where people still have an advantage and are what separates us from the computers. According to Brynjolfsson & McAfee (2014) have we never seen a truly creative, entrepreneurial or innovative machine, that there has not yet been a software writing a really good software. Computers are far from useless, but they´re still machines for generating answers, not posing interesting new questions. There will still be components needing to be changed that robots cannot do, for example a filter change need to be done by an on-site technician.

The underlining thought here is that at this step, where the offshore wind system is approaching or are at a digitally transformed state, there will still be need for decision makers, people monitoring, coordinating, organizing, performing maintenance, supervising installations, being creative and so forth. With the increasing share of data acquisition, control and analytical tasks handed to the machines, the humans will still be doing the innovative work, deciding on trying new solutions, and fail. But due to the help of machines we will fail and realise our mistakes faster, and we will succeed faster and more often. This will continue, when one benchmark has been reached we go on and try improving the next thing, at an increasing tempo. However, to get there we must do the digitalization right, the success of complete digital transformation is not only dependent on the right set of technologies, it also depends on leadership, culture and capabilities (Larsen, 2017). With the processes of where we interact and how we use the computers need to be thoroughly thought through. It is teams of humans with machines with better processes that are the winning formula. Machines are excellent within their frame, humans have the ability to think outside the box and with a proper plan on how to execute this combination we will see an offshore wind farm system run as smoothly as any pit crew in Formula One.

8 Established step-by-step and continuous development approach

As mentioned above, digitalization is not solely dependent on technologies, however, successfully implementing and combining technologies at the right timing is important. Figure 37 shows the combined approaches, the technologies following the step-by-step approach and the technological capabilities seen to be following a continuous development approach. Bearing in mind that digitalization is to happen throughout the offshore wind farm system, the take from establishing this framework is the high demand for maintaining a clear overview and coordination of the digitalization activities within the different modules. This is, to the greatest extent possible, to enable the entire offshore wind farm system modules to develop at the same rate. Ending up at a state where only parts of the offshore wind farm system has truly digitally transformed into the targeted state would be a step in the right direction. It is reasonable to believe that this could happen, however failing to elevate the other modules to the same digitalization level return an offshore wind farm system where the system connectivity and sharing potential is not fully utilized. Failing to do this could then implicate the different life cycle activities and work processes within, not reaching worry free production and near zero breakdown.

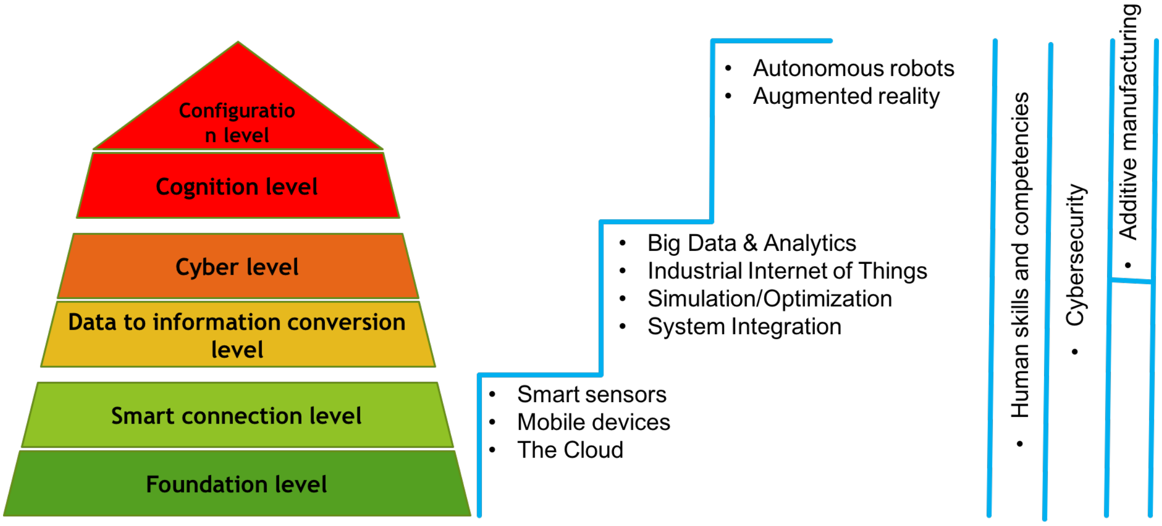


Figure 37 Complete framework for digitalization. Digitalization architecture adopted from adopted from Lee, et al. (Lee, et al., 2015), step-wise and parallel approach.

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Section 5: System Changes and Managing the Change

The following section focuses on having reached a complete digitalization of an offshore wind farm, the evident changes needed to an offshore wind farm system reaching this state and how to manage the change. The figure below shows the connection between the adopted 5C architecture, the discussed technologies in their step-by-step and continuous development approach, and the smart connected system with foundation layer and the decision and visualization layer on top. Having reached the top level of the 5C architecture and having established a decision and visualization layer parallel to this by combining the set of technologies and capabilities, it is reasonable to expect the wind power asset management system to change together with the physical interface.

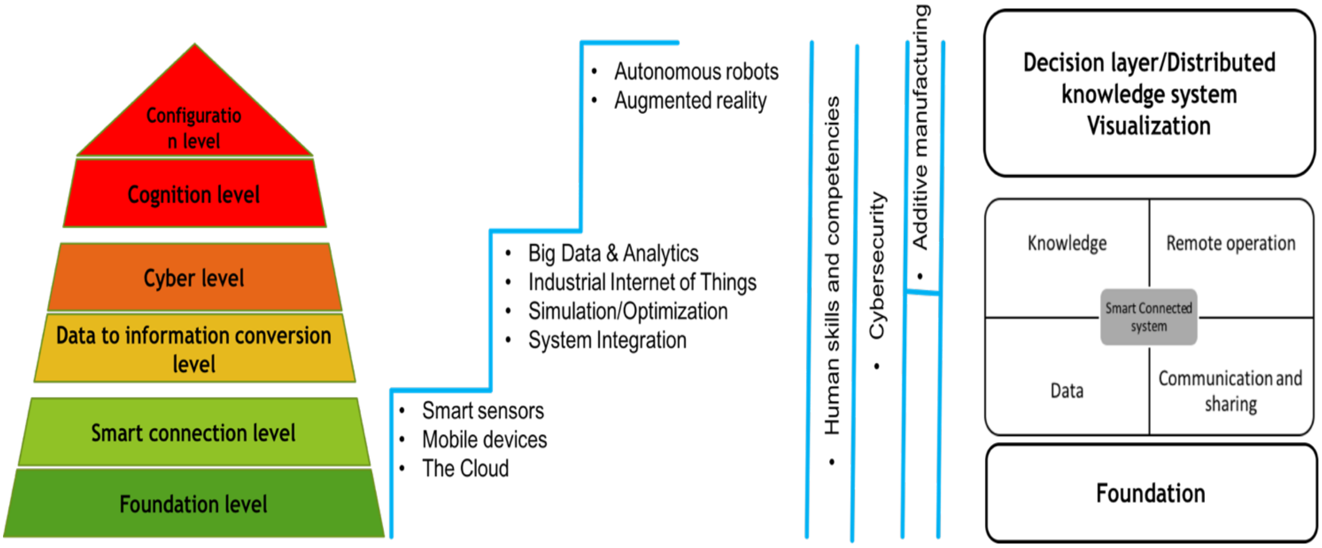

Figure 38 Connection between the systematic framework and the expanded smart connected system. Digitalization architecture adopted from Lee, et al. (Lee, et al., 2015)

9 Offshore wind farm system adaption to new technological climate

This chapter focus on the further development or adoption of the wind power asset management architecture presented in Section 1:2.4 It takes into consideration that especially through the IIoT and the cloud, the interfaces and the work-related input and output between the different modules is seen to change. The physical asset systems, the support systems and their functions and tasks is seen to inherently be the same as before. With the major difference being the eased and increased connectivity between them sought to increase and distribute sharing and knowledge.

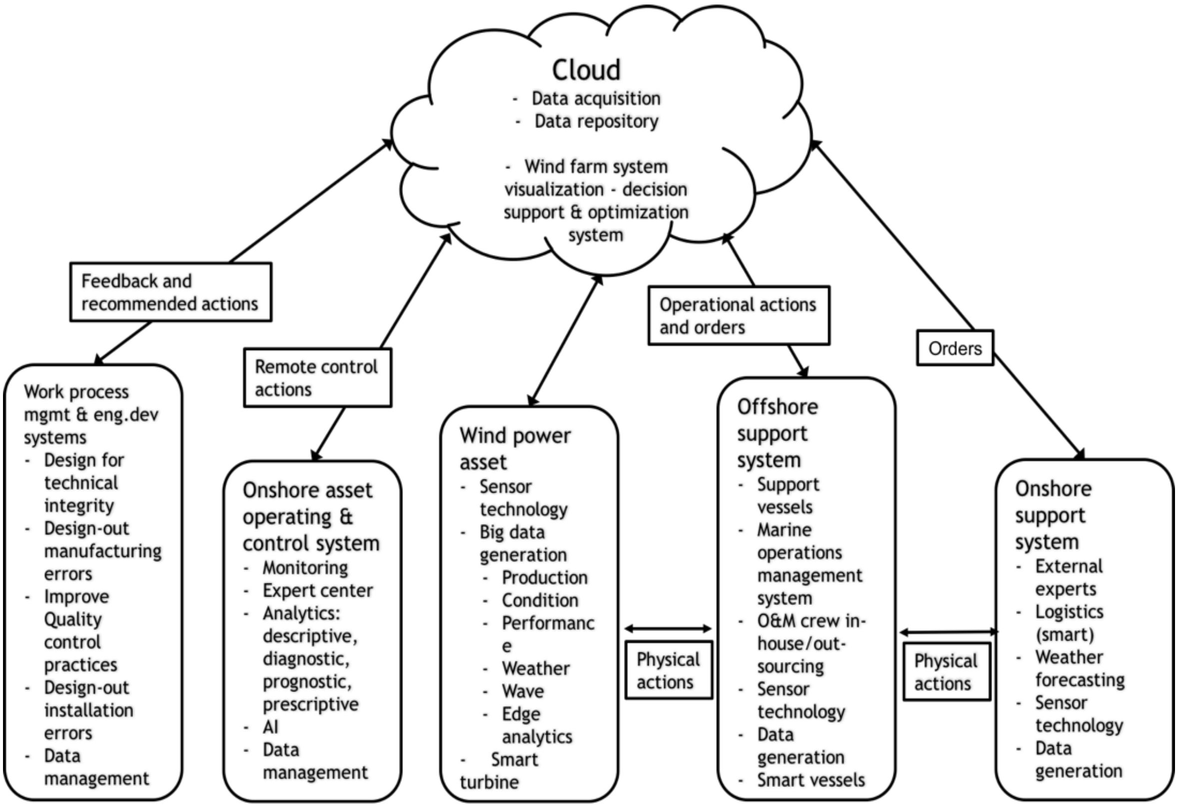

Figure 39 Updated wind power asset management system, inspired by (El-Thalji & Liyanage, 2010)

9.1 Industrial sharing and visualization platform

9.1.1 Break down the silos

The cloud and corresponding software will facilitate for the arrangement of data obtained throughout the offshore wind farm system. In figure 39, the analytics is set to be performed at the onshore asset operating & control system, this is just a suggestion as the analytics could also be performed in the cloud or partly at the edges of the system. The focus should be on this system´s ability to enable information-sharing and communication, and Figure 40 is explaining how the cloud could be segmented. The lower segment is where data from different entities are gathered and the dotted line indicate the data repository, where data could exist in raw format or analysed data from either the edge or from an analysis centre. If gathering data in this manner is successful, it could mean that one succeeds in breaking down the silos. This relies on a great confidence in connectivity as data and information would flow back and forth between the cloud and the modules. It also relies on that all data are accessible or as much as possible is made open for access.

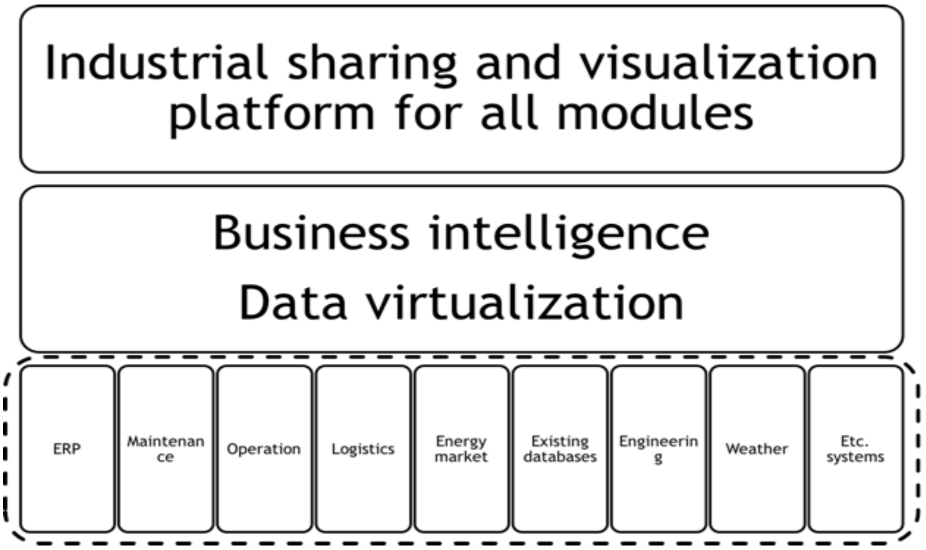

Figure 40 Suggested segmentation of the Cloud system

9.1.2 *Extract the value of accessible data and make it understandable*

The business intelligence (BI) section work to make sense of the different data and include the applications, infrastructure and tools to generate information and knowledge. The BI is the area where data in different forms are given deeper understanding. One example could be that the prescriptive analysis performed in module 2 is considered in relation to vessel and crew status, other prescriptive analyses, lessons learned and so forth to support decision makers as much as possible. It is here where implemented AI could enable learning as more and more iterations are made and situations encountered, thus over time establishing greater confidence in proposed decisions. This could potentially lead to a state where tasks and decisions, up to a certain level, could be handed over to the software. This area however, where machines makes high level decisions potentially affecting large portions of the organization needs thinking through to find a suitable solution with potential barriers to not take any chances. Data virtualization are central in the BI context, where some of the capabilities of data virtualization are; the ability to perform data federation, deliver data as requested by users, data transformation, quality improvement and integration of data depending on the requirements (Techopedia, 2017). In addition to this, data virtualization provide the abstraction layer for the platform to hide complexity and simplify information access (Cisco, 2017).

9.1.3 *Make the information and knowledge available to relevant persons and stakeholders*

On top is the industrial sharing and visualization platform that is seen to operate as an information distribution solution. The data and the business intelligence are the underlying criteria for the sharing and visualization platform to be established. This platform can contain applications, dashboard, portal and tools to enable all relevant parties, throughout the value chain of the wind farm, access to information and knowledge from any location. This platform is to be viewed as the decision layer above the smart connected system and parallel to the configuration and cognition level of the 5C architecture. Where outputs are easily obtainable, understandable and accurate, serving as the decision makers´, operators and technicians right hand and confidante. This relationship is visualized in the figure below.

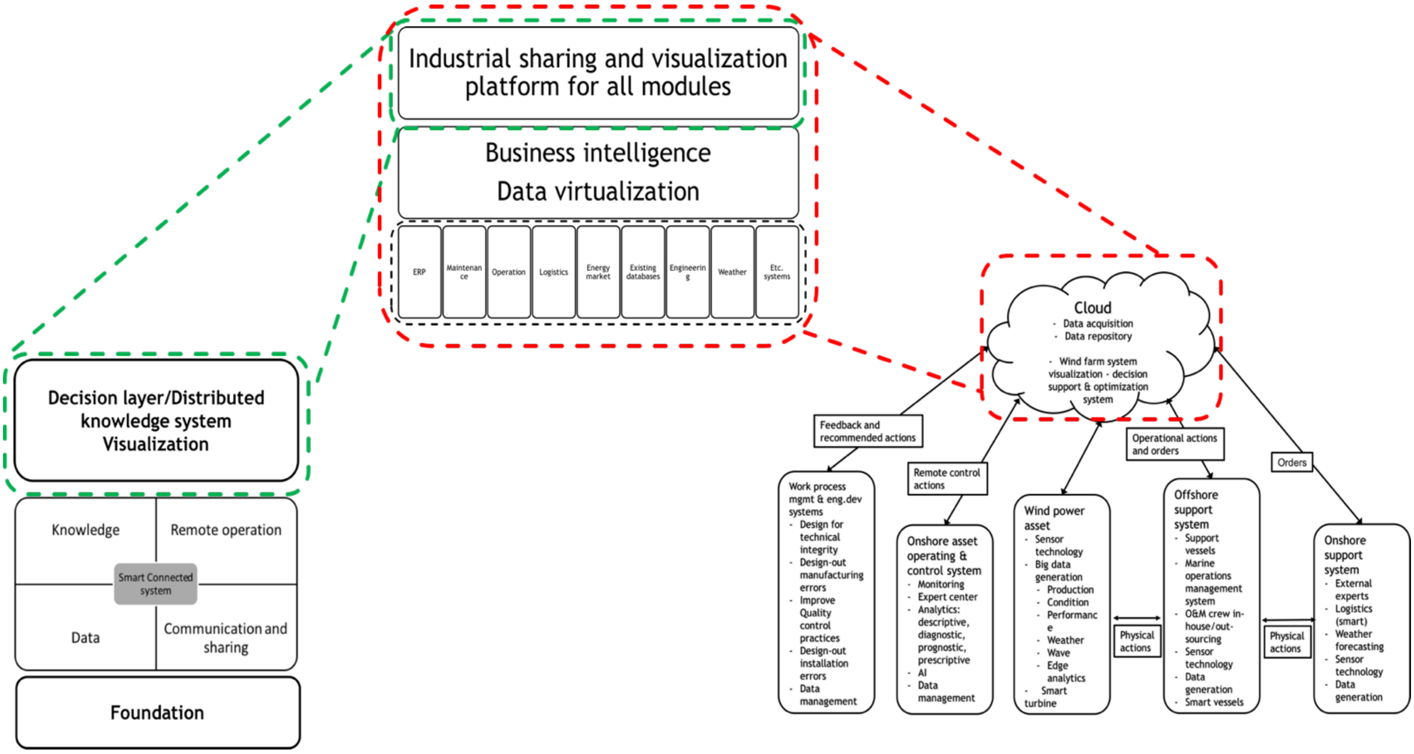

Figure 41 Connection between the cloud and the, decision and visualization layer

The platform will be an industrial social collaborative solution where workers from different companies or segments could interact and potentially improve work-processes, not having to wait for a printed-out piece of paper for instance. An interactive industrial community that through the federated and analysed data and expert knowledge together will establish a more complete decision base for problem solving, a distributed knowledge system. The entire platform should be flexible and scalable, when an increasing number of farms are planned, installed and operated, they should be included in this solution. The same goes for different stakeholders throughout the value chain, with a limitation to access depending on the time of contribution to the project, following a hierarchy and so forth.

Following this should there also exist a solution for knowledge transfer and an overview of who knows what.

9.2 Physical interface

Given that a decision layer of this sort gets established it could also have implication on the physical interface diagram described in Section 1:2.4.1. The main interface still being remote control and communication, however, it will be relieved from several work tasks and processes due to the established autonomy amongst the assets in the different modules. The diagram in Section 1:2.4.1 show that individual-assessed databases needs integration and responsible sharing, considering the described solution above, it is seen that the distributed knowledge system enabled through digital technologies could do just that. Considering the physical interface diagram, it highlights the information of life-cycle processes and the input/output of sub-systems representing the information creator-user relationships. A distributed knowledge system, an industrial social collaboration platform would enable a different user interface when it comes to messaging, notification and work order systems and user interface in general. Given a more lenient sharing approach and open access solution amongst stakeholders, it would return a more complex physical interface, but where the information creator-user relationships are more flexible and the information more obtainable.

Section 6: Discussion & Conclusion

10 Discussion

This thesis´ scope was focused around how existing and developing technology, comprised by the Industry 4.0 concept, could be organized into a framework for further improvement of offshore wind farms. This was done by exploring how these technologies could enable the offshore wind industry to tackle some of the challenges for it to be a true competitive new energy solution in the years to come. These technologies where: mobile devices, smart sensors, simulation/optimization, augmented reality, autonomous robots, cybersecurity, the cloud, additive manufacturing, IIoT, Big Data & analytics, and horizontal and vertical system integration.

By first establish the theoretical foundation of the state of offshore wind industry, their challenges and an overview of buzzwords related to digitalization, a set of relevant technologies from the Industry 4.0 concept could be identified. An elaboration and mapping of these technologies was conducted, this was crucial in establishing the systematic digitalization framework. Elaboration and discussion on the established framework resulted on some key points on how the offshore wind farm system could change due to digitalization and how to manage this change. Therefore, it is of the authors conviction that the defined scope of work of this thesis have been achieved.

The offshore wind industry is still a maturing industry that experience challenges throughout the value chain. Digitalization is a buzzword that explains the increased use of digital technology in an organization. For the offshore wind to cope with their challenges to obtain worry free production and near zero breakdown, a move to a digitalized remotely operated and controlled system that extract the value of all data generated and turn it into value is inevitable. Increasing the level of digitalization is linked to, but not confined to, implementing different technologies at the right time.

A future with an offshore wind farm system where the modules are autonomous to the largest degree possible, with a distributed knowledge system for making use of the increased connectivity, is foreseeable and realistic. This depends on a set of factors ranging from establishing a ground level overview of the entire system to getting different technologies, modules and stakeholders to enhance each other’s capabilities while not forgetting ourselves, the people, in the middle of it all. Given the successful digitalization of an offshore wind farm into a smart connected system, it is reasonable to expect and increased level of complexity. The development of a decision and visualization layer to cope with this complexity, work as a distributed knowledge system supporting the established connectivity, support decision making, and enabling the maximum extraction of value from the generated data is suggested.

The Industry 4.0 technologies considered, and their relation to digitalization of offshore wind, was discussed and mapped. Finding that cybersecurity and additive manufacturing is seen to could develop parallel to the stepwise implementation of the remaining technologies. Furthermore, where the technologies to potentially have the greatest impact on the offshore wind farm, meaning the ones that are relevant throughout the entire system, identified as mobile devices, Big Data & Analytics, IIoT, the Cloud, horizontal and vertical system integration and cybersecurity.

The offshore wind industry´s approach to new technologies is quite liberal, resulting in the industry finding itself already well on the way of having start digitalizing parts of an offshore wind farm system. The industry is already performing prognostic analysis on wind turbines, have established onshore control centres that monitors the offshore wind farms, performing simulations on both installation and maintenance work to obtain best possible solutions and continuously looking for ways to improve the reliability of turbines, installation procedures, maintenance planning, manufacture more reliable components and so forth. Where the industry still is lagging in terms of a digitalization process is the horizontal and vertical system integration, finding the optimal solution for sharing and open access of data and documents between stakeholders. Also, establishing a connectivity between the modules of the offshore wind farm system is necessary for and offshore wind farm to reach and work its way into step two of the digitalization framework.

10.1 What is learned

The work on this thesis has provided the author with a deepened knowledge and understanding on the complexity of an offshore wind farm system and the technical, organizational and operational challenges following a still maturing industry. In the process of covering the business and technological landscape of offshore wind what stands out is the vast number of different stakeholders and the great focus in continuous technological improvement. Being that this thesis´ main focus is on digitalization of an offshore wind farm system meant that the author needed obtain an understanding on terms such as digitizing, digitalization, IoT, IIoT, Industry 4.0, and so forth. In addition to this, learning a great deal on the digital technologies such as cloud computing, sensor technology, augmented reality, artificial intelligence and so forth was vital. The process of discussing and relate digital technologies with an offshore wind farm system, and establishing a digitalization approach opened the eyes of the author in the sense that taking on such an endeavour that digitalization is, would be an enormous challenge in practice. Starting a digitalization project, intended for the entire value chain and life cycle of and offshore windfarm is a great, long-term undertaking that involves people, technology and processes working extremely well together, requiring thorough planning and true commitment to succeed. However, the author has also learned that, if done properly, the benefits of digitalizing are great and could in general precede several of the prior industrial revolutions.

10.2 Main challenges

What proved to be a comprehensive exercise was the need for the author to enter and explore fields such as data-, digitalization-, operational and information- technology. Thus spending substantial time in getting an understanding of the technologies, how they could be relevant to offshore wind and what could be neglected. Further, the process of extending the smart connected system to also contain a foundation and a decision layer and that the digitalization process needed to consider both the value chain and lifecycles of an offshore wind farm while also including the different levels of the 5C architecture proved to be challenging. Keeping an eye on the red thread throughout the thesis, avoiding any pitfalls and not forget mentioning any important point was always in the back of the authors head.

With an increased level of digitalization, the different modules of an offshore wind farm get more connected, the data are aggregated from several locations, and following digitalization should also be the increased access of relevant information. In short, digitalization implies increased complexity and to present this in a simple and understandable manner could at times be a demanding task. Digitalizing is a concept reaching a lot farther than what has been considered in this thesis, it is a concept that have a different meaning to different people and industries. Concluding on a specific path to follow, assume how the future would look like and trying to state on how the offshore wind industry will develop is hard and there will be disagreements and exceptions.

10.3 Future research

Future research on the digitalization of offshore wind could be within several areas as we are only beginning to scratch the surface of digitalization. Some of these areas could be on economics, manufacturing, installation, logistics or O&M. Different perspectives could be chosen, either a system perspective, life cycle perspective or down to studying what programming, sensors, or protocols are the best fit for offshore wind. With that said, the author finds the following suggestions the most intriguing. Future research could be on increasing the level of details in each of the levels of the digitalization architecture and the corresponding technologies within the Industry 4.0 concept and see how to further adopt it to fit the case of offshore wind. Map the current and future skills and competencies of people working within offshore wind could prove to be an interesting task. Additionally, examine the general the state of the different offshore wind farm modules to get a comprehension of on what level of digitalization each module is at and to further establish what is needed to elevate each module to the next step of digitalization.

11 Conclusion

The offshore wind industry is facing several challenges for it to be a truly competitive and established alternative amongst renewable energies. This thesis set out to explore a range of technologies related to digitalization and analysed their potential impact on the offshore wind industry. It is evident that the wave of new and innovative digital technologies continues to gain momentum in a bid to help propel the industry to achieve better reliability, increased availability, optimized processes and increased value. Establishing an overview of these technologies and examining which combination provides the optimal benefits for the offshore industry has been a necessity. Due to this, a discussion on technologies encompassed by the Industry 4.0 concept has been conducted.

The technologies are at different stages of development and of different importance to an offshore wind farm. Where some higher level technologies are dependent on other lower level technologies to be either further developed or implemented into an offshore wind farm. Not all the technologies will directly affect the digitalization process. The digitalization process is defined as the approach to an autonomous system. As there are a range of technologies encompassed by the Industry 4.0 concept, not all of these technologies are fundamental in elevating the system to a higher level of digital capability. Technologies providing cybersecurity and technologies potentially improving production processes and reducing storage are therefore seen to develop parallel to a step-by-step digitalization approach. Given that the discussed technologies are either already developed or on their way being fully developed, the human aspect, and its increasing importance in reaching digital transformation is noticed and taken into consideration. Developing human skills and capabilities is vital in utilizing the full potential of a digitally transformed system, and could largely affect the end result of the digitalization process. Based on this, a proposed digitalization step-by-step approach has been established.

The proposed digitalization approach is divided into three steps with two levels each. Considering this, it appears vital that a thorough technical foundation is established prior to making any large alterations to today´s offshore wind farm system. This foundation level is the lowest level of the digitalization architecture and described as the basis for a smart connected system to be established. Having established steps for the digitalization process to reach the cognition and configuration levels, the author further argues for the development of a decision and visualization layer. This layer is seen to be established at step three of the digitalization approach.

The decision and visualization layer would act as an industrial social collaboration platform to facilitate increased interaction and sharing throughout the value chain of an offshore wind farm system. A further benefit would enable sound decision making and capabilities to fully utilize the capabilities of a near complete autonomous offshore wind farms. In the ideal world, this decision layer should be able to effectively manage the large amounts of data generated, thus contributing to real-time information sharing and informed decision making. A consequence of establishing a distributed knowledge system is the changing physical interface among the offshore wind farm system modules. This results in a complex physical interface, with flexible and scalable information creation relationships and easier access to the relevant information. The proposed solution is relevant throughout the offshore wind farm system modules, value chain and life cycle, making it a versatile and key component in driving success in the digitalization of offshore wind farms.

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