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Abstract

The technological advances have and are continuing to develop at an accelerating pace. One may argue that the speed has reached a limit that companies struggle to follow, something that may endanger their business model. The technological breakthroughs are announced so frequently, that a new need has emerged: a method for companies to identify how the rapid technological developments can benefit their business. A model that assesses the technologies up against their business segments and facilitates the identification of opportunities is thus necessary. This research undertakes this challenge and applies such a model to the industry. A suitable area to carry out this task is the offshore wind industry. The demand for sustainable power is continuously increasing, and the offshore wind industry has proved to be a highly promising solution when the massive challenge of decarbonizing the energy industry. This industry is strikingly fragmented, with few established procedures, especially within operations & maintenance (O&M). Furthermore, operational costs have to be driven down dramatically in order to prove its viability. The area of O&M is then an appropriate area for applying the model. The aim of this thesis is thus to identify and evaluate technological innovation opportunities in the O&M segment of offshore wind.

The model has five steps: 1) Breakdown of the industry and technology trends 2) application of technology trends to the industry segments, 3) identification of opportunities, 4) presentation and evaluation of opportunities, 5) presentation of the most promising opportunities through a business model canvas (BMC). The industry breakdown and the theory regarding technology trends (chapter 3 and 4) provides the theoretical introduction needed in order to digest the following chapters. Chapter 5 propose 14 innovative opportunities, which is immediately screened. Chapter 6 presents three of the most promising opportunities in the BMC. The offshore wind industry is characterized by harsh conditions and remote areas. This makes some technologies more suitable than others, and will thus be focused on in this research. Technologies that has proved to be particularly promising are MEMS sensors, Fiber Bragg gratings, LiDARs, AUVs, crawlers, drones, digital twins, distributed ledger technology, smart glasses, virtual reality and Big Data. The most promising opportunities that are identified in this research are: A method for monitoring scour with fiber optic sensors, a digital twin for data- and documentation control, and a method for remote maintenance support using smart glasses.

KEYWORDS: Offshore wind, Operations & maintenance, innovation, technology trends.

Abbreviations

AR	Augmented reality
AUV	Autonomous underwater vessel
BMC	Business model canvas
CM	Condition monitoring
CMS	Condition monitoring system
DLT	Distributed ledger technology
FBG	Fiber Bragg Gratings
FOWT	Floating offshore wind turbines
IoT	Internet of Things
IPR	Intellectual property rights
KPI	Key performance indicator
MEMS	Micro electrical mechanical systems
MG	Marine growth
ML	Machine learning
NDT	Non-destructive testing
O&M	Operations and maintenance
OWF	Offshore wind farm
OWT	Offshore wind turbine
PM	Performance monitoring
ROV	Remotely operated vehicle
SHM	Structural health monitoring
VR	Virtual reality
WF	Wind farm

Table of Contents

List of Figures

1 Introduction

1.1 Background

Today's industries are exposed to an increasing pace of technological innovation. An exponential growth in research allocated resources, and attention has led to a "second level" exponential growth in this development. Staying updated with these highly rapid developments has thus presented itself as a considerable challenge at which businesses are struggling to follow. Models and frameworks that address how companies of varying sizes and R&D budgets can undertake this challenge are therefore seen as a necessity for sustaining a healthy future business model. This thesis carries out a research, where such a model is applied, with a perspective on the offshore wind industry. It aims to identify and evaluate innovation opportunities emerging from technology trends in the operations & maintenance segment of the offshore wind industry.

It remains, however, a long way for the offshore wind industry to be competitive with other renewables. A significant degree of innovation in recent years has nevertheless proven that instead of being an industry based on practices from the onshore wind industry and the offshore oil & gas industry, it is now evolving to become a more characteristic and established industry. As the largest rotating machines on earth (IRENA, 2016), an extensive amount of resources, in fact, 30% (Röckmann et al., 2017), are put into operations & maintenance. Since new offshore wind farms (OWFs) are being installed at increasingly remote and harsh locations, serious efforts have to be implemented to avoid shortcomings in availability and reliability, and as a result, the effectiveness and quality of operations & maintenance in the offshore wind industry have to be dramatically improved.

The model used for conducting the research is developed to be completely generic, meaning that it can be applied to all industries and disciplines.

1.2 Objective

The objective of this research is to highlight that the dramatic pace of technology trends introduces major challenges to today's industries, and emphasize that there is a need for a structured way of identifying how these rapid advances can benefit companies. Furthermore, it will focus the offshore wind industry, and that the need for disruptive innovations that can reduce costs and prove its viability, especially within the O&M segment, has escalated. This is an industry that is gaining an increasing global attention and appears to be one of the most promising renewable industries. It is thus a highly relevant area to investigate how innovations can be achieved effectively. Thereafter, a model developed at the University of Stavanger by Knut Erik Bang and Muhammad Ahmad Tauqeer is applied, for identifying technological innovation opportunities. Specific ideas will be presented, with a thorough presentation and evaluation. The thesis thus seeks to investigate if a model-based approach is applicable for this purpose and if the results of such an approach are valuable. If so, companies in different industries and with different disciplines can utilize it for identifying innovation potential in their business.

1.3 Methodology

A mixed method of research has been used to achieve the objectives of the study. This includes literature review, discussions with academia and the industry, and inclusion in a research group where we had brainstorming sessions, and gave critical viewpoints to each other.

My internship at Shoreline, a company providing simulation solutions to the offshore wind industry, has given me a deep insight into the offshore wind industry. This experience has proven to be of an indispensable value to my understanding of the field. Here, I have been able to discuss a diversity of issues with people that have hands-on operational- and managerial experience from the offshore wind industry. Through this job, I have gathered knowledge about current practices, trends, and challenges. Furthermore, this thesis has been developed through a comprehensive literature review, including books, reports, publications, and web-based articles. This material has included topics such as the offshore wind industry, O&M, approaches to innovation, and a range of technology trends within energy, materials, sensorization, connectivity, digitalization, and autonomization.

During the research period, I have attended weekly meetings with Knut E. Bang, Muhammad A. Tauqeer, and a group of master students that applied the same model for other industries. Here, I have discussed and received feedback on my work, something that has proven to be valuable for my thesis.

1.4 Limitations

Since the research covers an area of a very large size, it has a high-level approach to most issues. Therefore, the technologies and O&M segments that are studied, are discussed in a manner which is easy to understand and not necessarily with deep technical descriptions. The research is meant to guide companies in how to achieve innovative ideas. The proposed opportunities are highly simplified in their descriptions. They are simply proposed ideas that it is possible to build further on. Another limitation is that I have not been given the budget nor the capabilities and resources to buy or produce the equipment needed to test the proposed opportunities.

2 Offshore wind

The offshore wind industry has grown considerably in the last years. Investing in clean and stable energy sources instead of exploiting limited fossil fuel reserves has been an increasing trend during the last decade. Since the first steps of the offshore wind industry back at the beginning of the 1990s, it has grown considerably in size, and we are now witnessing a trend towards moving the turbines further offshore, to even more remote offshore locations. This development is driven by even higher wind resources, more available space, and less interference with local communities (Anaya-Lara et al., 2018). Europe is the leading continent in offshore wind, with the UK and Germany as the countries with the highest installed capacity.

As figure 1 shows, the cumulative global offshore wind capacity has grown significantly in the recent years (GWEC, 2018). Of the 18,814 MW in 2017, a staggering 15, 780 MW was installed in European waters.

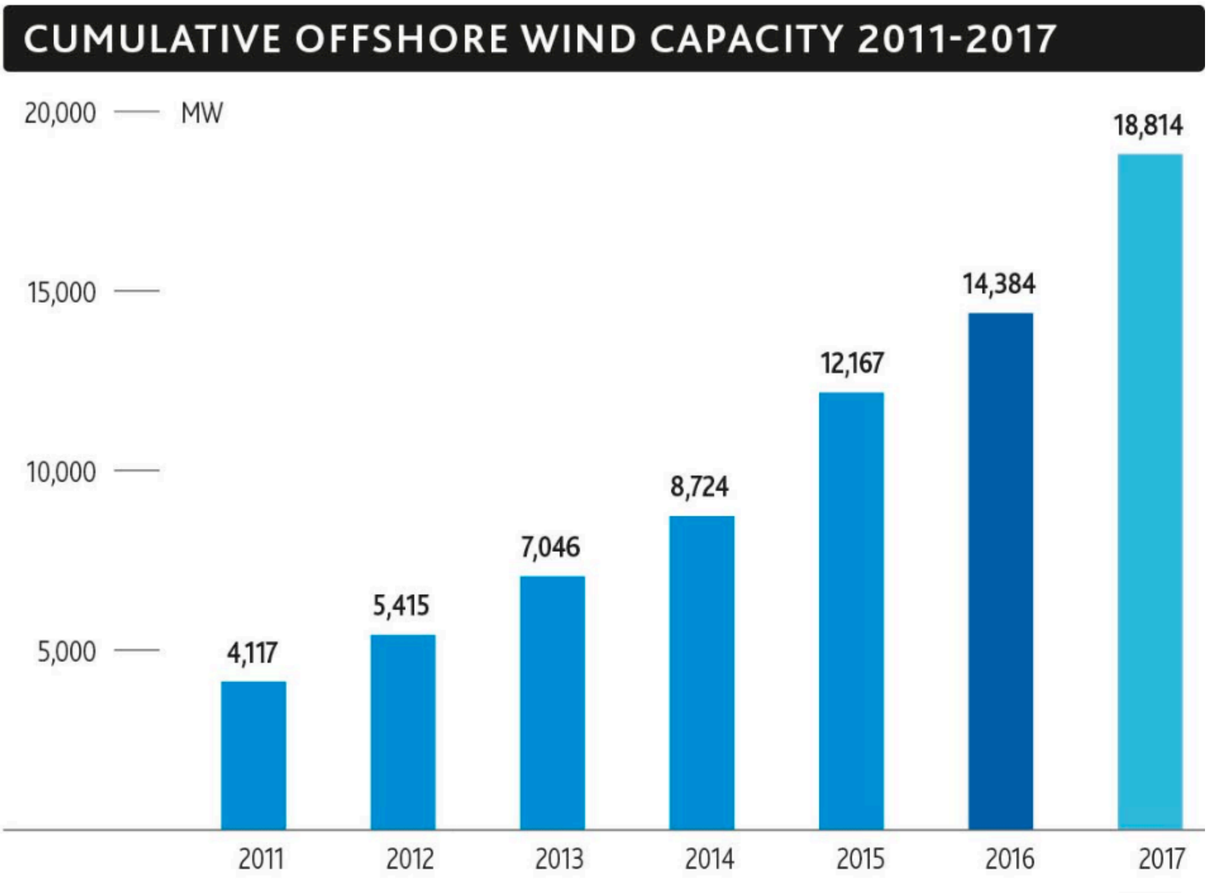

Figure 1: The cumulative installed global capacity of OWTs (GWEC, 2018).

Although offshore wind is significantly outnumbered by onshore wind, more than every third wind turbine in Europe is now installed at sea (Schwägerl, 2016). By 2020, it is estimated that the total installed capacity in Europe will reach 25, 000 MW (Offshorewind, 2017).

2.1.1 Turbines and power infrastructure

Figure 2 shows the different components of an offshore wind turbine (OWT). They are usually broken down to *foundation, transition piece, tower, nacelle, hub,* and *blades* (Dedecca et al., 2016).

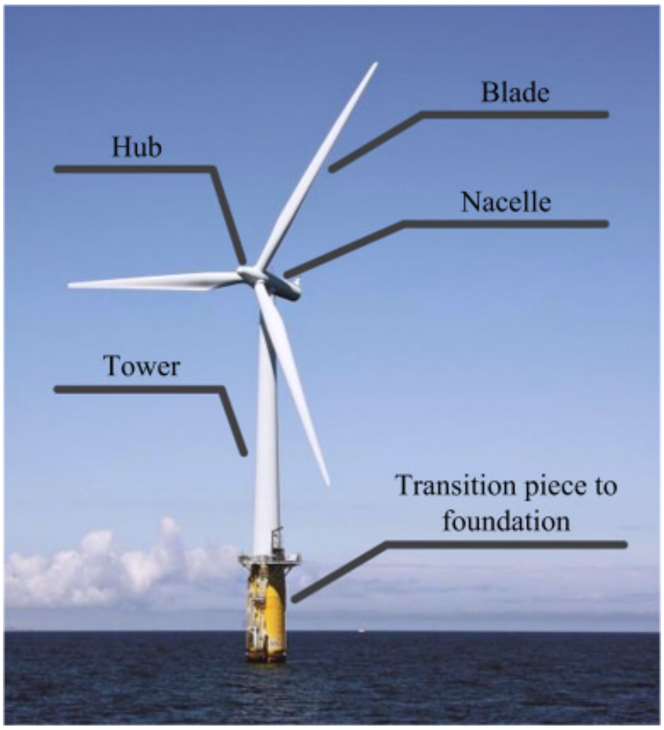

Figure 2: Components of an offshore wind turbine (Dedecca et al., 2016)

Figure 3 illustrates the different types of foundations used for OWTs. The monopile is undoubtedly the most common one. In recent years, floating offshore wind turbines (FOWTs) has been introduced as a viable concept for deeper waters (Offshore-stiftung, 2018).

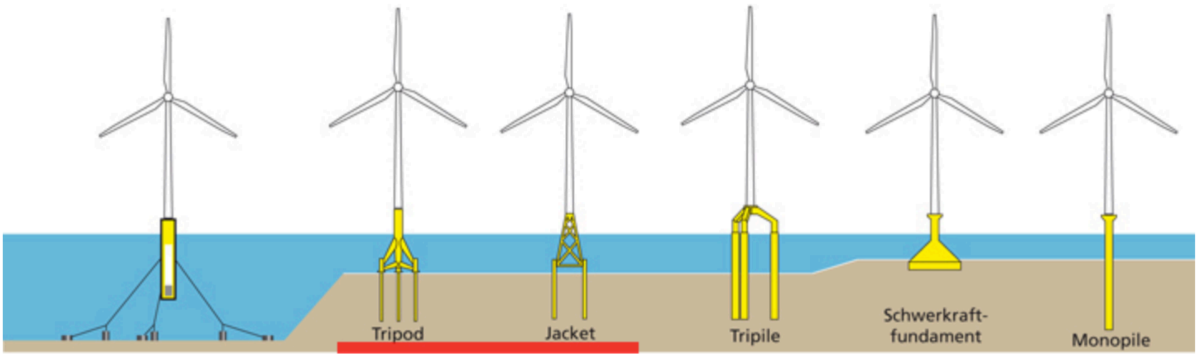

Figure 3: Types of OWT foundations (Offshore-stiftung, 2018).

(Offshore-stiftung, 2018)
Figure 4 illustrates the subsea infrastructure of an OWF. The power generated by each of the turbines is transferred through *inter-array cables* to the *offshore substation.* Here, it is gathered and transferred through an *export cable* to shore, where it is connected to the power grid (Sievert, 2015).

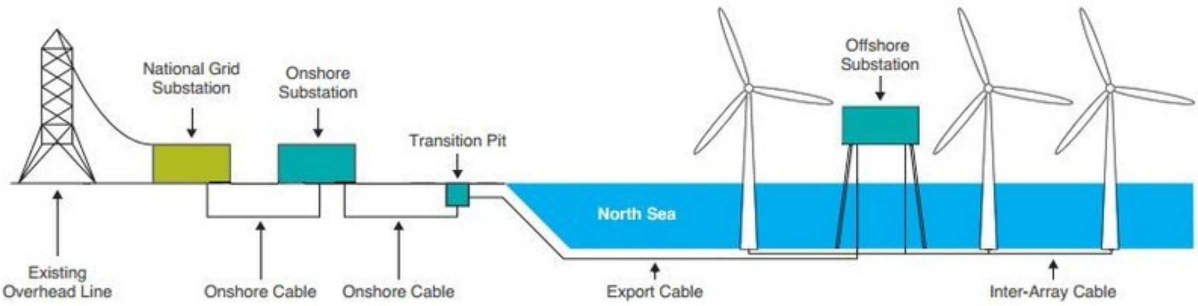

Figure 4: The subsea infrastructure of an OWF (Sievert, 2015).

2.2 Operations & Maintenance

O&M is an industrial segment of crucial importance to the overall operation. It is a term which is subject to a range of definitions. In this research, the term will be divided into the most common strategies, defined by Netland (2014):

- ***Corrective maintenance***
  Replacements or repairs carried out after a failure has occurred. This is a highly expensive and time-consuming strategy that can cause significant harm to the rest of the equipment.
- ***Preventive maintenance***
  Replacements or repairs carried out prior to a failure on a scheduled date. This way, much of the downtime is avoided. It can however be an expensive strategy, due to the fact that maintenance is basically done before it is actually needed.
- ***Condition-based maintenance***
  This strategy bases itself on data gathered through a *condition monitoring system.* Sensors mounted on the equipment continuously gathers data which is used to predict the time of potential failures. The "health" of the equipment is thus accurately monitored, and maintenance can be carried out at more precise point of time.

2.2.1 Operations & Maintenance in offshore wind

The O&M is a key segment of the life cycle of an OWF. The O&M activities must be managed in an effective way to avoid a backlog of maintenance activities. For OWFs, O&M stands for a stunning 30% of the total costs. Unpredictable weather windows are a major contributor to this number, as it hinders a long-term planning of maintenance operations. Constantly changing weather is a general concern in offshore wind decision making, and a huge cost-contributor in many areas (Dai, 2014). A project in the German North Sea focused in the *Alpha Ventus* plants revealed that the annual average time spent on maintenance was 450 hours for each turbine. For this specific project, it was further stated that this number had to be reduced to around 150 hours in order to be economically viable (Østbø et al., 2012).

3 Breakdown of offshore wind O&M

The sub-chapters in chapter 3 describe different segments from the O&M field that are quite different. This was done in order to show the flexibility of the model, and that is can be applied to several different areas. However, it does not necessarily cover every area of offshore wind O&M.

3.1 Marine logistics and supply

Marine logistics and supply operations have large implications on the total O&M costs, as well as the availability of the OWF. The most commonly used vessels in OWFs are illustrated in figure 5-8 and are called *crew transfer vessels (CTVs) - service operation vessels (SOVs) - heavy-lift vessels (HLVs) helicopters*. There is no doubt that ship-based transportation is most preferable regarding cost, but under some circumstances, a helicopter may be more suitable. Helicopters eliminate the possibility of getting seasick, as well as they substantially reduce the transportation time. Wave height and choppiness, which is a big access challenge is also eliminated by utilizing a helicopter (Drwiega, 2013). Helicopters have the ability to let off personnel on the turbine nacelles using wires and climbing equipment, while CTV-based personnel has to climb a ladder to get up to the turbine deck. SOV-based personnel uses a dynamic hydraulic bridge to board the turbine. Typical weather limitations for CTVs are 1,5-meter wave height and 10 m/s wind speed. A helicopter can operate in wind speeds up to 20 m/s (Garrett, 2011).

Figure 5: Crew transfer vessel (CTV) (Offshoretechnology, 2018)

Figure 6 Service operation vessel (SOV) (ShipTechnology, 2018)

Figure 7: Heavy-lift vessel (HLV) (Mordorintelligence, 2018).

Figure 8: Helicopter (Garrett, 2011).

3.2 Vessel chartering

Offshore transportation stands for a major share of the total offshore wind O&M costs. As OWFs are developed at increasingly remote locations in harsher weather conditions, this cost is likely to increase additionally. Measures for optimizing vessel operations and reducing the costs of such operations is key in order to minimize the overall cost of offshore wind projects. This is particularly crucial for the heavy-lift vessels as there are very few of them available, and they have extremely expensive rates (Dalgic et al., 2015).

There are different vessel chartering strategies. The most commonly used, are:

- ***Voyage charter*** – This is the contract used for only one trip (voyage), and it states that the shipowner should use a specific ship, a specific crew and carry a specific cargo. Running costs such as fuel costs and ports charges are covered by the shipowner.
- ***Time charter*** – Here, the charterer pays a fixed fee per day/month/year for a ship with a complete crew. The shipowner pays all operating costs.
- ***Bareboat charter*** – This is a contract where a crewless ship is hired. The owner has no operational responsibilities.

There is a range of documents and affairs that needs to be clarified when negotiating vessel chartering contracts. Timeframes, routes, fees, interests, crew expenses, insurance, fuel costs, port charges, canal dues, cargo claims, etc. (Dalgic et al., 2015)

3.3 Condition- and structural health monitoring

Condition monitoring (CM) and structural health monitoring (SHM) of industrial equipment are commonly used as part of the Condition Based Maintenance (CBM) strategy across a range of industries. By doing this, a more proactive approach to maintenance can be achieved, and the scheduling of maintenance becomes more precise. The monitoring data is usually gathered through sensors (vibration, temperature, pressure), and *non-destructive testing* (NDT) like ultrasound, thermography, acoustic testing etc. Huge costs can be saved due to the fact that one actually know the condition of the system. Since there is a huge focus on avoiding downtime in offshore wind, especially at the stage the industry is at this very stage, where costs still have to be driven down, it is crucial to avoid downtime (Østbø et al., 2012)

In the offshore wind industry, using *indirect* measures such as power output and signal noise is commonly used for monitoring the equipment. However, this is a *passive* method, meaning that it may be hard or even impossible to discover a fault propagation prior to a potential incident. Since design tools and new materials have given OWT structures more complex structures and aerodynamics, new practices on CM and SHM should be implemented (Sheppard et al., 2010).

3.4 Performance monitoring

Performance monitoring (PM) is the measuring and validation of power curves. The power curves show the relationship between power output and wind speed. The turbine manufacturer measures this during the production phase, but it has to be measured by the operator in order to validate them, as well as for forecasting power output, which has a big importance for economic aspects. The accuracy of the curves is thus a critical area. To measure realistic power curves, the measurement of wind speed must be highly precise (Howe, 2018).

Usually, when wind speeds exceed 25 m/s, the turbine shuts down in order to avoid overload of the drivetrain, but with more precise power curves, a gradual decrease in power output rather than complete shutdown could be achieved. This will increase overall power output and thus the cost-effectiveness of the turbines. Figure 9 illustrates this principle (Siemens, 2012). The industry is now witnessing huge developments in this area, with floating LiDAR technology arising as the future solution for accurate and cost-effective power curve measurements (Howe, 2018). Today, the wind measurements are usually taken by a cup anemometer (a small turbine) mounted on to the nacelle (Kim and Dalhoff, 2014).

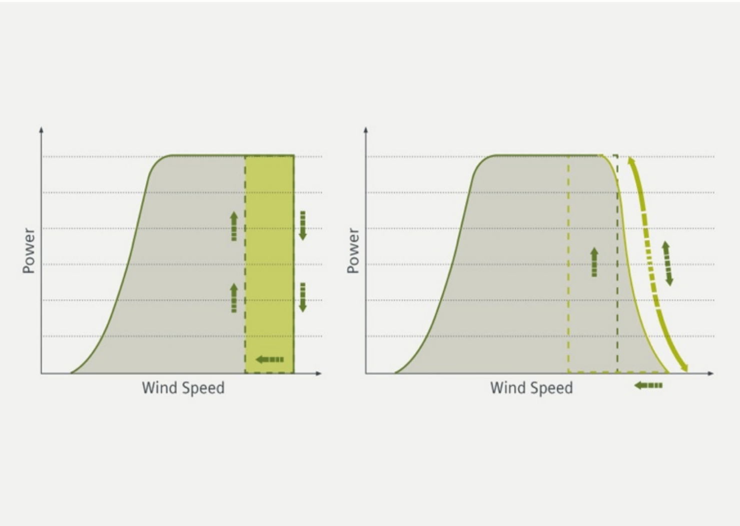

Figure 9: Typical power curve of an OWT (to the left). The potential for increased power output (to the right). (Siemens, 2018).

3.4.1 Pitch and yaw control

3.4.1.1 Pitch control

The pitch of a wind turbine refers to the rotation of the blades around their own axis. The pitch angle is determined by many factors, but the main objective is to pitch the blades in order to obtain a high and stable power output and to achieve an even distribution of load across the blade. Pitch control systems have traditionally worked in the way that if the wind speed reaches a certain level, typically 25 m/s, the pitch control is activated to reduce the power output in order to obtain a stable output and avoid too high loads to the structure (Element14, 2011). High fluctuations in load cause fatigue concerns for the turbine. Figure 10 shows a typical wind profile and its fluctuations. With the growing increase in the size of modern wind turbines, the importance of analyzing the loads subjected to the blades is becoming even more crucial both for the purpose of the structural integrity and for the production performance of the turbine. As a result, many resources have been devoted to research projects for *individual pitch control,* which is a wind turbine where every blade has the ability to rotate independently has an individual pitching. A *collective pitch control*, where the blades rotate collectively with same pitch angle, has been the standard until now. Since it can be up to 20% difference in absorbed power from the blade in the top position to lowest position when using collective pitch, there is a huge potential for increased performance by implementing an individual pitch control system (Kumar and Yadav, 2016).

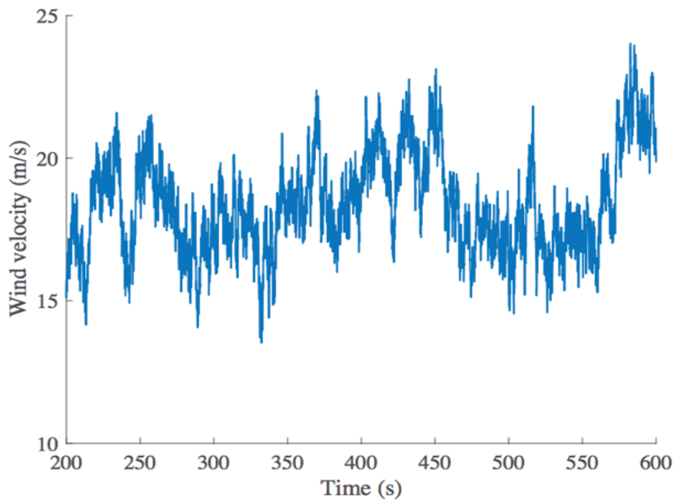

Figure 10: Typical wind profile at an OWT (Vidal et al., 2017).

3.4.1.2 Yaw control

Yaw is the rotation of the turbine, around the axis of the tower. The *rotor swept area* - the plane of the rotor must be directed in a certain position in order to regulate the power output and reduce the structural loads. The system is driven by several electrical motors that are controlled by a yaw controller. The yaw control system serves many of the purposes of the pitch control, but the essential role of directing it towards the wind is done by the yaw system. The yaw system must receive high-quality wind measurements in order to serve its purpose (Kim and Dalhoff, 2014).

3.5 Inspection

Inspection of OWTs is a huge area within O&M and involves a range of sub-activities. It provides information about the status of the OWF so that the overall integrity can be mapped and safeguarded.

In addition to the inspections that come as a result of deviations in the CM, the main categories of inspections, defined by (Sheppard et al., 2010) are:

- ***Annual Inspection Activities -*** These are primarily above water activities that are carried out once a year or more. These inspections consist of visual surveys of the structures to inspect areas such as coatings, weldings, corrosion etc. The inspections can be done remotely or close-up.
- ***Intermediate Inspection Activities -*** These are activities that demand more effort than the annual inspections, such as subsea inspections of the structures, bolts, weldings, and corrosion. Non-destructive testing of the structures is also part of the intermediate inspections. These inspections are typically carried out every 3 to 5 years.
- ***Extended Inspection Activities -*** These inspections are focused on cleaning the subsea structures for marine growth, as well as a more in-depth investigation of cracks in subsea weldings, deviations in the concrete substructures. In general, these activities are focused on the subsea structures, and they are performed every 6 to 10 years.
- ***Post-Event Inspection Activities -*** Following large and damaging events like hurricanes and earthquakes, specifically inspections must be carried out. These must be timely carried out and target specific to ensure that the system can be repaired as soon as possible. Even though they must be carefully planned, these types of inspection come as a result of unexpected events, and they are therefore categorized as unplanned.

The size of the OWF determines the time needed for the inspections. For the larger ones, planned inspections can take more than a year to carry out. Sometimes, a few reference turbines are used to generalize an overall state of all the turbines. After all, the turbines in n OWF have the same design and is located in proximity to each other. This approach introduces larger uncertainties, but reductions in cost (Sheppard et al., 2010). The accessibility of the maintenance location is a huge challenge in OWFs. In fact, 80-90% of the total O&M costs are generated by the need for site access. Since most of the inspections are done by humans, huge resources are put into the right access equipment. Hence, there is a substantial need for improvements in the area of accessibility (UniversityofManchester, 2017).

3.5.1 Above sea inspection

The inspections that are carried out above sea level are concerned about the structural integrity of the transition piece, tower, nacelle and blades. This is done visually or by using NDT. Mobile devices such as portable vibration sensors are often used. According to (RomaxTechnology, 2018), the most critical areas to inspect are:

- Structural integrity of blades and hub
- Leaks from hydraulic cylinders

- Subsurface defects (especially in the composite structures)
- Gearboxes, main bearings and generators
- Welds
- Oil quality
- Coatings

Structural degradation to composite materials is hard to localize with visual inspections as they do not show the same deformations as metallic materials. Therefore, close access to the blades is a requirement. Rope access operations are subject to high risks and require extensive training. They are also time-consuming compared to operations that do not require rope access. Particularly, the access of blades is a challenging task. Due to their complex structure and length, they require highly specialized equipment. Internal inspection of the blades is also an area with significant access challenges. Since the rotor must be stopped while inspecting the blades and the rotor hub, it is crucial to perform the inspection within a time window as small as possible. Also, the weather is a highly unpredictable and limiting factor for inspections above sea level (Sheppard et al., 2010).

3.5.2 Subsea inspection

Subsea inspections are challenging compared to the above water inspections. They are therefore performed less frequently. According to (Sheppard et al., 2010), critical areas to inspect are:

- Circular welds on monopiles
- Cracks in braces
- Corrosion of structures
- Cathodic protection
- The integrity of cables
- Scour
- Marine growth
- Cable wear

Figure 11 shows a series of typical critical faults that will be discovered by the subsea inspections.

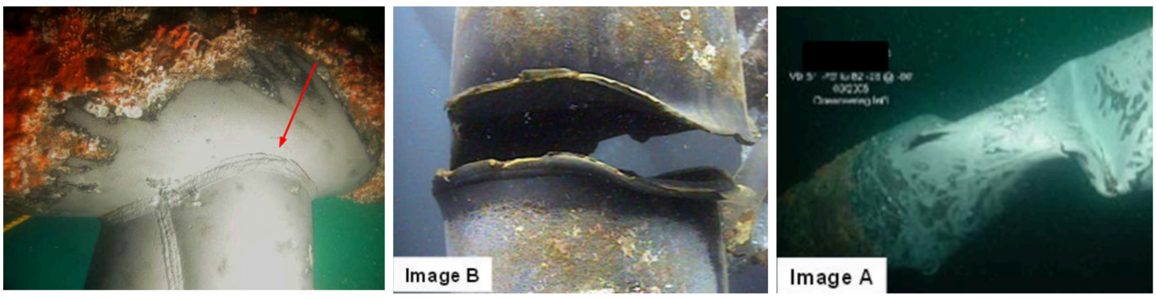

Figure 11: Critical faults at subsea foundations. From left: fatigue-induced welding crack, separated brace, and a buckled brace (Sheppard et al., 2010).

The fact that the subsea operations are dependent on vessels to be carried out, make them highly expensive. Comprehensive inspection operations are very time-consuming, as they need to cover huge areas. Human divers are frequently used, a method that introduces a major risk regarding their health, as well as it is dependent on a costly support operation with specialized vessels and personnel (Tipping, 2016). The introduction of FOWTs with their increased water depth, as well as even bigger turbines will introduce even more challenges to the field.

3.5.2.1 Marine growth inspection

Marine growth (MG) on substructures is a controversial area in which there are many aspects to consider. The layer of MG varies, but the literature operates with an MG thickness of 200 mm with a 900-1300 kg/m^3 density. It is a fact that MG on the substructures causes changes to the marine life in the surrounding areas, something that has been regarded as both beneficial and harmful. It may contribute to the recovery of marine populations, and on the other hand, introduce non-native species that interfere with the natural marine habitat and population. Additionally, MG increases the mass and surface roughness and hence the natural frequency and hydrodynamic load. It also challenges the corrosion- and fatigue inspections. So far, practices have varied, and no prevalent methods have stood out. There are no design standards that count for MG on substructures (Carswell, 2015). Figure 12 and 13 show typical MG challenges.

Figure 12: Mussels on fixed structures (Subseaworldnews, 2018)

Figure 13:Barnacles on subsea cables (PGS, 2018).

3.5.2.2 Scour

Scour is the phenomena where the sand or mud surrounding and supporting the submerged substructure of the turbine is gradually disappearing. When the sea current hits the cylindrical piles of the structure, it turns into a horseshoe-shaped formation surrounding the piles, and hence washes away the seabed sediment (sand, mud, gravel etc.). The depth of the resulting holes can reach a depth of 5 times the diameter of the pile. Efforts are made to re-fill these holes, but this has had various effects. There is a general lack of knowledge regarding this area, especially since there are few or no monitoring devices detecting the scour, as well as little research on the consequences. The industry has coped with the problem by designing turbines with wider fundaments, and piles that go deeper into the seabed. A reason for the limited research has been that the theoretical models regarding scour have not been validated due to the lack of field data. Thus, data from scour monitoring will have a huge effect on the further wind turbine foundation research (Michalis et al., 2013).

3.5.2.3 Inspection of mooring lines

FOWTs are exposed to challenging weather conditions, and an accurate monitoring of their responses are key to establish the feasibility of the concept. The mooring lines are a good indicator of the responses, and a good understanding of this area enables a corresponding good understanding of fatigue- and loads within the lifetime of the structure, which is crucial knowledge in the future design developments of this promising concept. There is no real continuous monitoring of mooring lines for FOWTs. Their structural integrity is usually inspected every 5 years or so, as part of the *intermediate*- and *extended inspection activities* (see chapter 3.5) (FMS, 2018). However, there are methods for measuring the tension. The world's first FOWT, *Hywind* in Scotland, has used *static line monitors* (se figure 13) for measuring the load of the mooring lines (Strainstall, 2018). Some OWFs are exposed to surface ice, which causes additional challenges for the integrity of the ropes, as the ice can easily damage the rope fibers (Nortek, 2018).

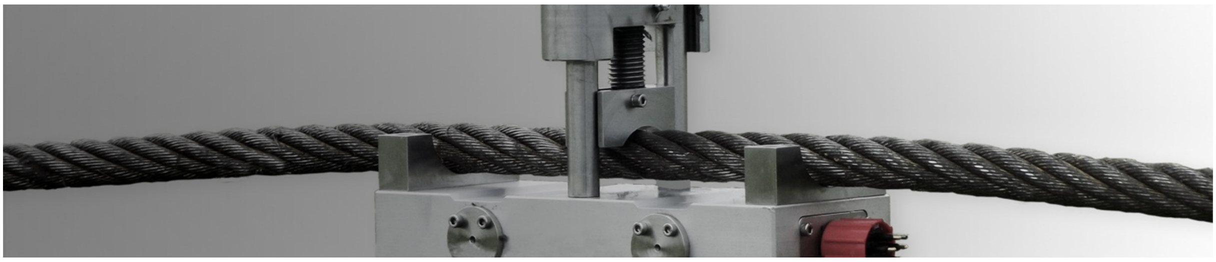

Figure 14: Equipment for measuring mooring loadings (Strainstall, 2018).

4 Technology trends

The study of technology trends is an important element of the model. It establishes the fundamental knowledge that is needed to fully understand the ideas that are presented in chapter 5. The different technologies are categorized into *Materials/hardware, Energy, Digitalization, Connectivity, Sensorization,* and *Autonomization.* The chosen technologies should all have a reasonable potential for the selected industry segment and are thus carefully selected.

4.1 Materials/Hardware

4.1.1 Fiber optic sensors

Fiber Bragg Grating (FBG) is a technology where a fiber optical cable has small *mirrors,* or so-called "*gratings"* in it. The gratings act as sensors, in the sense that when light passes through the fiber, the gratings causes a spectrum of light to be reflected back. The flexibility of the cable enables the cells to change in length and shape. A change in strain or temperature will hence give an instant response the reflected light spectrum, and thus give an instant indication of a certain change in the physical parameter. Figure 14 illustrates an FBG sensor exposed to strain. FBG sensors do not react to electromagnetic interference. They are small, agile and lightweight, as well as durable in harsh conditions. Furthermore, they have *multiplexing* capabilities, meaning that signals from many different gratings can be *gathered* in one fiber (Lin et al., 2006). Parameters that can be monitored include pressure, shape deformation, liquid level, strength and operational loads (NASA, 2015).

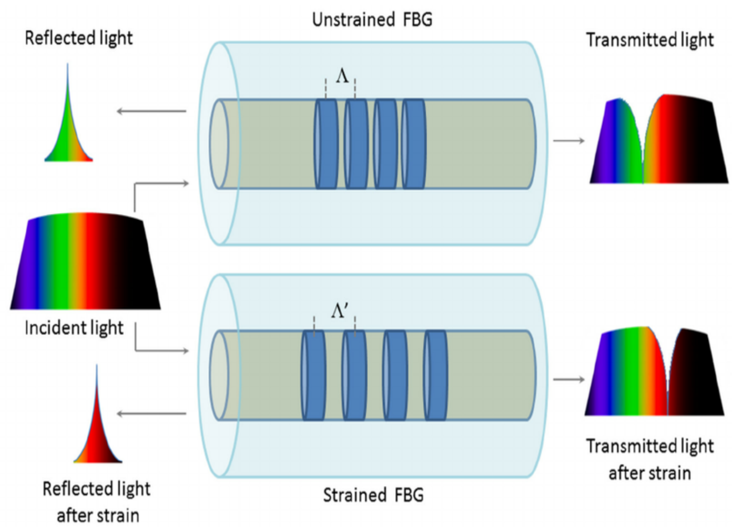

Figure 15: How FBG sensors work (Massaroni et al., 2015).

Another area in which FBG sensors are advantageous is the integration of sensors in materials. The cables can be integrated into composite materials and materials that are produced using *additive layer manufacturing* (3D printing). This able the materials to measure their own loads continuously (Li and Prinz, 2003).

4.1.2 Processing power

Computers today can process information extremely fast. If we were to follow *Moore's Law,* which has proved itself to be true for almost 50 years, the computational capacity will double in size every two years. An IBM Supercomputer was in 1956 able to do 10 000 *FLOPS – floating operations per second,* which is a measure of processing power. In comparison, an Apple watch, when first launched, had a FLOPS capability of over one billion (McCarthy, 2017). We basically walk around with supercomputers in our pockets. Among other things, this trend is enabled by the developments in hardware and computer chips. The computational capacity is likely to grow even faster with the introduction of *deep learning* and *cloud computing,* which is computing in a different way than we have seen until now, where the "traditional" algorithm principles are reinvented and *neural networks* are introduced, which is a way of processing more similar to the human brain (TheEconomist, 2016).

4.2 Energy

4.2.1 Solar panel technology

Through the last couple of years, solar panel technology has accelerated significantly. While traditional solar panels have had an efficiency rate (power out/power in) of below 20%, affordable panels with efficiencies up to 23,5% are now being delivered. Different researchers are also working with applying a technique which can potentially double the rate by harnessing more of the "waste-heat" (Richardson, 2018).

4.3 Digitalization

4.3.1 Digital twin

Today's industries are exposed to enormous amounts of data. This data is put into numerous different models using various and non-cooperating platforms and software, resulting in a fragmented and unorganized chaos. When information is needed, huge resources are therefore put into actually finding it. This has generated a need for a common model representing the assets, where data is stored and put together in a holistic overview through a visual representation. This is called the *digital twin* and is gaining increasing attention among industries. Data coming from sensors and other sources are directly linked through a cloud-based digital twin, making real-time data easily accessible. Data concerning asset integrity, engineering simulations, performance, inspections, and CM are gathered, facilitating for a cross-disciplinary, collaborative, and cost-efficient work environment (DNVGL, 2016).

4.3.2 Distributed ledger technology

Distributed ledger technology (DLT) is a common term for a range of sub-technologies that describes a system that performed transactions of data between independent computer nodes. Traditionally, data has been stored in centralized databases. For instance, money has been transferred via a bank system. With DLT, so-called *peer to peer* transactions are done, meaning that only the peer parties, and not a centralized third part has an involvement in the transaction. The system maintains its trust by storing the information of every transaction in a "ledger", a shared database across every peer (TheWorldBank, 2018).

One type of DLT is *blockchain.* Here, every transaction is stored as a "block", which is stored together with other blocks, forming a *blockchain.* In order to maintain trust, every block has to be approved. This approval is carried out by *miners*, which is an entity that uses its processing power to approve transactions. The information within a block is encrypted so that counterfeit or changes are impossible (TheWorldBank, 2018). *Tangle* is another DLT, which operates on the same DLT principles, only that the approval of transactions is even more distributed. For every transaction in the tangle network, two additional transactions have to be approved by the user. This means that every peer stands for the approval, while in a blockchain, more single entities can approve an unlimited amount of transactions (Liebkind, 2018).
Cryptocurrencies are financial digital assets that can be used for financial transactions in a DLT (TheWorldBank, 2018) Examples are *IOTA, Ethereum, and Bitcoin.*

4.3.2.1 Smart contracts

A smart contract is a contract in the same sense of traditional contracts, only that it is *self-executing.* In practice, this means that the agreement of the parties is coded, like a computer program. It is then encrypted and stored on a distributed ledger. They are built up with the logic of *if this, then that,* which means that if a certain event is triggered, for instance, a certain gearbox maintenance need, then a gearbox maintenance provider is contacted, and a negotiation based on predetermined constraints is automatically carried out, and a customized contract for that specific operation is generated. (Engheim, 2018).

4.4 Connectivity

4.4.1 Internet of Things

Internet of Things (IoT) is the term describing how devices are increasingly connected to the internet. Sensors, mobile devices, cars, home equipment are some examples. These can be remotely monitored. These devices are expected to reach a number of 24 billion by 2020. The devices are usually connected to an IoT platform, which are applications that integrates and make meaning out of the data, so that businesses can manage and analyze it. IoT will likely to be accelerated by the launching of the 5G network (Meola, 2018).

4.4.2 5G Network

The 5G network is the next generation of mobile internet, and is expected to be launched by 2020. The 5G network will work in the way that it opens up new wave spectrums, so-called *millimeter waves,* that have not been used before. These waves are often absorbed or damaged by objects, a problem that is solved by installing numerous small base stations that receives and transmits the signals. These base stations will have more antenna-ports that broadcast the information on specific directions, rather than in 360 degrees, meaning that they can broadcast much more information than earlier. The 5G network will enable sharing of data at a substantially higher speed than today. HD movies can be downloaded in under a second, and huge amounts of sensor data from autonomous cars can be shared instantly with other units (IEEESpectrum, 2017).

4.4.3 Big data

Big Data is concerned about trying to extract meaning from vast amounts of data. The term is often described by using the so-called "four Vs", which is data of a large *volume,* data that moves with high *velocity,* data with a substantial *variety,* and data that has a high degree of *veracity,* meaning that it is accurate for the problem it is analyzing, and that "dirty" data is not accumulating. In order to transform the huge amounts of data into something of value, specialized and customized technologies is required, and the term Big Data is thus referred to as a technology. The implementation of Big Data in businesses has increased rapidly this decade, and healthcare in particular has already witnessed its great value. It is predicted that Big Data in offshore wind has a huge potential, especially due to the fact that the industry is still quite immature (Brinch, 2015).
Michael E. Porter, the man behind *Porters 5 Forces,* mentioned that after having witnessed two dramatic changes to industries, namely the automation of factories, and when the internet went online, we are transiting into the period of *smart-connected-products*. According to (Porter and Heppelmann, 2014), Big Data will be a prerequisite to this period, as the performance in this period relies on four main characteristics, of which are dependent on high-quality data:

1. *Monitoring* – Monitoring the performance of an asset, and react when needed.
2. *Control* – Highly developed algorithms will control the performance.
3. *Optimization* – Optimization of the performance.
4. *Autonomy* – Increase the independence of the product or service, making 1,2 and 3 happen by themselves.

A group of researchers, including the highly recognized MIT professors Andrew McAfee and Erik Brynjolfsson that has done extensive research on the field of Big Data, expressed in *Harvard Business Review* that the more data-driven a company is, the more capable they are to achieve their objectives. A company that bases its business on the actual data that make the business dynamic, will be a more fact-driven and “true” business (McAfee et al., 2012).

4.4.4 Cloud- and edge computing

Cloud computing is when servers, storage, and databases are outsourced to so-called *cloud providers.* The data processing will then take place on a centrally located server, rather than at each decentralized location. It is used all the time by almost everyone, whenever data needs to be processed (Microsoft, 2018b). Until now, the cloud has handled most of the data processing alone. One problematic issue may however arise, namely the *latency*. When the amount of data that is being processed, and physical distance from the cloud to the end users increases, the latency becomes increasingly big. This could be serious to the user because it hinders the ability to get real-time information. This challenge can be solved by performing the computing at a more distributed level like in *edge computing*. Either by using state-of-the-art sensors that are able to process the data it gathers or by installing a server at a physical location more close to the users, allowing some information to be processed here instead. This is likely to be used frequently in the era of IoT, as there will be even more devices and data sources (NTT, 2016), and *General Electric*, one of the world leaders in turbine manufacturing, predict that edge computing will be a dominating solution for remote offshore locations (GE, 2018).

4.5 Sensorization

4.5.1 MEMS sensors

Micro electrical mechanical systems sensors, commonly known as *MEMS* sensors, is the name of a range of small sensors. They differ from conventional sensors by their microscopic size, durability, reliability and their low operating cost (Lin et al., 2010). Lately, huge advances have been made in MEMS technology and has now become one of the technologies that really drives the IoT movement (Anand and Rathore, 2017). Advances in manufacturing have reduced the size dramatically, and their low cost and small size may now contribute to the sensorization of areas that previously have been labeled too expensive for the implementation of sensor systems (Doe, 2018). Figure 15 shows an integrated pressure- and temperature sensor system.

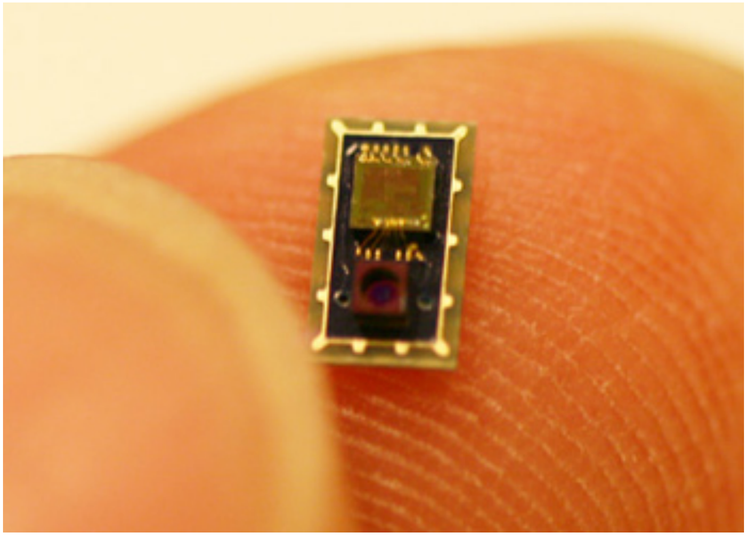

Figure 16: MEMS pressure- and temperature sensor (MicroElecTechnical, 2018).

A study by the University of Petroleum and Energy Studies in India (Kumar and Bajpai, 2012), it was claimed that MEMS sensors have a huge potential in structural health monitoring of large engineering structures. They investigated the potential for bridges specifically and found that by implementing a comprehensive wireless MEMS sensor monitoring system would dramatically reduce the O&M costs.

4.5.2 LiDAR

Light detection and ranging, LiDAR, is a relatively established remote sensing technology used for many different purposes. This is the technology where a device emits small amounts of energy, which is reflected back by microscopic dust particles in the air. Among their applications are the measuring topography, distances and wind speeds (Land et al., 2010). In offshore wind, LiDAR is not yet a commercially established technology. However, there are some projects where LiDAR units have been utilized, and in 2016, the first floating LiDAR completed a 12-month commercial test period with no maintenance issues. It is primarily floating LiDAR units that are being developed, as they have proven to be the best alternative. They operate autonomously with power supply from mounted solar panels and transfer the gathered data via WLAN or satellite (Fraunhofer, 2015).

4.5.3 Computer vision and voice recognition

Computer vision is the concept of how computers extract meaning from images. It is a principle where computers interpret data by utilizing specific computing systems, or *neural networks* (due to its similarities to the human brain) to break down images to small matrices of pixels, and comparing them to other patterns of pixels called or *labels.* Once they match with a label, the matrices are organized and soon add up to a complete image. This is an ability that facilitates for autonomous systems, as they do not need humans to process visual information for them, which has been the traditional method. Self-driving cars and autonomous ships will have to rely on this technology in order to navigate and dodge obstacles (Robinson, 2018).

Voice recognition works with a similar logic. It is the technology where a machine or program interpret spoken commands. The *Siri* function from Apple is one popular example. Voice recognition enables interactions with technology by speaking to it. It uses so-called *analog-to-digital conversion* to transform analog audio to digital signals. These are compared with a vocabulary database and the program then interprets the sentence (Scardina, 2018)

4.5.4 Augmented reality

Augmented reality (AR) is simply an enriched display of the real world. It is a visual model of something real, with digital information added to it. An example is a 3D model of a processing facility displayed on a screen, like *smart glasses.* They appear just like normal glasses, but with a light projector built in it, that directs low energy light towards the pupils (TheVerge, 2018). It may also be a screen on a mobile device with a visual image of a real landscape, with distances between certain areas, altitudes temperatures appearing on the same screen (see figure 16) (Jansen, 2010).

Figure 17: AR in topology (Jansen, 2010)

4.5.5 Virtual reality

Virtual reality (VR) is the simulation of a person's presence in a virtual environment. The environment is made up of 360-degree true scale images and can react to motions and gestures done by the user. The motion of the user is tracked, and by using sophisticated sensors, the virtual movement is as real as possible. The system can predict exactly where the user is located. This is done by accelerometers detecting the 3D movement, gyroscopes detecting the angular movements, and magnetometers detecting the position relative to the earth. A small stereoscopic screen covering the eyes of the user, together with controls for grasping objects is the most common way to experience VR. Many VR systems also include sounds to enhance the experience further (Mullis, 2016).

4.6 Autonomization

4.6.1 Machine learning

The term *Machine learning* (ML) describes the process of machines learning from previous computations in order to autonomous and reliable decisions. The area of ML is enormous, so this paragraph will provide just an overarching definition. It is used in a variety of applications and is a continuous area of research. While traditional computer programs are built around the following scheme:

program = algorithm + data,

machine learning is extended to

program = algorithm + data + domain knowledge,

where the domain knowledge represents knowledge about the problem, encoded in specific data structures. The task of formulating the knowledge correctly is not necessarily straightforward, as it may be too complex. Some will therefore argue that instead of the programming being the "bottleneck", it is the knowledge engineer (Kubat et al., 1998).

4.6.2 Autonomous underwater vessels

In recent years, huge developments have been made in *autonomous underwater vehicles, AUVs.* AUVs are unmanned systems that operates autonomously underwater. They can be used for subsea inspections, seabed mapping, intelligence etc. (MINewsNetwork, 2016). Until now, AUVs have been regarded too expensive for subsea inspections and surveys in the offshore wind industry. Instead, using human divers and ROVs (Remotely operated vehicles) have been the current solution. Nevertheless, recent advances have laid the ground for potential future applications in subsea operations in the offshore wind industry. According to (Gafurov and Klochkov, 2015), the advances are mainly in the following areas:

- ***Miniaturization*** - Components have become smaller, making them more agile and simpler to operate. As a result, so-called *micro AUVs* that can be carried by one man have been developed. This area is also a main driver for the huge cost reductions.
- ***More intelligent*** - The computational capability has increased, resulting from the smaller electronic components, something that able them to do more complex tasks. They are now to some extent capable of comparing the data it gathers to standard values, and therefore detect deviations (Tangirala et al., 2011).
- ***Materials*** - Replacing heavy metals with composites such as carbon reinforced fibers makes them more lightweight, but also able to withstand heavier loads.
- ***Engines*** - Instead of using traditional propeller technologies, so-called *bionic* AUVs, where the classical hydrodynamic shape is replaced by a rather lifelike structure (see figure 18), have the potential of increasing the cruising range and energy consumption significantly. The so-called *gliders*, that utilizes changes in buoyancy and wings to move are already being used in certain operations where long underwater stays are needed. Their battery life has also been significantly strengthened, and we are now witnessing the installing of solar panels and piezoelectric elements on the AUVs in order to make them even more autonomous, with no need for human intervention in the recharging of batteries.

Figure 18: Bionic AUV(EvoLogic, 2017)

Another trend that has emerged lately within the field of AUVs, is the principle to use AUV *crowds*. This involves the use of multiple AUVs, that communicates with each other and forms an interconnected subsea network that is able to continuously monitor large areas.

Like figure 19 illustrates, the data can be transmitted via the acoustic communication to a mother ship or an offshore installation. Multiple different sensors can be carried by the different units so that a bigger ranger of parameters can be monitored. Since satellite- or wireless internet communication systems do not function underwater, the current solution has been to use communication systems based on acoustic signals (Tena, 2018). These systems function well in some cases but faces challenges with acoustic signals being reflected by the seabed and objects, as well as acoustic signals interfering with each other, something that may damage the data (Giodini et al., 2018).

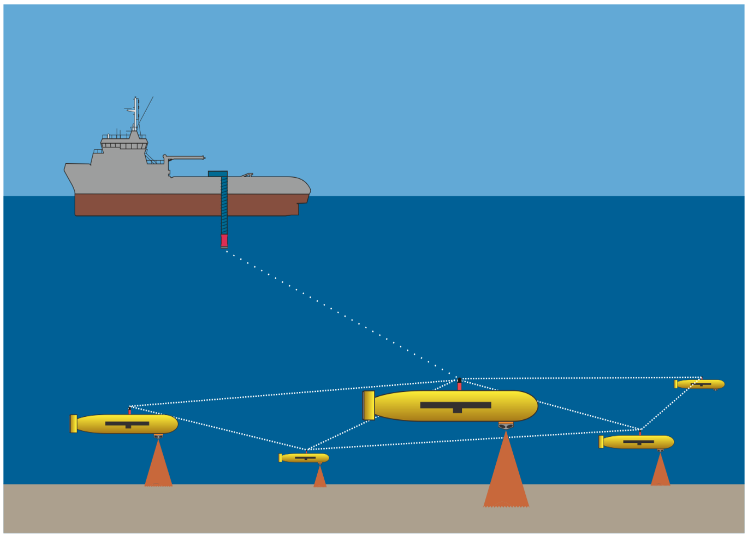

Figure 19: An AUV crowd (Tena, 2018).

4.6.3 Robots

The *GE Global Research Center* in Niskayuna, New York are developing tiny robotic *crawlers* for inspection the inside of jet turbines. The robots have dimensions of just a few centimeters (see figure 20) and can be deployed to highly confines areas to gather high-resolution visual data, wirelessly transmitted to a mobile device (Anderson, 2017).

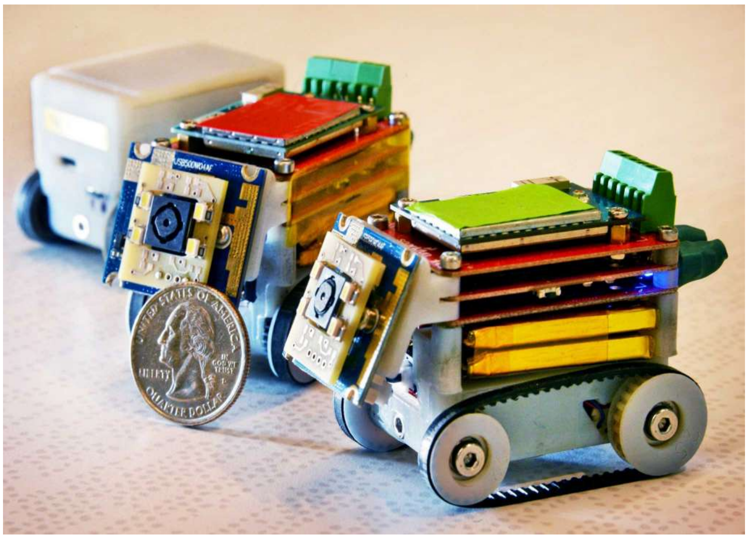

Figure 20: Robotic crawlers (Anderson, 2017)

4.6.4 Drones

We are now witnessing reports of successful commercial trials of *passenger drones,* or so-called *VTOL (Vertical Takeoff and Landing)* vehicles. They have slowly overcome the traditional barriers such as safety, regulations and air traffic management and are starting to look highly realistic, something that would have an enormous impact on our flexibility (Lineberger et al., 2018). However, the use of drones for maintenance activities is already starting to establish itself. This will not necessarily increase the mobility of humans, but at least the mobility of the *functions*, which can be customized by equipping them with technologies, depending on the task it performs. Humans can then sit safely in a remote control room and either control the activity or just watch it as it is carried out autonomously (Leightell, 2018).

The use of drones in offshore wind is starting to gain increasingly high attention. Within few years, the technology is likely to become highly commercialized, and in some OWFs, they have already been deployed. One example is *Force Technology,* a company that has started offering drone services to the European offshore wind industry. A certified drone pilot controls the drone
with a remote control, providing high-resolution images and thermal images of the area of interest. Drones are capable of accessing remote locations within a short time and gather data that often is even better than with manual inspections. A typical example is the turbine blades. Wear in the coating and delamination in the composites is hard to detect without seeing it close up. Drones can do this and give precise images of the relevant location. Figure 20 shows coating damages that can be discovered by drones, and figure 21 shows a drone inspecting an onshore turbine.

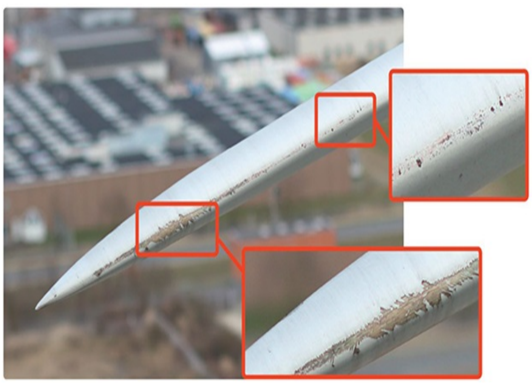

Figure 21: Coating damages to an onshore wind turbine (ForceTechnology, 2018).

Figure 22: Drone inspection of an onshore wind turbine(AviatDrones, 2018)

The *intelligence* of the drones has increased significantly lately, and they can now be programmed to do almost everything. Also, some companies are trying to deploy *swarms* of drones. This is inspired by how animals operate and has proven to be highly effective in certain missions. According to (Leightell, 2018), the use of drones for inspection is likely to have huge effects in the following areas:

- *Increased capabilities and scope of inspections*
- *Reduction of inspection time and cost*
- *Increased safety of operations*
- *Increased accuracy and reliability of inspection data*

5 Innovation opportunities

The following proposals were generated by crossing the industry segments from chapter 3 with the technology trends presented in chapter 4. This was done using a matrix-approach which is a fundamental step of the model. Two examples of these matrices are displayed in Appendix A.

This chapter contains the presentation of the innovation opportunities, and a following screening of every one. The opportunities are referred to as "proposals". The presentation of the proposals is divided into the following categories:

- ***General*** **-** A brief introduction to the proposal, containing arguments of why such a proposal is relevant and why that specific industrial field needs to be improved and some relevant research.
- ***Current method*** **-** Elaborates on current practices used to carry out the process in which the proposal addresses.
- ***Technical specifications*** **-** The technical details of how the proposal will carry out its functions, and how the physical infrastructure will be made up.
- ***Challenges*** **-** Issues with the proposal that may cause problems, or barriers of developing the proposal.

The screening is divided into two steps, where different parameters are discussed before a score with respect to the parameters is given in a diagram (see figure 23):

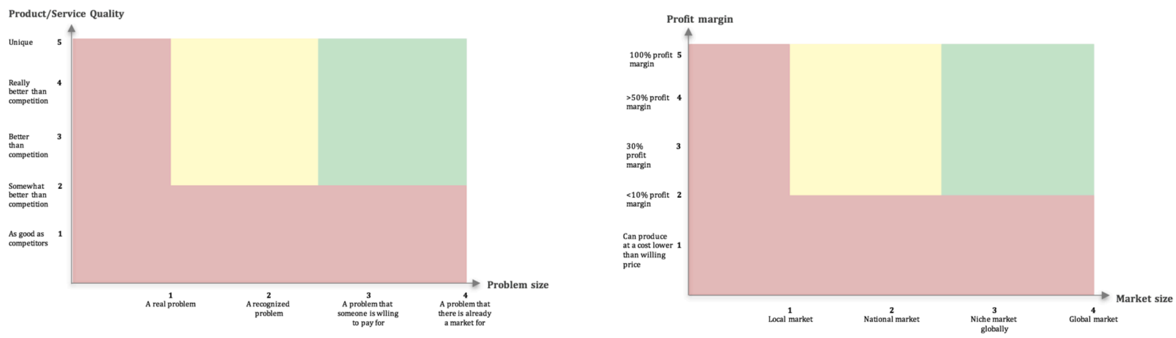

Figure 23: Visual representation of the screening criteria.

- ***"Problem size" and "Quality"***
  "Problem size" explains the scope of the problem that the proposal aims to solve, and how the industry struggles with it. The "Quality" explains how satisfactory the presented solution is in solving the problem.
- ***"Market size", "Profitability" and IPR***
  "Market size" estimates the potential size of the market in which the proposed solution will reach. The "Profitability" explains the likely profit margin the proposal will end up with after a certain period. These two variables will be affected by a potential intellectual property right (IPR) that the solution may obtain. Thus, the potential for IPRs is discussed. Also, a brief description of how the solution can be commercially deployed will be presented.

5.1 Proposal 1: Real-time monitoring of scour using MEMS pressure sensors

General
A permanent and cost-effective scour monitoring solution is very much needed in the offshore wind industry (Michalis et al., 2013). One of the world's leading technology centers for offshore renewables, *ORE Catapult* stresses that improved scour monitoring is a highly important area for the development of new and innovative solutions (Tipping, 2016). A system for monitoring the scour depth by using MEMS pressure sensors may thus have a suitable application for OWTs.

Current method
Sonar technology has been the main solution for scour measuring in offshore wind. Sonar surveys are costly to carry out, which also result in long time intervals between the surveys, allowing big holes to develop (Michalis et al., 2013). The use of sonars has additional challenges, such problems with noise damaging the data, and the fact that they are unreliable for real-time monitoring (Lin et al., 2006).

Technical specifications
Figure 24 illustrates the setup of this proposal. When scour occurs, water depth is increased around the turbine. As a consequence, the hydrodynamic pressure (pressure caused by moving water) is increased at places that have previously been exposed to only hydrostatic pressure (the static pressure caused by liquid on an object). This results in an increase of the total pressure at that very point. By mounting MEMS pressure sensors connected to fiber optic cables at certain vertical locations at the piles of the turbine fundament, the potential increase in pressure can be monitored (Lin et al., 2010). The signals are transferred through the cables and connected with the existing sensor infrastructure.
The sensors should ideally be mounted on two or three vertical axes around the pile so that all sides of the pile are covered. This way, a more reliable monitoring is obtained.

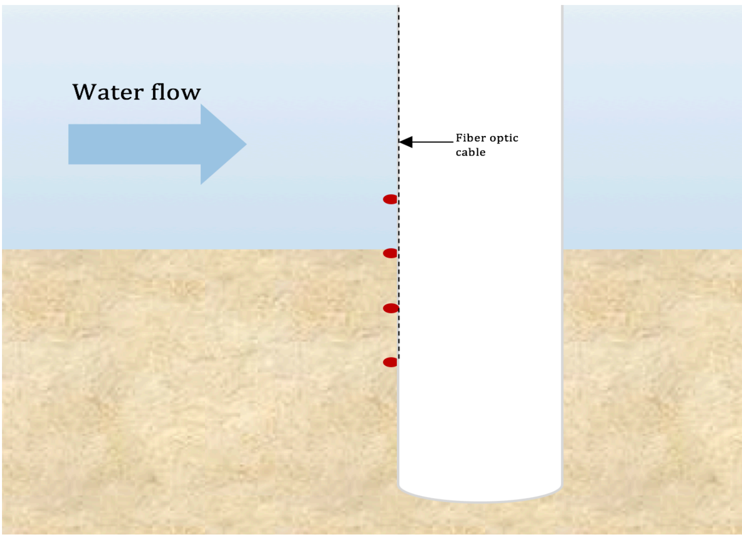

Figure 24: Illustration of the concept.

Challenges
The sensors are very likely to be affected by noise. Small movements in the sediments can give high variations in the pressure values. Thus, it is uncertain whether this system will work or not. However, by installing a high number of sensors, this challenge can be reduced to some extent. The integration of the cable to the existing subsea cable infrastructure could also be challenging to carry out.

5.1.1 Screening

Quality and problem size
As explained in chapter 3.5.2.2, scour is a serious issue that may cause severe damage to the wind turbines. It is a big research area and a challenge that many innovative developers try to address. In the subsea segment of offshore wind O&M, scour is definitely an issue that operators find challenging to deal with, and are constantly looking to solve. This proposal is likely to save costs on monitoring the scour, but has some uncertainties with its functionality. The score is thus given in figure 25.

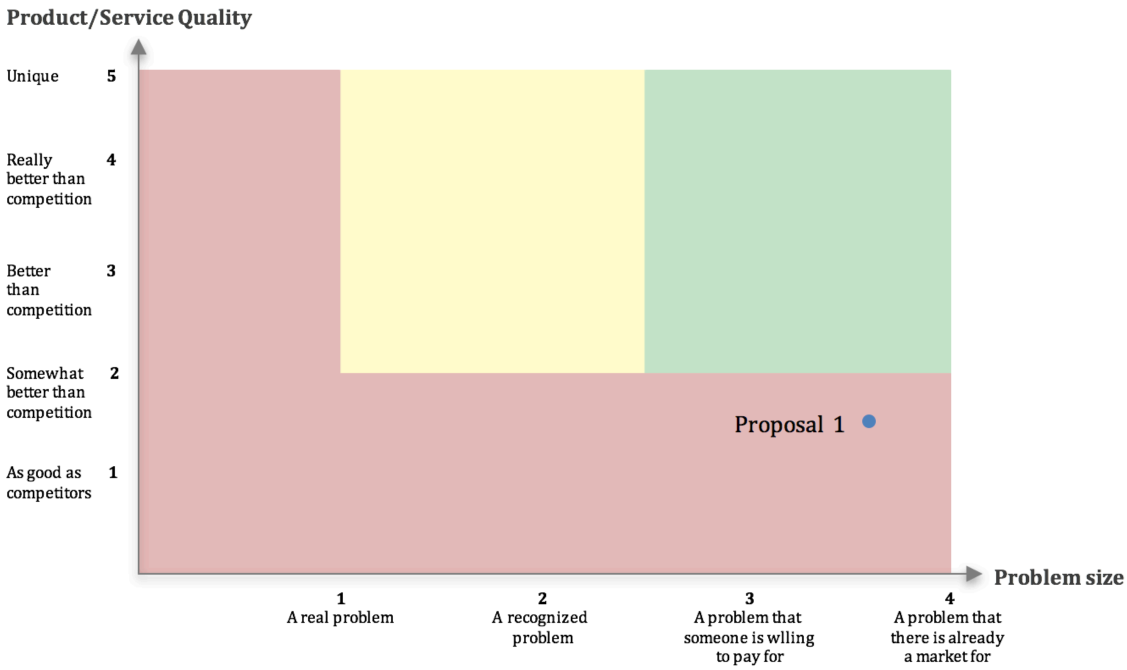

Figure 25: Problem size vs product/service quality for proposal 1.

Profitability, market size, and IPR
The market for such a solution could arguably be big for the areas in which the seabed is mainly made up by sand or mud. Some areas, like the coast of Japan, consist of rock- and reef-based seabed (HitashiZosen, 2018). Here, this solution would not apply. For the FOWTs, the solution could be highly useful for measuring scour around the mooring piles. If a company were to develop this solution, they could try to patent it, but since some similar solutions already exist, it is uncertain whether it would be granted. A trademark on the brand name could, therefore, be the best solution. A profit margin of around 30% reflects the investment costs, and the potential cash flows and revenues. The final score is given in figure 26.

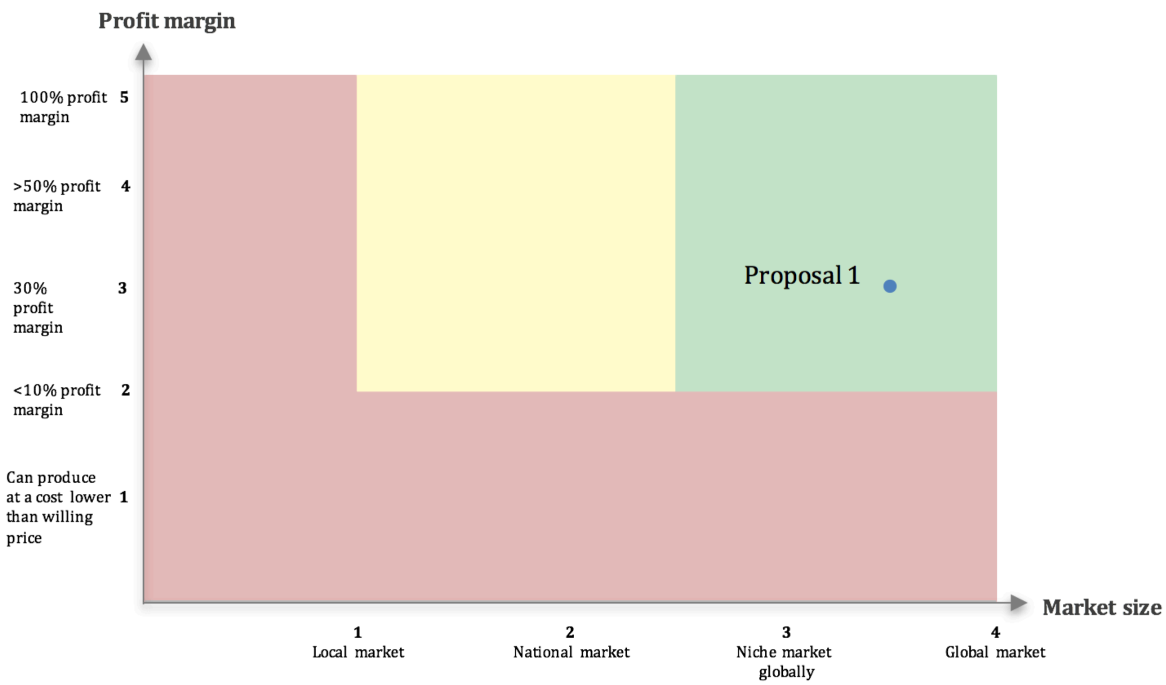

Figure 26: Market size vs profit margin for proposal 1.

5.2 Proposal 2: *Real-time scour monitoring with fiber optic sensors*

General
For the purpose of monitoring the height of scour surrounding a substructure, a fiber optic cable with FBG sensors can be utilized. Several research projects have experimented with using this technology for monitoring bridge scour, yet no established commercial product exists.

Current method
See *current method* in chapter 5.1.

Technical specifications
The idea is illustrated in figure 27. A cantilever beam made of a steel foundation and a flexible composite rod is submerged in the seabed in the proximity of the turbine foundation pile. A fiber optic cable with FBG strain sensors is integrated into the beam. The sensors are marked as red dots in figure 26. A minimum of three sensors must be used; one below the sea bed, one at the seabed level, and one over the seabed. While the submerged part of the beam will be supported by the surrounding sediments, the upper part will be more reactive to outer forces. As water current passes the upper part of the beam, it will bend, causing strain to be applied to the FBG sensors. This strain is recorded by the strain sensors, and the position of the sensor, together with the strain value will then give an indication of the amount of sediment that is transported – the scour. The recorded data will be connected to the current sensor data infrastructure.

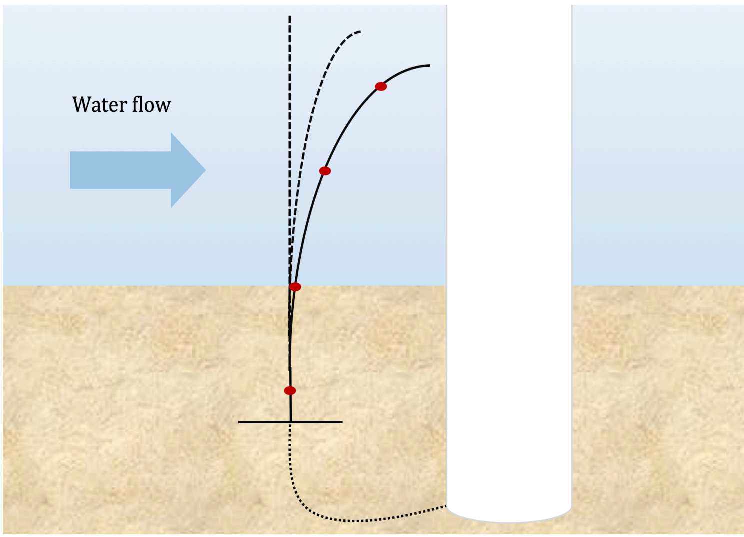

Figure 27: The presented concept.

Challenges
The fiber optic cable that goes from the cantilever beam to the turbine could be a vulnerable area, although it should be highly feasible to build it as a solid structure that withstands the dynamic forces. The integration of the cable to the existing subsea cable infrastructure could also be challenging. However, for monopile structures, the cables are often incorporated into the substructure at the very bottom, as shown in figure 28. This may ease the integration process since the fiber cable is in the approximate same area.

The stability of the submerged cantilever beam could also be compromised over the years. Marine growth could be a challenge, yet this would be easy to clean with conventional cleaning methods for marine growth.

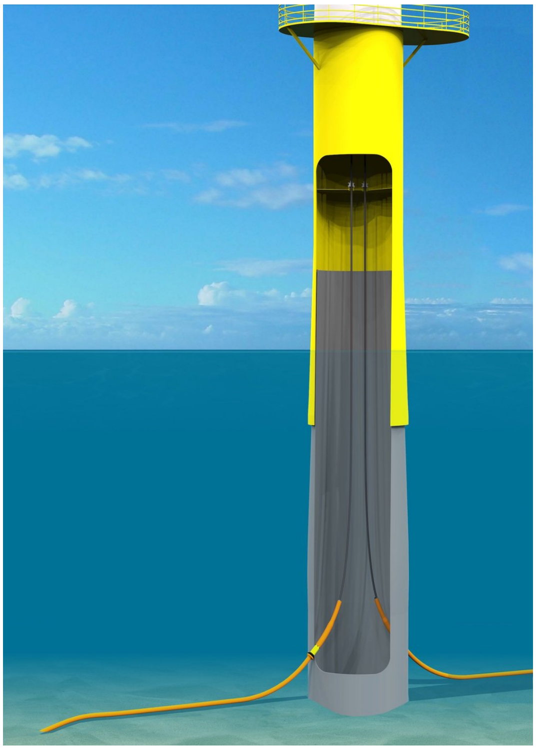

Figure 28: Cables in monopiles (SeaproofSolutions, 2018).

5.2.1 Screening

Quality and problem size

Regarding the problem size, the arguments are the same as in chapter 5.1.1 under *Quality and problem size*. The quality of this solution is really good, as it is likely to reduce costs related to scour measuring significantly, and because of the fact that the existing method is highly expensive. The score with regards to the problem size and the quality of the proposal in solving the problem is shown in figure 29.

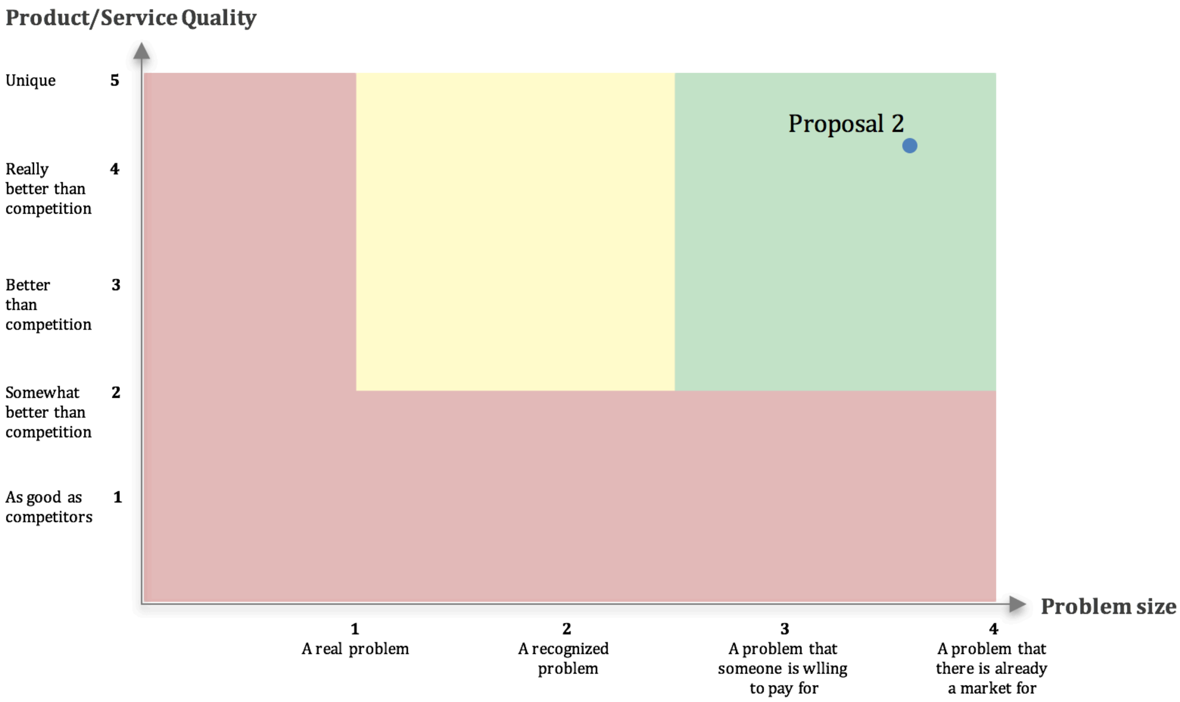

Figure 29: Problem size vs product/service quality for proposal 2.

Profitability, market size, and IPR

Regarding the market size of such a solution, the arguments are the same as in chapter 5.1.1 under *Profitability, market size and IPR*. A company delivering this solution should be able to obtain a profit margin of around 50%. A patent could be highly likely to achieve, and the future cash flows and revenues could also be quite good. It could, however, be an expensive solution to invest in and to install and commission. The proposal then ends up at the score illustrated in figure 30.

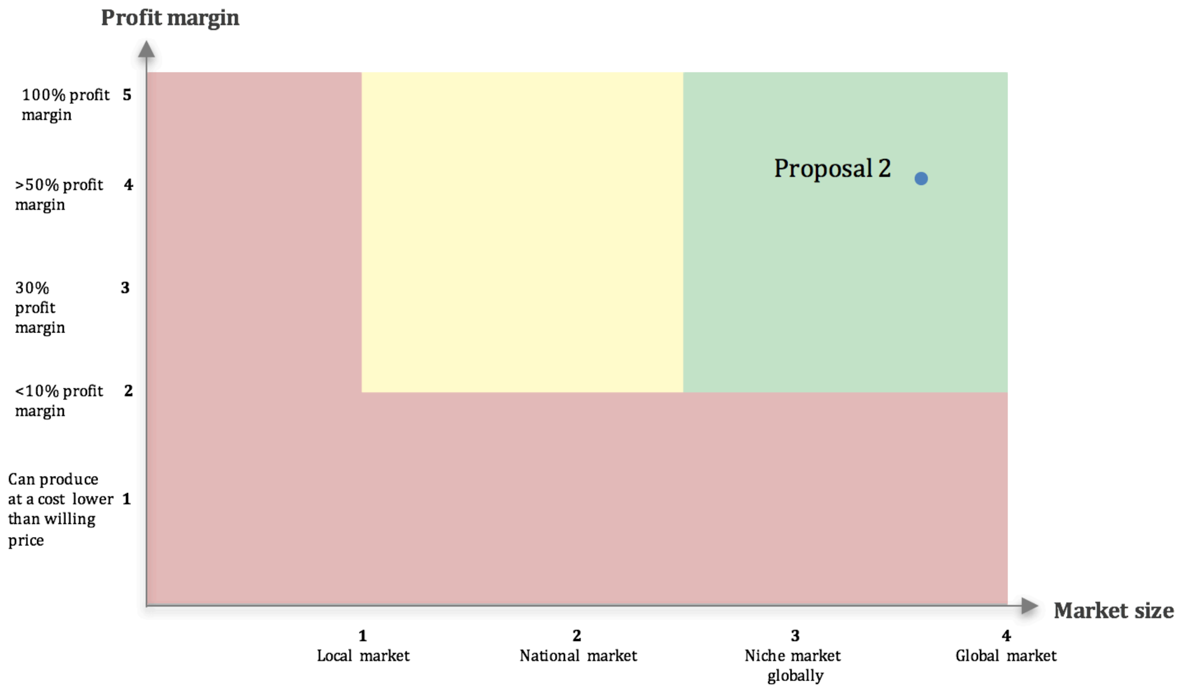

Figure 30: Market size vs profit margin for proposal 2.

5.3 Proposal 3: *Strain monitoring of mooring lines using Fiber Bragg Grating*

General
For FOWTs, synthetic mooring lines have shown exceptional results and is likely to be widely used in newly installed FOWTs. As opposed to traditional chain-based moorings, mooring lines made of nylon materials offer a potential for huge cost-savings and is also very much applicable for catenary/taut mooring lines (Foxwell, 2017). In synthetic moorings, it has been showed that by integrating fiber optic sensors, the strain and twist of the rope can be accurately monitored (Rebel et al., 2000).

Current method
Fiber ropes are still a fairly new concept in offshore wind. OWF developers are however increasingly swearing toward the use of fiber ropes. The DNV GL standard, *DNV-RP-E304,* contains recommended practices for damage assessment of fiber ropes for offshore operations. The main procedure is to do visual inspections. If the damage is located in the outer fibers, minor repair can be done. However, if the core fibers are damaged, the rope must be discarded (DNVGL, 2017). Some OWFs, like the *Hywind,* have practices for measuring the strain (see chapter 3.5.2.3).

Technical specifications
As figure 31 illustrates, the fiber optic cable is embedded within the thin filaments that comprise the rope. It is twirled around the filaments rather than integrated into parallel with them. Since the stress in unevenly distributed across the cross-section of the rope, a parallel twirling is likely to increase the reliability of the measured values. Furthermore, the cables are connected to the existing subsea cables that are tied up to the FOWT (see figure 32). It is connected to the already existing condition, or performance monitoring software. If deviations are recorded, an alarm is communicated to maintenance management.

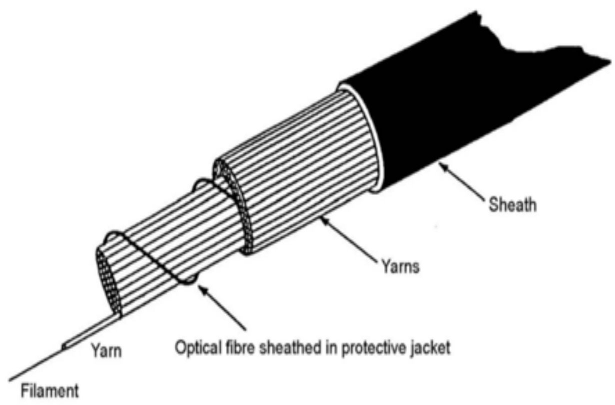

Figure 31: Fiber optic cables integrated to a rope (Rebel et al., 2000).

Figure 32: How subsea cables are tied up to the FOWT (PEi, 2010).

Challenges
The concept of FOWTs is still in an early phase and is still trying to prove its viability. This could be seen as an opportunity for new technologies, but the concept is still largely dependent on proven technologies, as completely novel and unproven technologies may be regarded too risky to implement in an already risky project. Comprehensive tests must, therefore, be carried out first. It is also uncertain whether operators see the monitoring of mooring lines as necessary, or if visual inspections would be preferable instead.

5.3.1 Screening

Quality and problem size
It may be argued that the need for monitoring the mooring lines is unnecessary. However, the consequences of a potential tare can be quite severe, so the investment in such a solution should be considered. The FBG sensors provide real-time, accurate measurements, without the need for using ROVs or divers, and is therefore really better than competition. The score is given in figure 33.

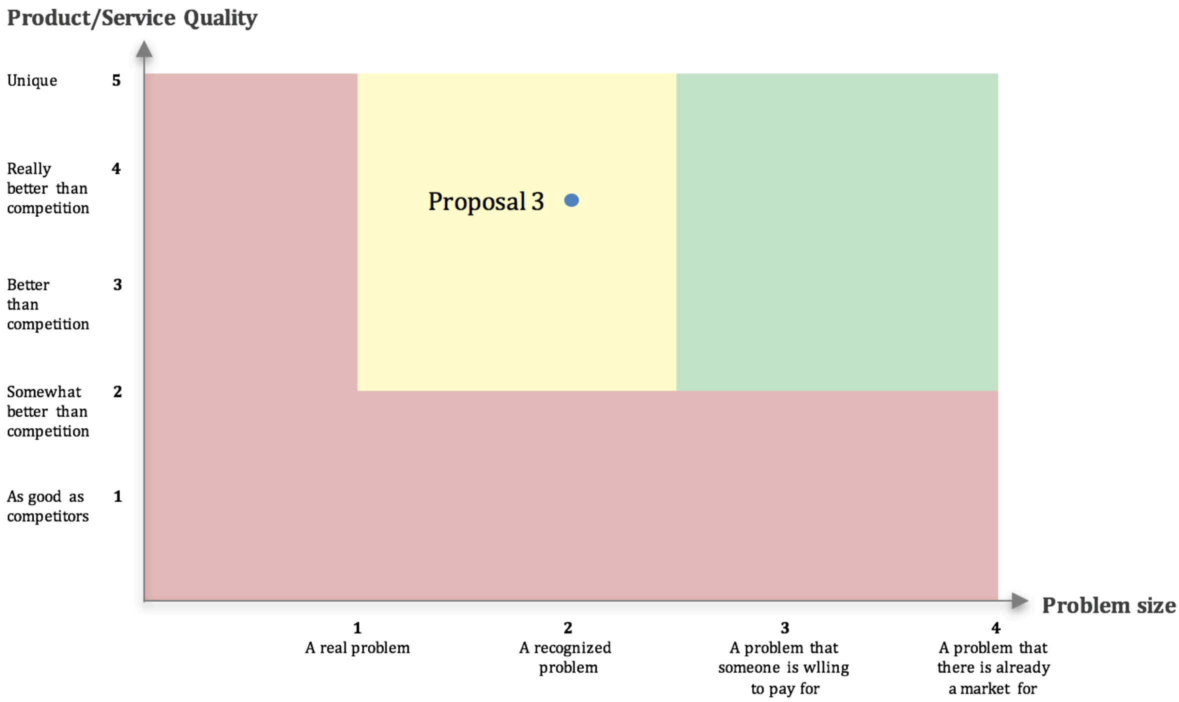

Figure 33: Problem size vs product/service quality for proposal 3.

Profitability, market size, and IPR
Since FOWTs are a new concept that is not very established yet, it is safe to say that the market for a system like this would be of a national scale. A profit margin of around 20% reflects uncertainties in future cash flows, and revenues, and the investment costs. The investments, however, do not need to be that large. As the concept of integrating FBG sensors into fiber-based ropes already exist for certain purposes, the solution of delivering this solution through a trademarked name could be an option. This adds up to a score as given in figure 34.

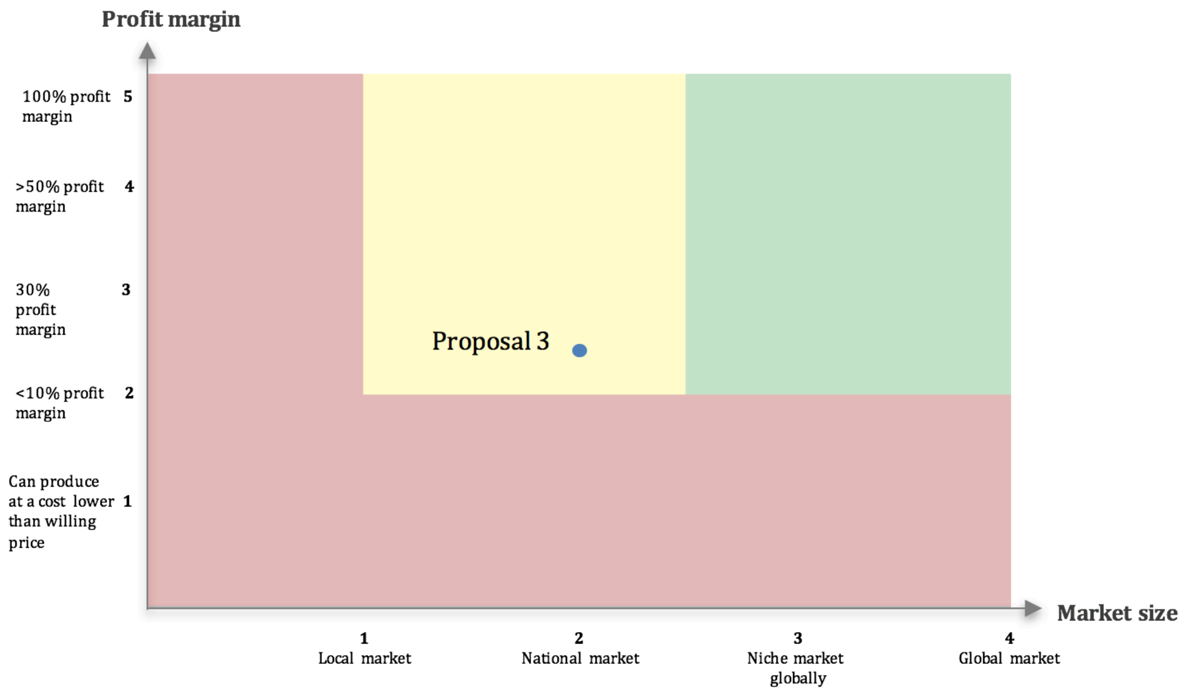

Figure 34: Market size vs profit margin for proposal 3.

5.4 Proposal 4: *Using a floating LiDAR for real-time individual pitch and yaw control*

General

The applications LiDAR technology in the offshore wind industry is mainly focused on measuring metrological factors and turbulence to verify the power curves from the turbine manufacturer. However, integrating this technology into the pitch and yaw control systems of the turbines creates an opportunity for optimizing the performance of the turbines, as well as reducing mechanical stress and fatigue. With the advances made in the individual pitching of blades, real-time wind measurements taken by a floating LiDAR can be used to achieve more accurate pitch and yaw angles that fit the actual wind conditions.

Several research projects have suggested the use of local wind measuring sensors mounted on the blades, or cup anemometers (a small turbine measuring wind speed) (Thomsen et al., 2008), (Natarajan et al., 2012). However, accurate measurements remain a challenge. LiDAR units have through several publications proved that their measurements are highly comparable to the conventional met masts (Müller and Crockford, 2015).

Current method

The conventional method for metrological measurements has until now been so-called *met masts* (metrological masts) for the wind measurements. Met mats are highly expensive, and their accuracy is limited by the fact that they are fixed to the same location, which makes the measurements generalized and not turbine specific. The data gathered by the met-masts, is transferred to the pitch- and yaw controllers through fiber optic cables. The control systems then adjust the angles according to the data. This change is a quite slow process that takes a long time to carry out.

Technical specifications

A LiDAR is capable of collecting hundreds of winds speeds per second. Transferring these measurements to a computer at the turbine which signals the pitch- and yaw controllers, should according to the current research be able to do in real-time (Natarajan et al., 2012). Instead of having a fixed LiDAR unit on each turbine, one floating unit can be used for several turbines. This may save costs, as well as the problem of the rotor interfering with the measuring is eliminated, which is a significant challenge with nacelle-fixed LiDARs (Kim and Dalhoff, 2014). The data collected by the LiDAR is transferred to the controllers either through satellite communication, or a WLAN network set up on the turbine. Using the WLAN option will probably require more LiDAR units, to reduce the distance to the turbine, something which will enable even better communication. The two principles are highlighted in figure 35.

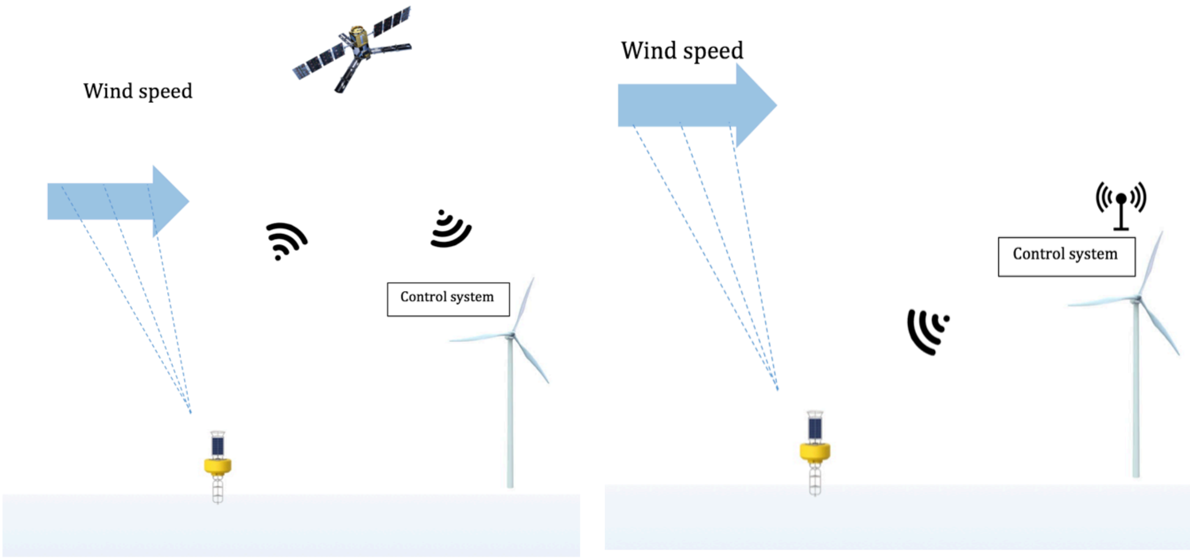

Figure 35: Two ways proposal 4 can be set up.

Challenges
This system will require large initial investments in equipment, in a novel technology that is not well established yet. Some may argue that it would be more preferable to stick with the current met masts instead. However, as the floating LiDAR technology gets more mature, and new OWFs increases in size and numbers, it could be a viable solution. Also, for FOWTs that are installed at large depths, this solution would be very relevant since fixed met masts will become too expensive.

5.4.1 Screening

Quality and problem size
The data gathered by the met masts for pitch- and yaw control is currently working at an acceptable level. However, the fact that the turbine needs to shut down at 25 m/s still works as a bottleneck for higher power production (explained in chapter 3.4). If this system would work properly, the quality of compared to the met masts is much better. These facts result in the score given in figure 36.

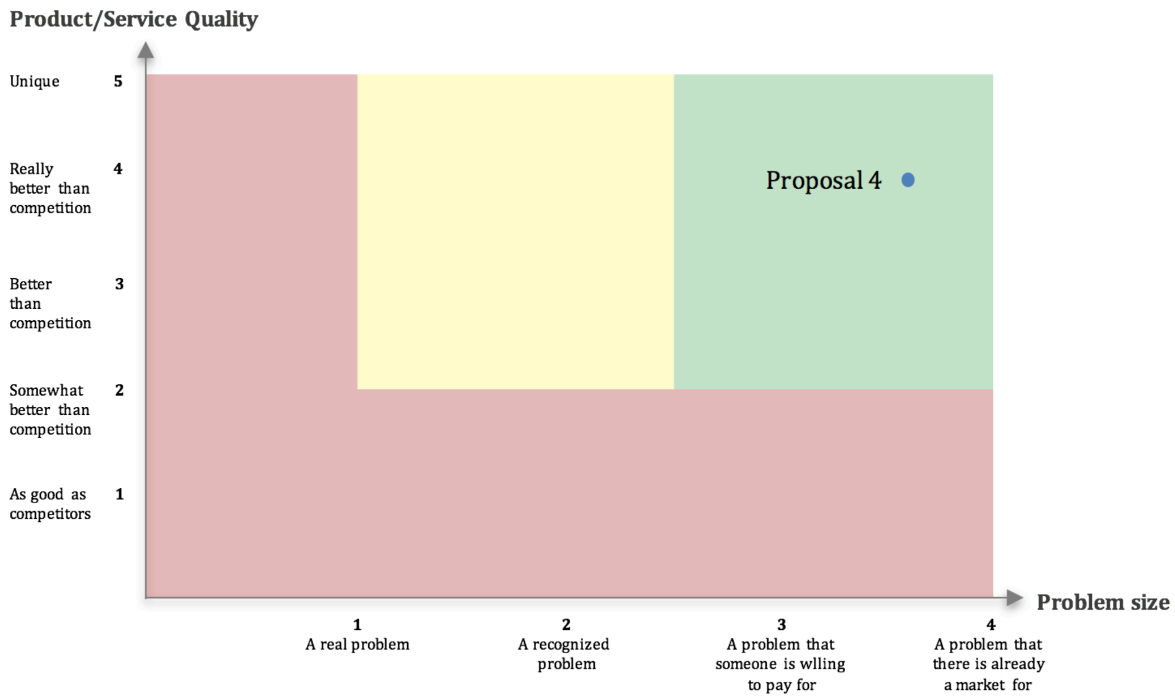

Figure 36: Problem size vs product/service quality for proposal 4.

Profitability, market size, and IPR

New and modern OWFs would be a suitable application for this solution. However, older OWFs that want to exploit their turbines further and increase their productive life, could also be highly relevant. The profit margin should be around 50%, as it reflects the investment costs and the relatively high future cash flows and revenue. It may be possible with a patent, but if not, it could be delivered through a trademarked name, that hopefully would gain recognition, increasing their market share. Figure 37 shows the score.

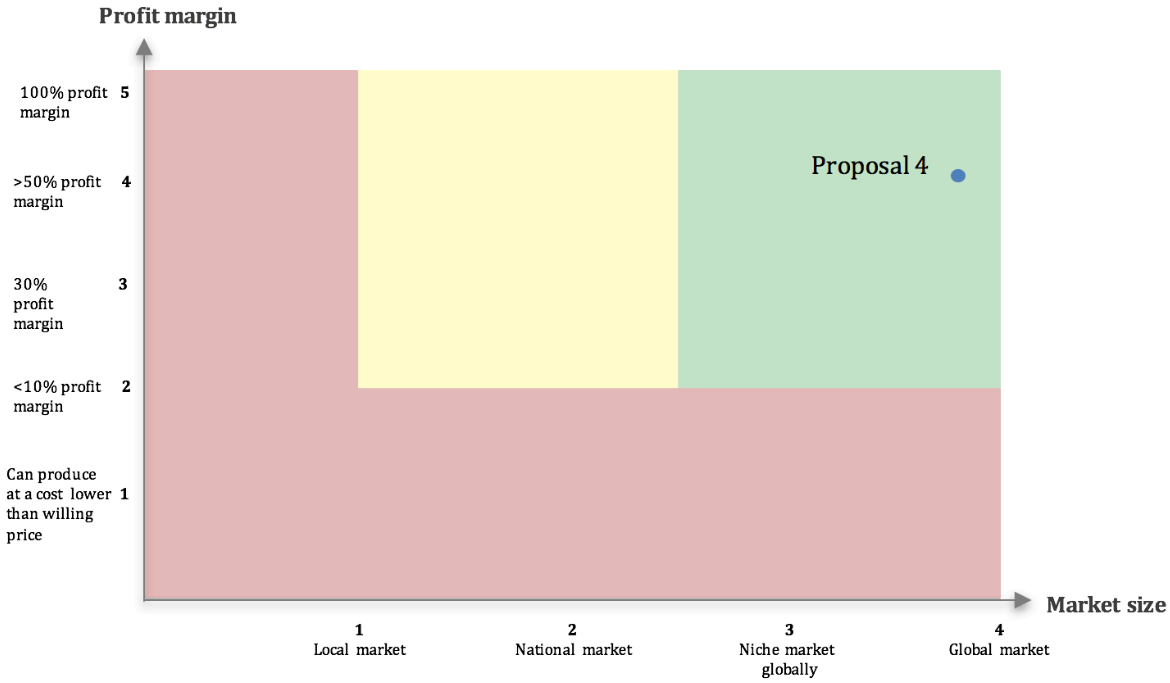

Figure 37: Market size vs profit margin for proposal 4.

5.5 Proposal 5: *Autonomous subsea inspection system with an AUV swarm*

General
As highlighted in chapter 4.6.2, AUVs have a huge potential for inspection of substructures and cable infrastructure. This proposal can potentially increase the quality of inspections significantly, as well as reducing the costs due to the fact that it is not dependent on a nearby ship. Figure 38 shows a prototype of a research project done by the British subsea company *Modus* using a docking station for recharging an AUV (Offshorewind.biz, 2018).

Figure 38: An AUV approaching a docking station (Offshorewind.biz, 2018)

Current method
Most subsea inspections have until now been performed by human diving crews. A diving crew is usually 6-7 people deployed on a diving support vessel. In recent years, ROVs have been introduced as an alternative to traditional diving methods. ROVs are small underwater robots, controlled remotely by humans through an umbilical. There is still a need for a crew to operate them, but they can still do inspections faster, safer and cheaper (ROVDRONE, 2018).

Technical specifications
An illustration of this proposal is provided in figure 39. This idea presents a concept where a network of small AUVs are used to continuously monitor and report on the condition of substructures, subsea infrastructure and the seabed conditions (scour, holes etc.). The proposed system contains a number of AUVs (depending on the size of the area they will be deployed in), a floating docking station (a buoy) powered by solar panels mounted on it, a satellite communication system, and a data acquisition and interpretation site (on- or offshore). There is no need for WLAN as the information not necessarily has to be real-time. The floating buoy should be designed so that the AUVs can be autonomously connected to it. It will then transfer its data to the buoy, which subsequently transfers it to a remote control center. While the AUV is docked, it will also be charged. The AUV swarm will have an anti-collision control system with motion sensors. They will be deployed with sonars, laser scanners, photographic scanners with

flash strobes, depth sensors and hydrophones for receiving ambient sound. A computer vision feature processor will be included to the AUV so that by processing the data, the AUV can detect basic deviations from standards, such as holes and cracks. However, the gathered data can be visualized by a remote CM team. The AUV will frequently rise to sea level in order to charge and transmit its data and to confirm its geographical position with satellite signals.

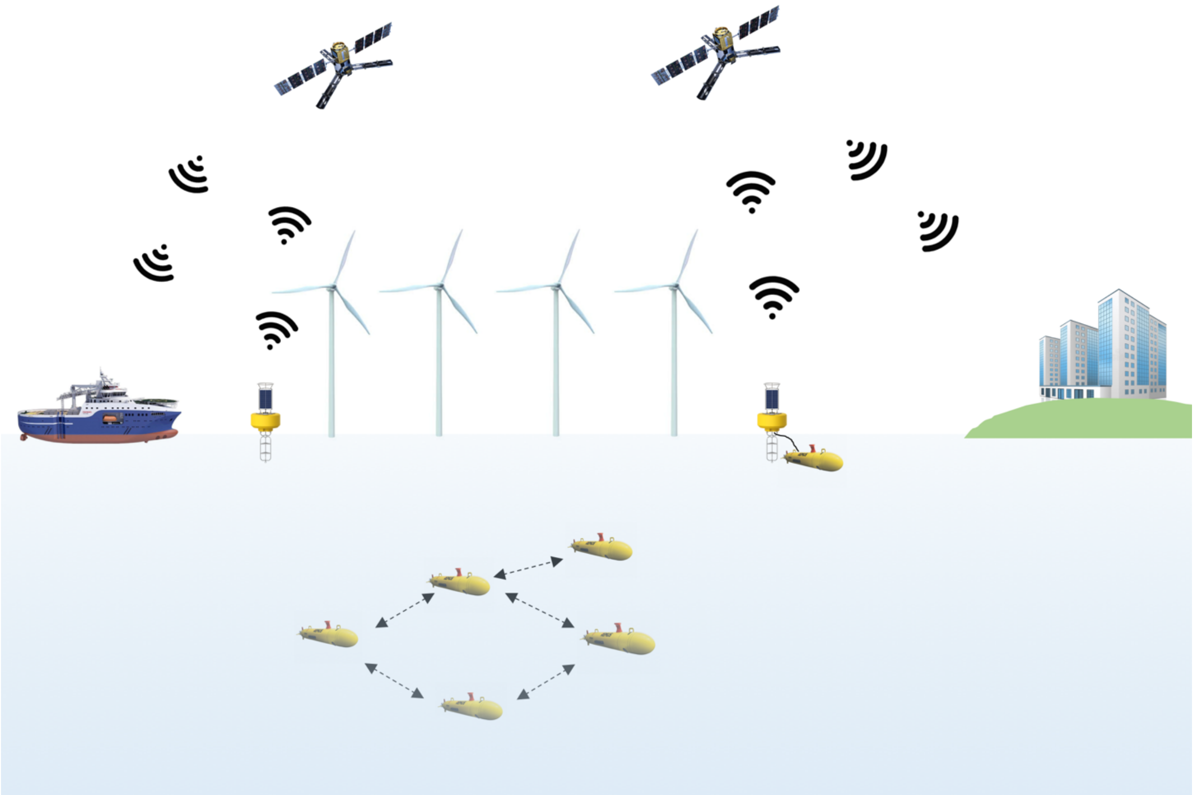

Figure 39: The concept of proposal 5.

Challenges
It is a challenge whether the AUVs will be able to stay within the defined area. Just leaving highly expensive equipment to operate on its own in the ocean may not be the first thing OWF developers want to do with their money. If for some reason, the geographical location is lost, it may run out of power and disappear. It will also require significantly high investment costs. Harsh environments with low temperatures and high wave heights, like the North Sea could also cause additional challenges.

5.5.1 Screening

Quality and problem size
Normally, it is not first and foremost the subsea conditions that cause the high downtimes, and some would maybe argue that a continuous subsea monitoring would be needless. However, since the subsea conditions have to be inspected when the *extended inspection activities* are carried out anyway, it could be a viable solution. Regarding the quality in solving the problem, it is highly time- and cost-effective compared to the use of human divers. The final score is given in figure 40.

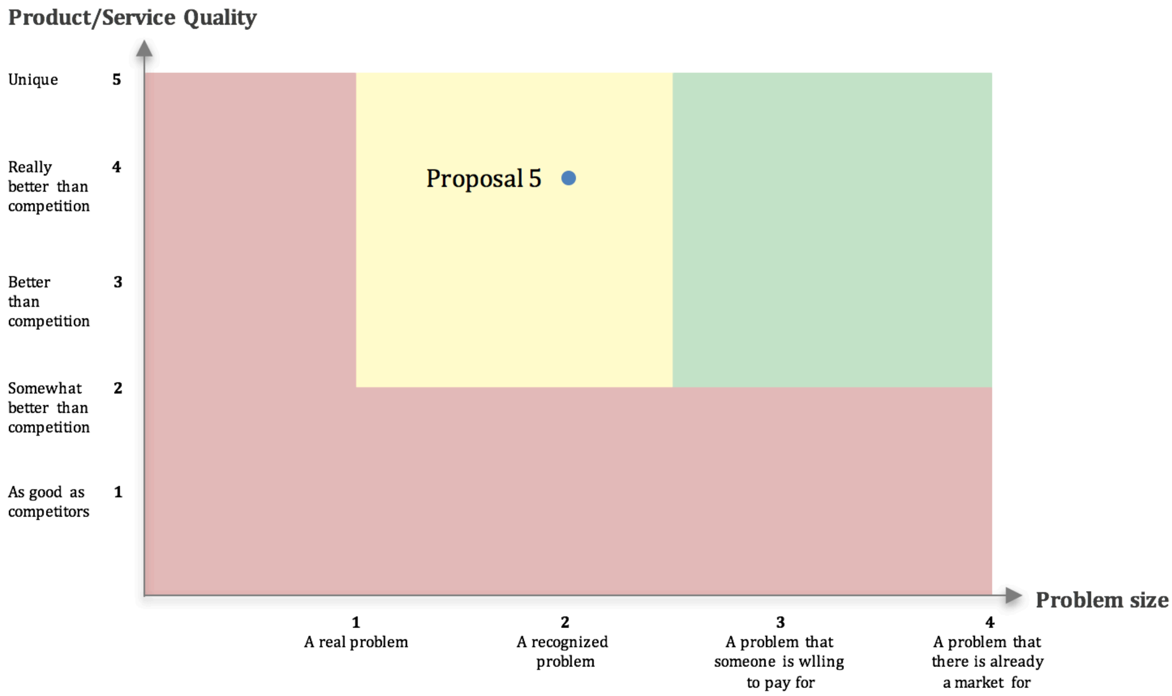

Figure 40: Problem size vs product/service quality for proposal 5.

Profitability, market size, and IPR

Every OWF in the world need to have subsea inspections, so the potential market size of this concept could be a global niche market. The company that chooses to develop such a concept, could try to apply for a patent, but it is uncertain whether it has the required originality. Unless it could be delivered through a trademarked name. The profit margin is likely to be around 30%, as the system is quite unique in the offshore wind industry. The future cash flows could, therefore, be high. However, it requires extensive investments and may be costly to maintain. Figure 41 illustrates the final score.

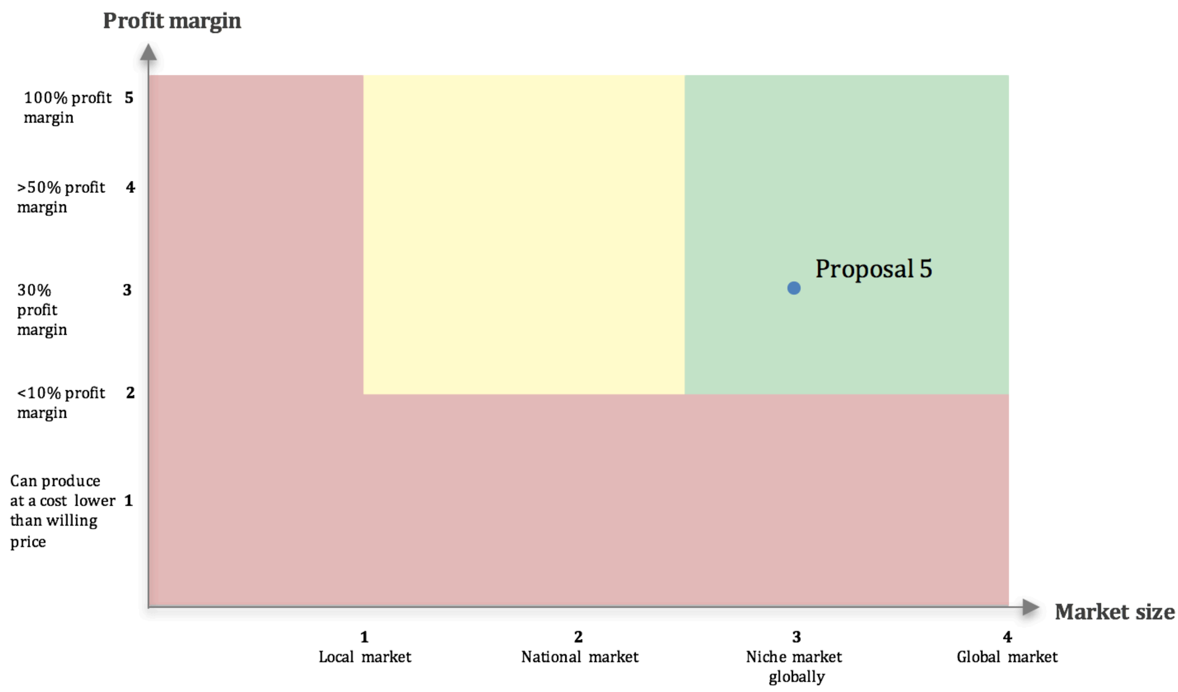

Figure 41: Market size vs profit margin for proposal 5.

5.6 Proposal 6: *AUV for cleaning substructures for marine growth General*

General

Even though many operators choose to not implement an MG removal strategy, it is recommended to perform thorough analyses in this field. It is no doubt that in order to maintain the structural integrity and reduce the dynamic loading, the ideal strategy is to reduce the amount of MG as much as possible (Subseaworldnews, 2018).

If the substructures are continuously cleaned, there will simply not be enough time for MG to start growing on the surfaces. Therefore, this proposal introduces an autonomous cleaning system for OWT subsea support structures, cable infrastructure, and moorings.

Current method

Most subsea structures are treated with coatings that delay the marine growth to occur. Nevertheless, as part of the *extended inspection activities* (see chapter 3.5), cleaning of marine growth has to be done in order to uncover potential damages. Procedures vary, but two main methods are used; human divers and ROVs, both equipped with customized tools (pressure washers and brush-tools) for marine growth removal (Dürr and Thomason, 2009). OWF operators must follow certain standards for the treatment of MG. *ISO 19901 Petroleum and natural gas industries – Fixed steel offshore structures* is one such standard (Fevåg, 2012).

Technical specifications

The proposed system will be made up by an AUV equipped with an underwater water pressure washer. It will use high-resolution cameras together with computer vision capabilities to detect the areas in which it will operate. By frequently rising to sea surface it will expose its solar panels (see figure 42) to sunlight, allowing it to charge, as well as navigate with satellite communication through a satellite-based GPS-system. The AUV will maneuver itself and flush the monopiles, jacket structures, mooring lines and subsea cables, flushing high-pressure water, removing all MG development.

Figure 42: AUV with solar panels (BluebirdMarineSystems, 2017).

Challenges

The amount of MG that grows between every visit from the AUV is hard to estimate, something that makes it difficult to decide the required pressure in the pressure washer. Nevertheless, the integrated pressure washer is likely to stand for a significant share of the total power consumption, and whether this will be possible or not with the power produced by the solar panels, is uncertain. However, due to the continuous cleaning, there will probably be minor MG developments that have to be flushed off. Also, by using *gliders* (described in chapter 4.6.2) instead of thrust-driven AUVs, the total power consumption will be significantly reduced, making this solution more viable.

Another challenge is the navigation, and how the AUVs should find their way towards the subsea structures. As highlighted in chapter 4.6.2, underwater communication is challenging. The frequent risings to the surface will, however, make it possible for the AUV to use GPS navigation. Another possible solution is to install special *beacons* on the seabed and at the turbine substructures that transmit acoustic signals to the AUV so that it is able to navigate underwater. Figure 43 illustrates this principle.

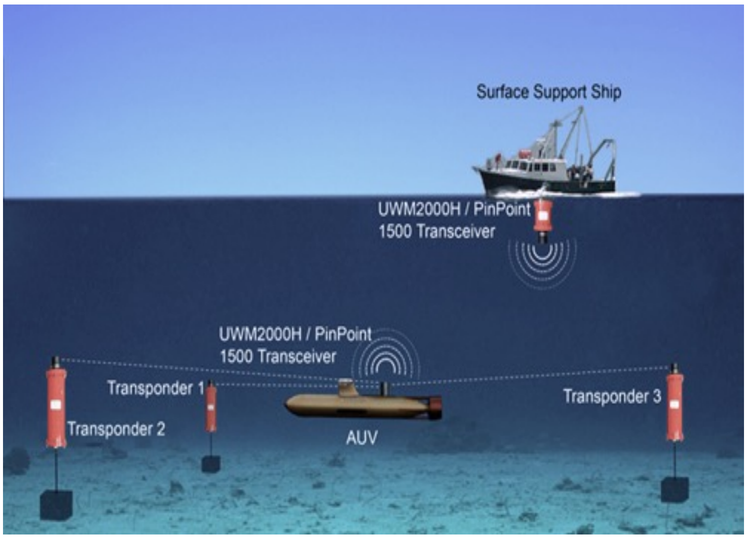

Figure 43: AUV system with acoustic beacons (AUVAC, 2018).

5.6.1 Screening

Quality and problem size

Marine growth can cause significant harm to the marine structures. There are numerous studies that conclude with the fact that MG has a negative impact on the structural integrity and contributes to fatigue, which is one of the leading mechanisms in determining the service life of offshore structures (Soares, 2016). Regarding the quality of this solution, it is uncertain whether it will work satisfactorily or not. The final score is given in figure 44.

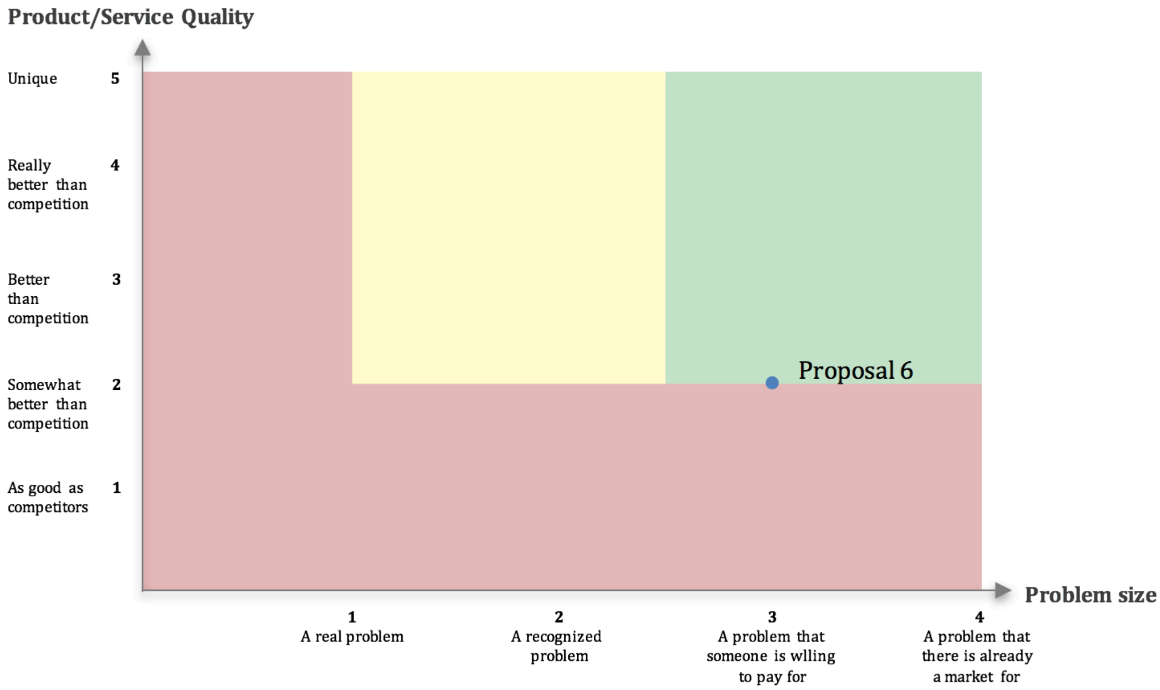

Figure 44: Problem size vs product/service quality for proposal 6.

Profitability, market size, and IPR

Every OWF operator has to have a strategy that addresses the MG problem. Not dealing with it at all can cause serious damage.

An external service provider could develop this solution and deliver it as a service, earning monthly cash flows over a specified contract period, and being fully responsible for the operation. As it has a high degree of originality, a patent could be achievable. After break-even is reached, a stable profit margin of 10% is imaginable. It reflects the investment costs, the uncertainty of predicted sales, and running costs. Figure 45 shows the final score.

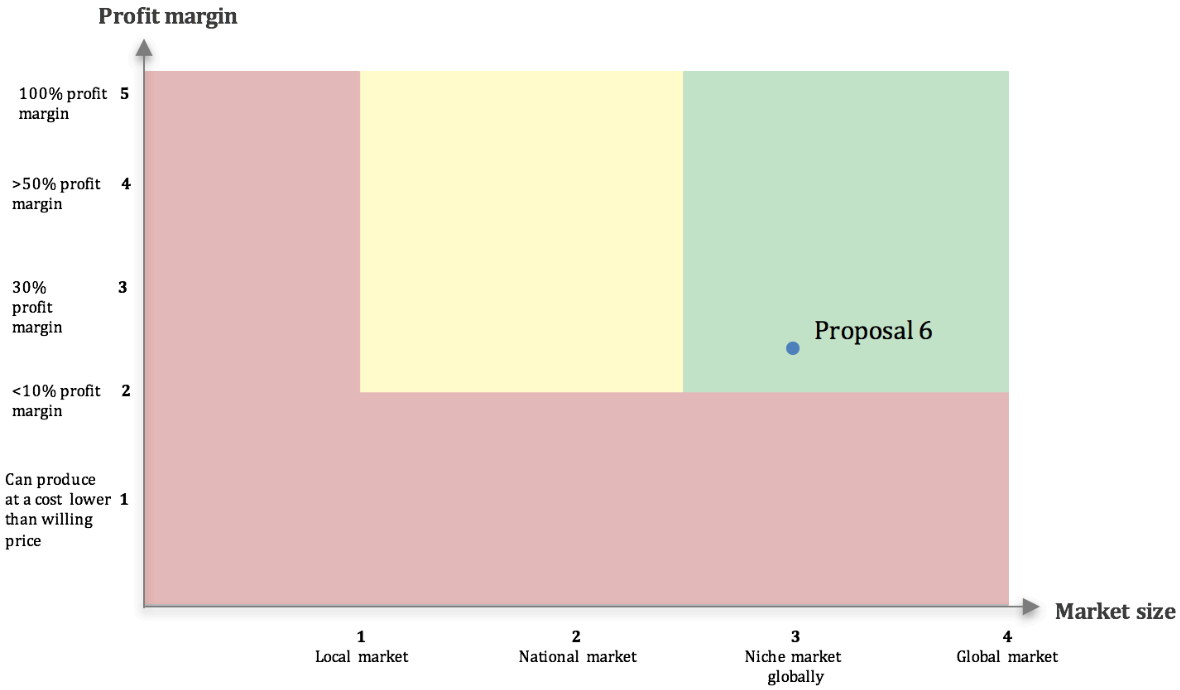

Figure 45: Market size vs profit margin for proposal 6.

5.7 Proposal 7: *Crawler-based blade exterior- and interior inspection- and intervention system*

General
To cope with the presented challenges regarding accessibility, so-called *crawlers*, with both inspection- and intervention capabilities can be utilized. They can be deployed to the inside of the blades, as well as other interior locations, and the outer surfaces of the turbines. This proposal suggests one crawler unit for inspection and another one for performing small maintenance tasks.

Current method
Inspections above sea level are covered in chapter 3.5.1. Visual inspections that do not require close views are done using binoculars. When close-up inspections of the turbine exterior (tower, blades) are needed, rope access using climbing equipment is utilized. The *splash zone,* which is the around the sea level, are exposed to harsh and changing environments and is important to inspect for corrosion development. This is typically done by visual inspections from a boat (Sheppard et al., 2010). Regarding the inspection of the blades inside, a frequently used technology the last years has been to "drop" a *borescope,* a small camera that rotates into the blade when hanging downwards. The camera is connected to a screen for remote supervision (Miller, 2017).

Technical specifications
Figure 46 illustrates the technologies and the functions of the proposed crawlers. They will be based on state-of-the-art crawler technology used for inspection of gas turbines. They rely on magnetic adhesion in order to stay attached to the surface. This means it can "crawl" upside down if necessary (Miller, 2017). The inspection crawler should not be bigger than a cubic decimeter (10*10*10 cm), and should be equipped with a high-resolution pivoting camera and a LED light, and a wireless communication system connected to a WLAN at the turbine, so that it can be remotely maneuvered from a control center onshore, or from a mobile control device. In case of a small defect, this unit will be able to "shoot" some material from a small tube, onto the surface. The operator will visualize the operation and maneuver the crawler units from a mobile device remotely.
The small size of these units would also make it possible to operate them while the rotor is running, potentially increasing the operating time of the turbine dramatically. This would be highly attractive for the owners and operators.

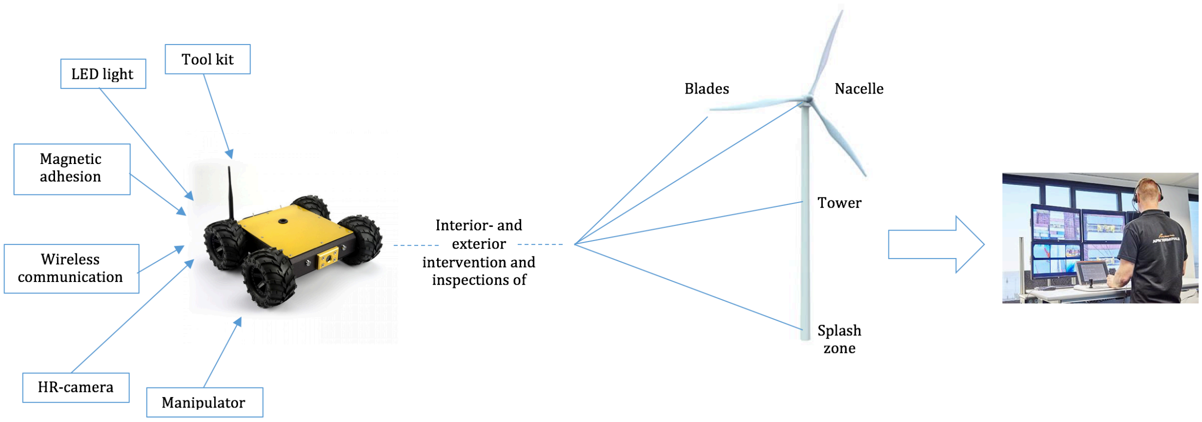

Figure 46: Proposal 7 illustrated.

Challenges
The manipulator may face challenges when intervening in complex geometries. The accuracy may just not be precise enough. If there is a tear in a composite structure that is highly confined, it may have problems with covering the area accurately enough with the repair material. If an operation turns out to be impossible to carry out, and maintenance personnel has to do it instead, this will increase costs significantly. The usability is thus an issue. Communication challenges may also occur since the concept is wireless.

5.7.1 Screening

Quality and problem size
Inspections account for a huge part of the total O&M costs. Equipment and procedures enabling humans to access the complex structures are challenging to develop, and with the harsh weather and HSE issues, it is definitely a recognized challenge in the offshore wind industry. The quality of the proposed solution is quite good, as it can perform operations at a much higher speed than with human personnel. It thus receives the score illustrated in figure 47.

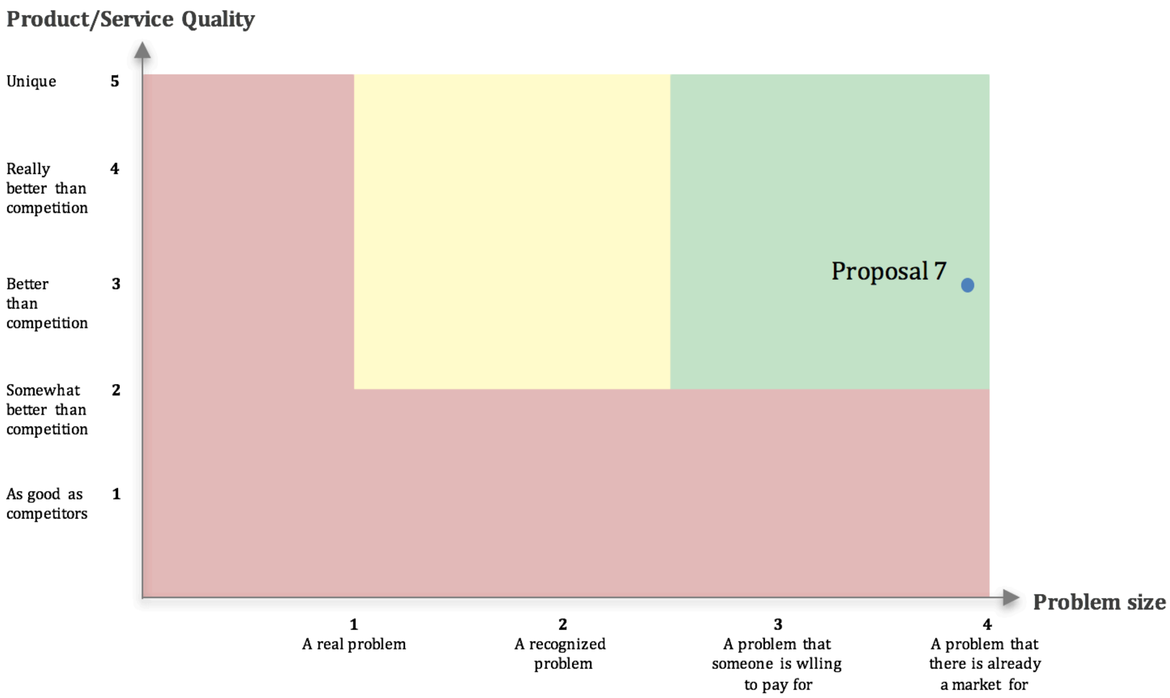

Figure 47: Problem size vs product/service quality for proposal 7.

Profitability, market size, and IPR
The market for a solution like this would be a global niche market. Every OWF operator has to perform exterior- and interior inspections, and if this solution could enhance the quality and reduce costs of inspections, it would have a global potential.
An engineering company can develop the technology, and engage in a collaboration with the operator, where the operator performs the inspections, with the possibility of reaching out to the developer for technical support if needed. This way, the people that know the turbine best, also perform the inspections. The savings in inspection costs will

then hopefully make up for the initial investment and the fee which is paid to the developer. After a certain period, the crew will be fully trained, and the support from the developer is no longer needed. Since the service is performed by the operator itself, and the equipment is bought from an existing supplier, there will be no need for IPRs. A suitable profit margin will then be around 40%. The score is highlighted in figure 48.

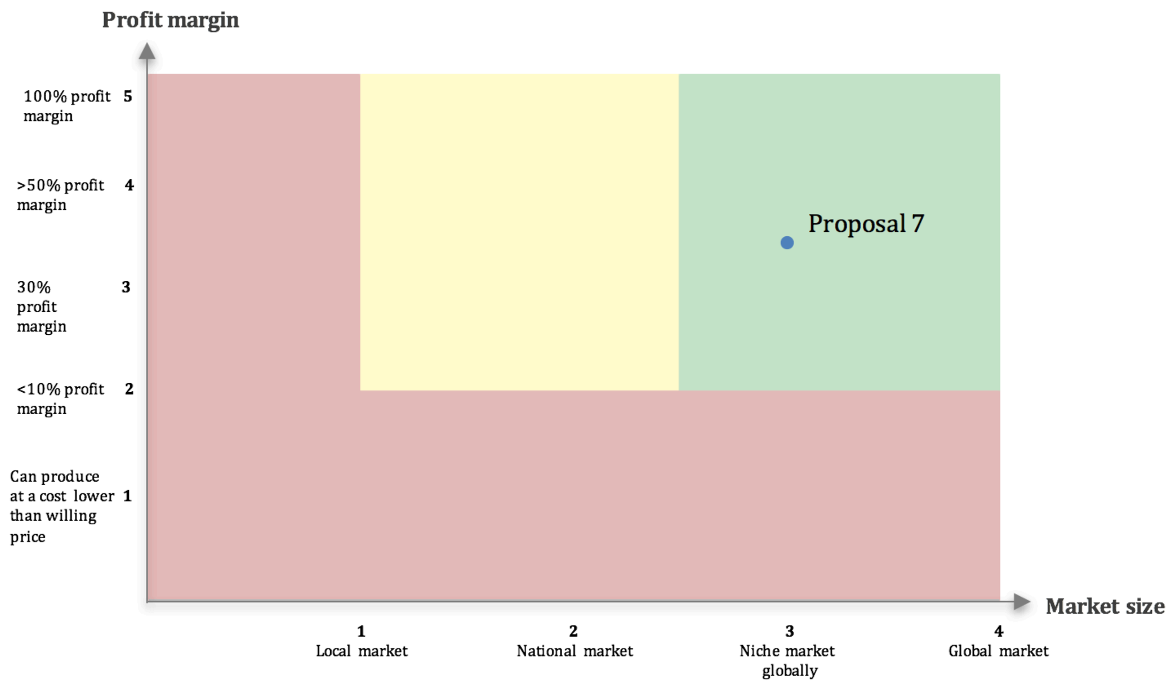

Figure 48: Market size vs profit margin for proposal 7.

5.8 Proposal 8: *Drone swarms for turbine exterior inspection*

General
As mentioned in chapter 4.6.4, drones are already being tested for offshore wind inspection. However, there is a potential in utilizing increased computational capacity and algorithms so that they become even more "intelligent". This proposal is about deploying "swarms" of drones that operate autonomously and continuously.
A concept developed by the Department of R&D at *Amerapex Corporation* in Houston, build on many of the same principles. The concept is illustrated in figure 49. Here, a swarm of drones with specialized "wall-sticking" capabilities is deployed to a refinery tank farm, performing ultrasonic testing.

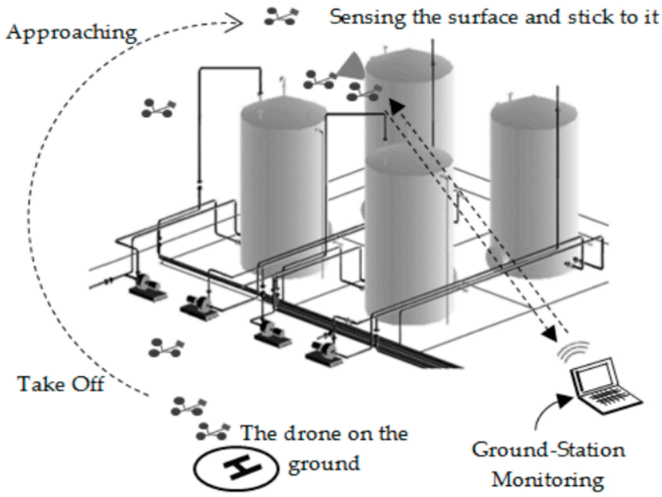

Figure 49: A similar concept with wall-sticking drones (Mattar and Kalai, 2018).

Current method
See chapter 3.5.1.

Technical specifications
Figure 50 illustrates the functionality of the system. As with the AUVs, "swarms" of drones can operate autonomously and continuously in the OWF. The drones in this proposal will have several intelligent capabilities. A computer vision system using high-resolution cameras will enable it to detect deviations from pre-programmed standards. The gathered inspection data is compared with maintenance requirements, and potential deviations are reported. A similar system that performs NDT with thermal scanning sensors will also be pre-programmed to detect defects within the structures. Sophisticated algorithms will enable the drone to develop reports that are wirelessly communicated to a remote maintenance management facility through satellite communication. Charging will be done at the charging stations which is installed at the top of each turbine, and the data is transferred via a WLANs which is set up at every turbine.

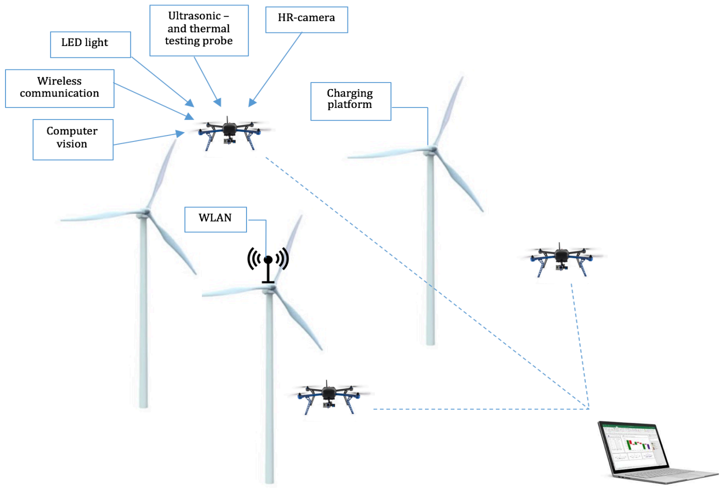

Figure 50: Proposal 8 illustrated.

Challenges
This proposal would introduce significant investment costs to the operator. Also, the cost of installing, managing and maintaining this concept is hard to estimate. The data gathered by the drones should be stored and analyzed in a structured way, an issue that many operators and owners may be inexperienced with. The maturity of this technology is also an uncertainty. If a drone fails or crashes, it may require extensive resources to locate it again, and it may also damage expensive equipment. Future changes to drone regulations may also change.

5.8.1 Screening

Quality and problem size
Challenges regarding inspections of the structural integrity are covered in chapter 3.5.1. Access is a serious challenge that OWF operators is constantly working to solve. Drones have to some extent been deployed to OWFs. However, this proposal extends the scope of the current solutions quite significantly, and have the potential of reducing inspection costs by far. Nevertheless, it is a highly comprehensive proposal, which needs thorough development and planning before it can be deployed. The final score is given in figure 51.

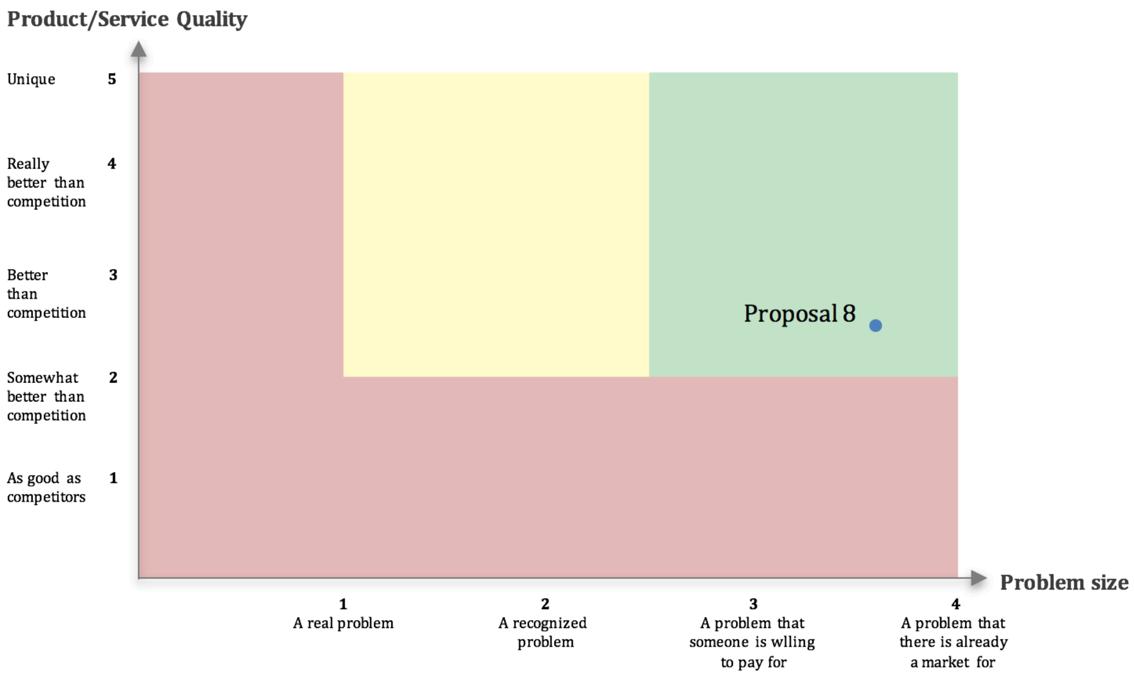

Figure 51: Problem size vs product/service quality for proposal 8.

Profitability, market size and, IPR
It is likely that the market for this proposal would be of a global scale, due to the fact that it covers a need in which every OWF is subject to, and it may reduce costs significantly. An external service company could deliver this solution as a service, with varying contract periods. A trademarked name would prevent others from using the brand name. The concept very innovative, but since it is completely new, the sales number and estimated cash flows are uncertain. Taking the investment cost into account, it could potentially make a profit margin of 30%. Figure 52 illustrates the final score.

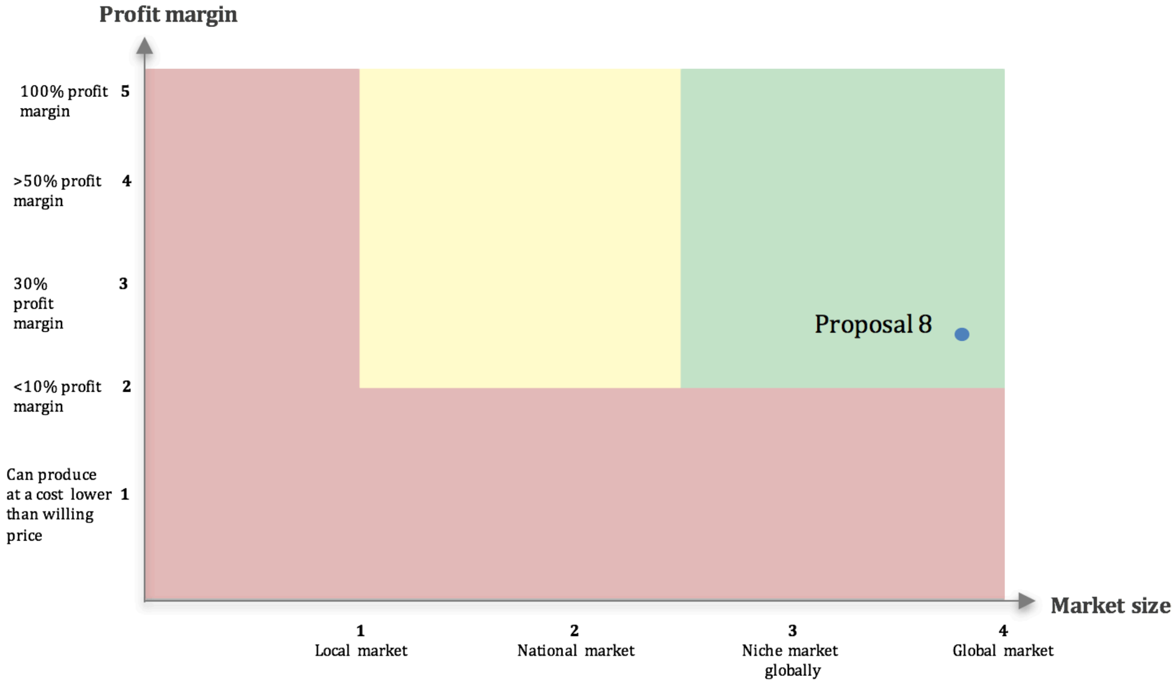

Figure 52: Market size vs profit margin for proposal 8.

5.9 Proposal 9: *Asset data- and documentation control with a digital twin software platform*

General

This proposal presents a digital twin that can be used to provide a general and holistic overview of all the assets in the OWF so that maintenance technicians and managers can access the information in a more optimal way. This will ensure a better allocation of resources and increase the performance of the assets.

Current method

In an OWF, different types of data, such as documentation, specification, reports, historical data, real-time sensor data is distributed over multiple access platforms. This means that in order to retrieve information about a specific component or system, it is likely that it will take a long time. Since the different platforms are non-compatible, the operator has to use a lot of resources in order to put the data from the various sources in one perspective (DNVGL, 2016).

Technical specifications

Figure 53 shows a graphical overview of this proposal. All the data within the digital twin will be securely stored and accessed from a cloud. It will contain a visual 3D model of the whole OWF, which contains information about the single components in each turbine, and general performance data from the whole OWF. Documentation, reports, historical data, standards and sensor data from the condition- performance- and weather data sources will be integrated, structured and linked to the relevant equipment so that it can be visualized by clicking on the specific component. Relevant financial variables will be associated with each area. For instance, vibration data will be linked to costs such as the remaining operating life, operating efficiency, and replacement of components. By utilizing voice recognition and QR-codes, operators can access all relevant information of a component or system by simply asking for it, or by scanning a component. Sophisticated AI algorithms will enable the twin to suggest measures to a problem.

Furthermore, the digital twin will work as a simulation model, in the sense that it can provide accurate predictions based on statistical analyses, as well as running simulations on the implementation of new equipment or potential changes in weather data. Finally, the digital twin will be distributed to platforms such as tablets and smartphones, so that any operator easily can access real-time information by simply asking for it.

Figure 53: The essentials of proposal 9 illustrated.

Challenges

Communication will be an issue, due to the increasing remoteness of many OWFs. Those that are located closer than 100 km to the shore will be able to use *terrestrial* communication systems, meaning those that do not require satellites, like 4G/5G. However, more decentralized processors and edge computing may reduce the size of the data that is communicated (Höyhtyä et al., 2017).

Due to the complexity of the system, the model must be highly precise. Changes and inconsistencies between the real and the virtual model are also likely to appear at some point. These must be identified and managed properly.

It will require an extensive amount of data in order to be of any use. The existing data flow from sensors must, therefore, be of a significant size.

5.9.1 Screening

Quality and problem size

In the oil & gas industry, a technician spends up to 60-70% of his time in just looking for information, a trend in which other offshore industries also are subject to (Telenor, 2018). Enormous resources are thus spent on non-value creating activities.
Compared to the current solutions, that are highly time-inefficient, this proposal has a very high quality in solving the problem. Figure 54 shows the score.

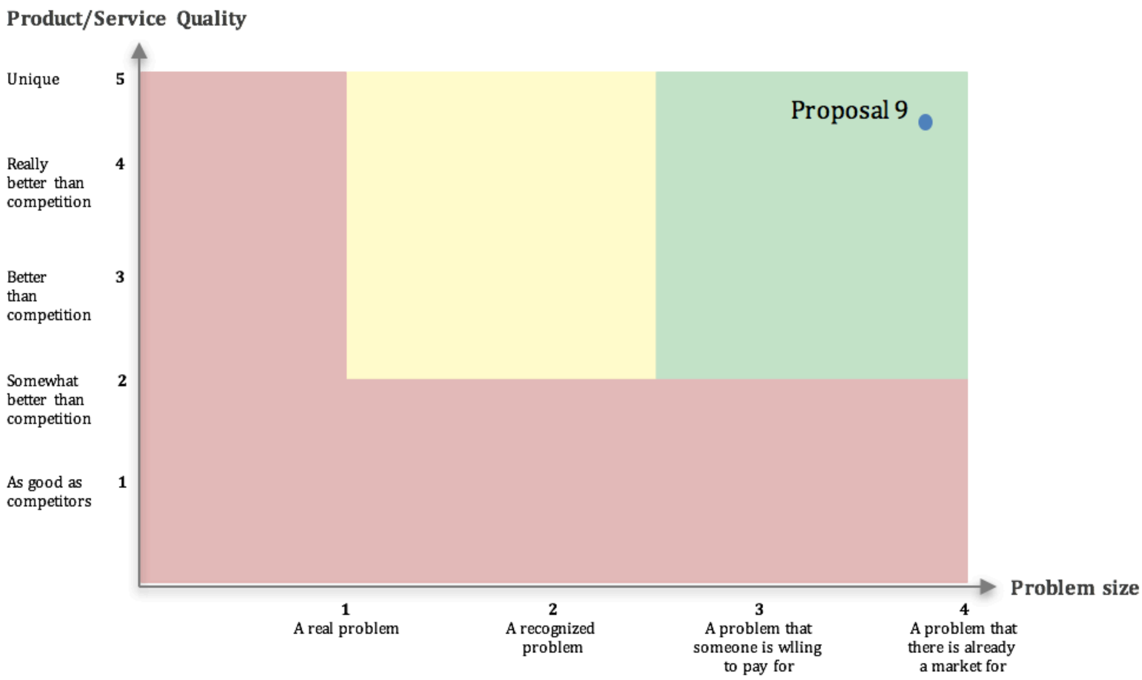

Figure 54: Problem size vs product/service quality for proposal 9.

Profitability, market size, and IPR

The market for using new technology to integrate information has grown in recent years and is likely to grow even further. Regardless of the global location, OWFs have many of the same characteristics. They are remote and they contain numerous complex systems that operators need to put into a holistic overview. A system that can make this process more seamless and less time-consuming is thus likely to have a global potential.
An ICT company could develop this solution and through a software subscription, earn stable cash flows. Taking investments, running costs and revenues into account, this solution can have a profit margin of 50-60%. See figure 55 for the final score.

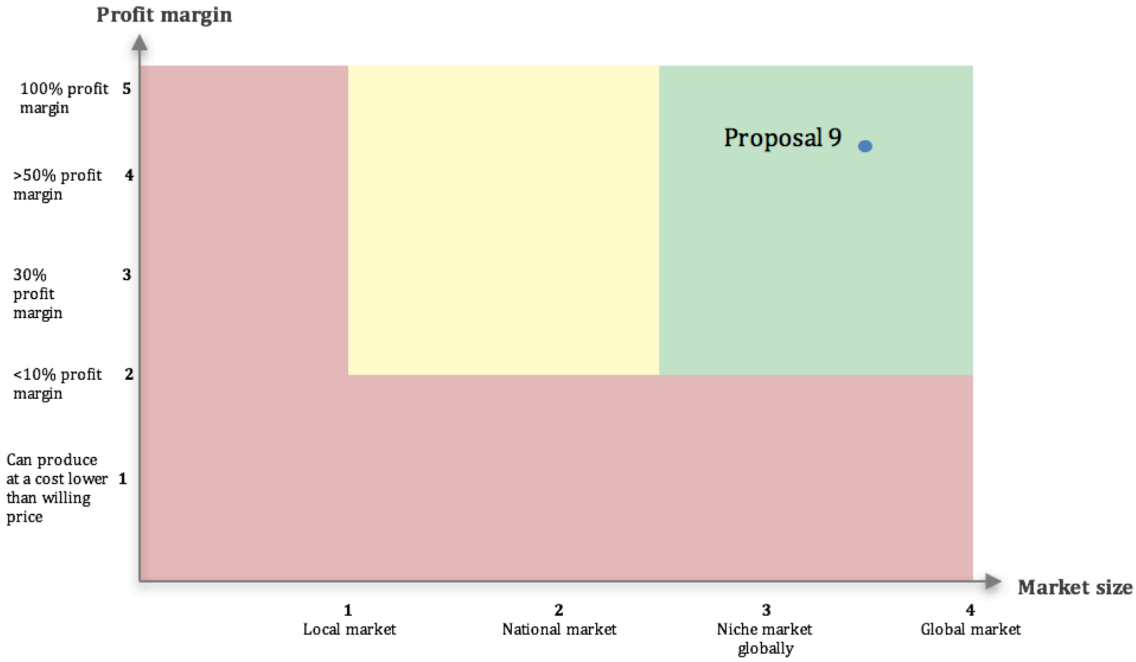

Figure 55: Market size vs profit margin for proposal 9.

5.10 Proposal 10: *Distributed ledger technology in vessel chartering*

General

As explained in chapter 4.3.2, DLT decentralizes and secures transactions between parties in an efficient way. The potential for utilizing this technology in the marine industry is enormous. As explained in chapter 3.2, vessel chartering is a segment that involves several stages with paperwork. By applying DLT, these processes can be made more seamless, and the duration can be significantly reduced.

Current method

See chapter 3.2.

Technical specifications

A smart contract can be used for making the vessel chartering processes time-efficient and seamless. The contractual agreements between the vessel owner and the OWF operator are coded in a DLT like a blockchain or a tangle network. If a need for maintenance triggered, a contract based on the predetermined terms and constraints is generated instantaneously, based on the code. There will be no need for going through every party and their databases for validation. As third parties are not involved, and the code is stored and encrypted in the DLT, a sufficient level of trust between the parties is also ensured. Like figure 56 illustrates, this will integrate several time-consuming activities into one instantaneous process. For jack-up vessels in particular, which often has day rates of in the 100k–200k GBP range (Dalgic et al., 2013), this would potentially mean huge cost savings, since the time used for contract agreement and negotiations goes from several days to almost zero.

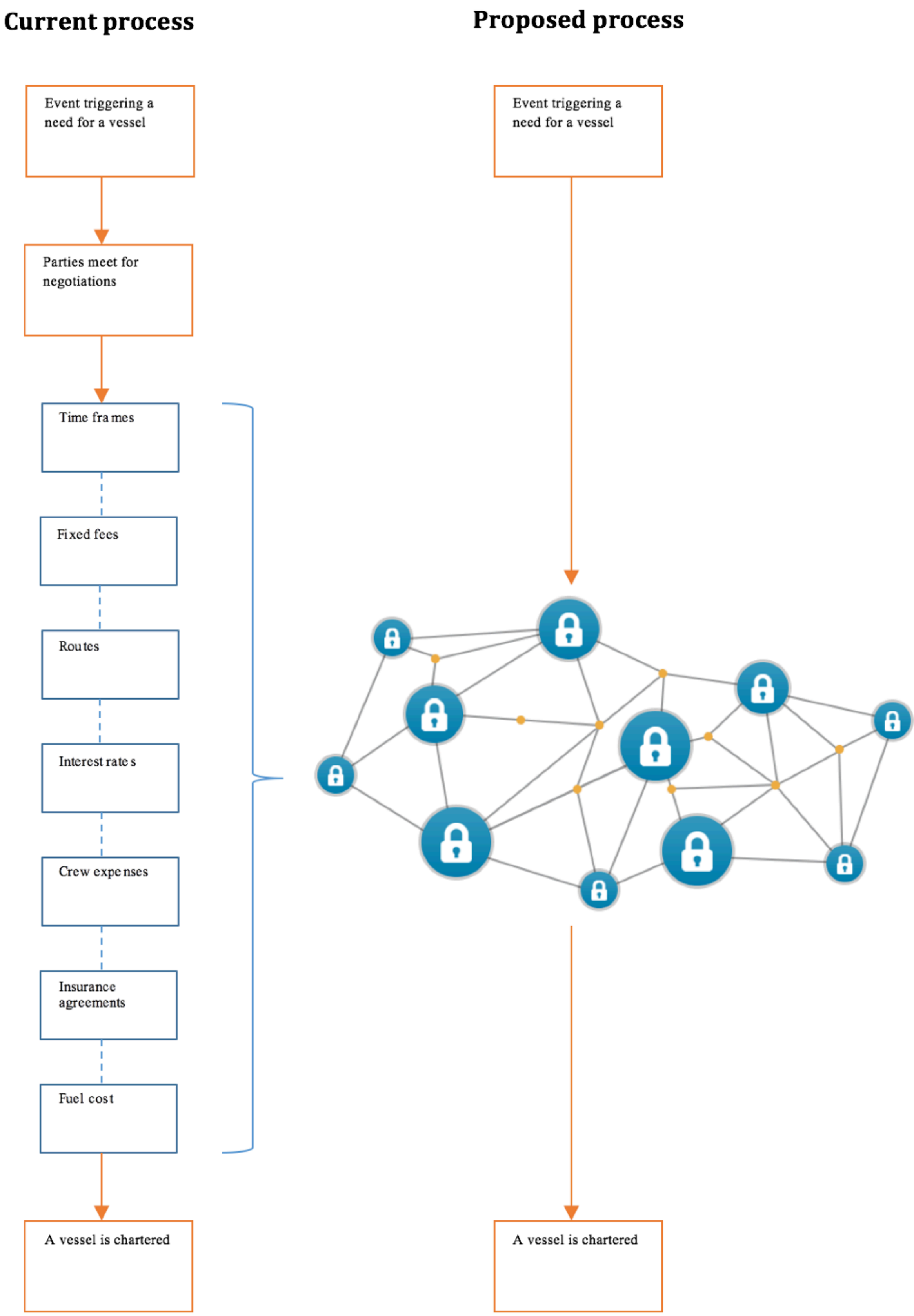

Figure 56: Proposal 10 illustrated. The proposed process integrates several stages of paperwork into the distributed ledger.

Challenges

There are some parties that actually may profit more from doing it the current "inefficient" way. For instance, a vessel owner could argue that they have higher incomes with the current way because the total length of the charter period is longer (it includes the contractual period).

There are some additional critical questions. Accuracy for instance. How do we know that the code perfectly resembles the actual contract that we want, and what if there are hidden "bugs" in the code? This may have catastrophic implications for the business. If a code needs to be changed, how should the existing users that have already agreed to the existing terms be addressed?

Finally, this is a highly disruptive technology that has the potential of eliminating traditional services and thus the jobs. For this example, the need for traditional shipbrokers will be significantly reduced or even eliminated, meaning that some may try to delay the implementation of it.

5.10.1 Screening

Quality and problem size

The area of vessel chartering is a recognized research topic within offshore industries. Many tries to develop models and frameworks in which how to deal with the highly unpredictable weather windows. The constantly changing weather is a major obstacle in planning the vessel utilization in OWFs (Kirkeby and Mikkelsen, 2016). Compared to the current methods, the proposed method is highly effective in solving the challenge of effective vessel chartering. Therefore, the proposal gets the score highlighted in figure 57.

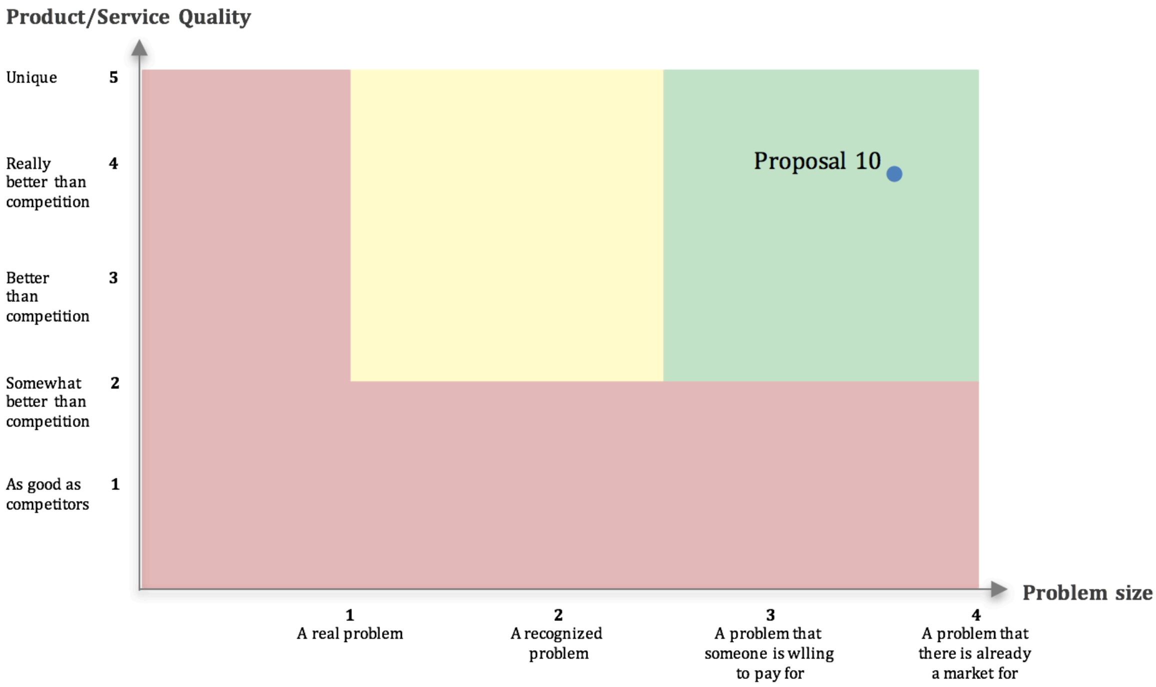

Figure 57: Problem size vs product/service quality for proposal 10.

Profitability, market size, and IPR

Vessels are key assets in all OWFs, and every operator has to have a strategy in how to charter them. The proposed method is likely to streamline this process significantly. However, it may be that the offshore wind industry is not yet ready to implement smart contracts yet, as it is a highly disruptive technology. The OWF owner or operator can implement smart contracts by utilizing the *Hyperledger composer,* an open source platform developed by the Linux foundation for building smart contracts (Hyperledger, 2018). The only significant cost will be a few software developers hired to generate the codes for the smart contracts. It will not be necessary with IPRs, since this is something that everyone is free to implement, without significant costs. After implementation, huge costs are likely to be saved, something which could increase the profit margin with approximately 50% in the segment of vessel chartering. See figure 58 for the final result.

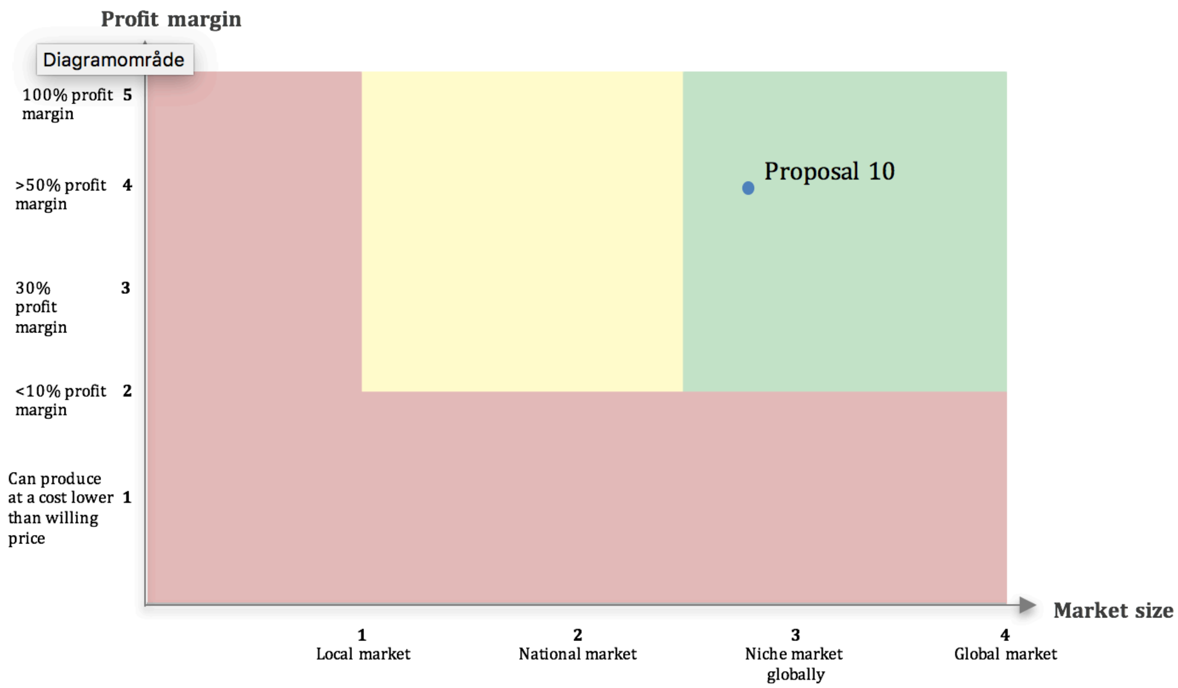

Figure 58: Market size vs profit margin for proposal 10.

5.11 Proposal 11: *Remote maintenance support with augmented reality and computer vision*

General
This proposal presents a solution where a customized AR software for maintenance support at OWTs should be utilized through the use of smart glasses. As the operator is on site, carrying out a maintenance task, a remotely localized expert can follow and aid the operation.

A publication from *MerInnovate,* a French-British research collaboration focusing on maintenance on offshore assets, conclude that intelligent glasses are among the most important innovate technologies in the future technology advances within maintenance (HAVARD et al., 2014).

Current method
If a technician localized on-site need support from experts, the traditional way this is done is that he completes the inspection, take photos which are emailed to the experts, while the technician either waits, returns to a ship, or even to shore. After some email correspondence and phone calls, or in the "worst" case, an on-site investigation from the expert, the technician has got his help and is deployed back again (Froese, 2017).

Technical specifications
The purpose is to use an open source product, like the *HoloLens* smart glasses hardware from Microsoft (see figure 60). Since it is an open source product, one can develop customized features to it (Gren, 2017). The glasses will be wirelessly connected to a network which is set up on each turbine (connected to the fiber optics in the umbilical). The glasses are equipped to the technicians on site, and through the small high-resolution camera within the glasses, a remote expert can follow the operation in real time.
The software will have a user interface which enables both the technician and the expert to draw virtual figures, and highlight equipment to explain procedures and issues to each other, or to simply point out what kind of equipment one is referring to (see figure 59). Relevant documentation, reports, standards and historical data can be retrieved by both parties and displayed on the screen. Through a microphone, the two parties can have conversations with each other.
This way, the expert can give real-time supervision and react immediately to deviations. The remotely localized expert will visualize the operation on an AR screen, displaying relevant information of the system. The glasses have built-in microphones, enabling the technician to have conversations with the remote expert. As an additional, customized feature is an external battery that can be connected through a power cable.

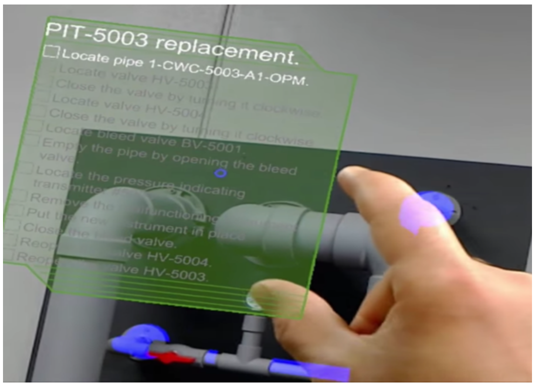

Figure 59: Highlighted equipment (BEAppliedResearch, 2016)

Figure 60: Microsoft HoloLens (Microsoft, 2018a).

Figure 61 shows a schematic overview of the solution, where the remote expert is reached through the internet which is set up at the turbine. The features of the smart glasses are shown in the boxes.

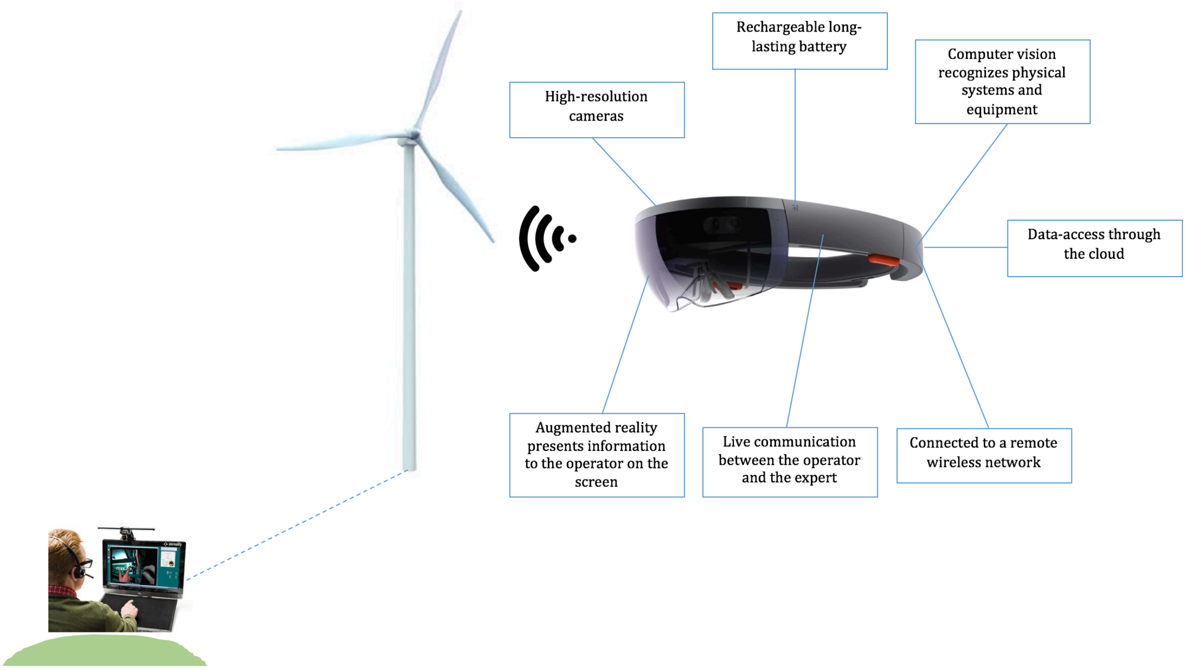

Figure 61: Proposal 11 illustrated.

Challenges
An implementation of this system may feel like a radical change for the personnel, and some implementation issues will probably arise. People may experience it as a barrier for doing the communication in the traditional and proven way. If the user interface is dissatisfactory or uncomfortable, the results may be the opposite of the intended, namely increased quality and effectiveness. If the connection is lost, the battery runs out, or the system crashes, it may lead to frustrations to the personnel. Since this technology is yet to be significantly proven, it may also be challenging to convince the investors of spending resources on it.

5.11.1 Screening

Quality and problem size
Reaching support from experts that are remotely located can be challenging. A collaborative research project between *The Rocky Mountain Institute (RMI)* and *Business Renewables Center (BRC)* used a similar solution as this as part of a customized software for inspecting onshore turbines, a project that yielded very good results (Dvorak, 2017). The use of smart glasses in the offshore wind industry is thus very promising compared to the current methods. The final score is shown in figure 62.

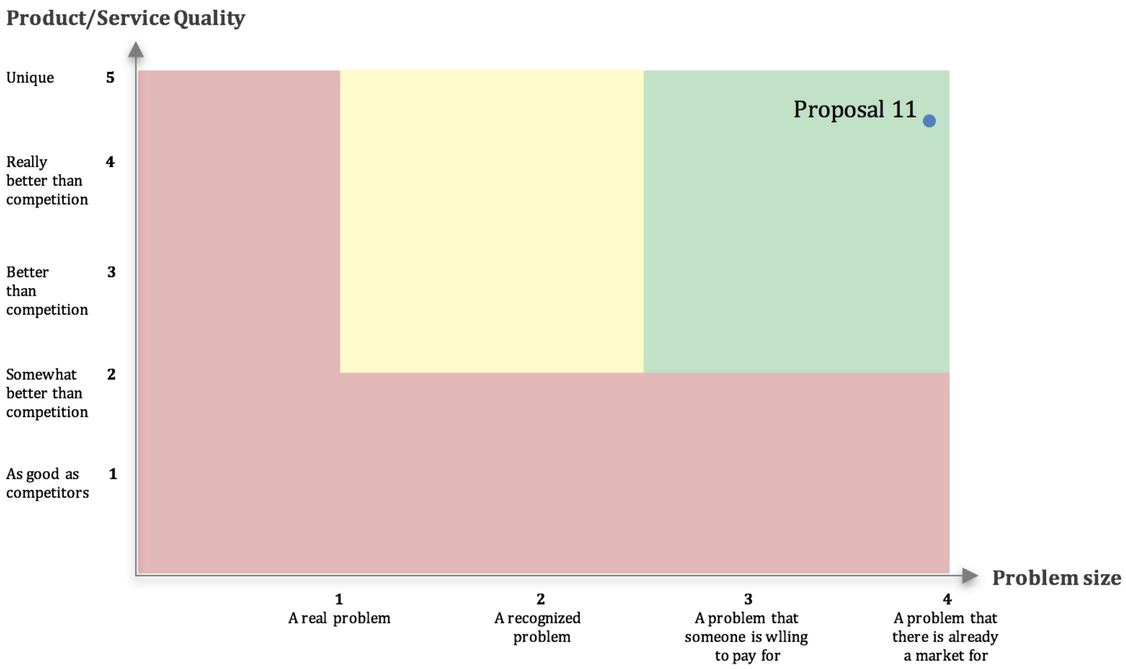

Figure 62: Problem size vs product/service quality for proposal 11.

Profitability, market size, and IPR
There is reason to believe that this proposal could have a global market potential, as it can spare OWF operators for huge costs. Since this is a solution that is fairly simple to try out, without risking high financial costs, it should be something that customers are willing to pay for.

The originality of the technology would probably not qualify for it to be patented. There are other solutions that may be too similar, for instance, the *TGW Service Package* that uses smart glasses to connect logistics engineers to an information hotline (TGW, 2018). However, a trademark on the brand name and a copyright on the software could be a suitable solution. An ICT engineering company could develop it, delivering it as a service to OWF operators. It is likely that the cash flows would be of a size that covers the initial investments quite fast, and ensures a stable profit of 50%. See the final score in figure 63.

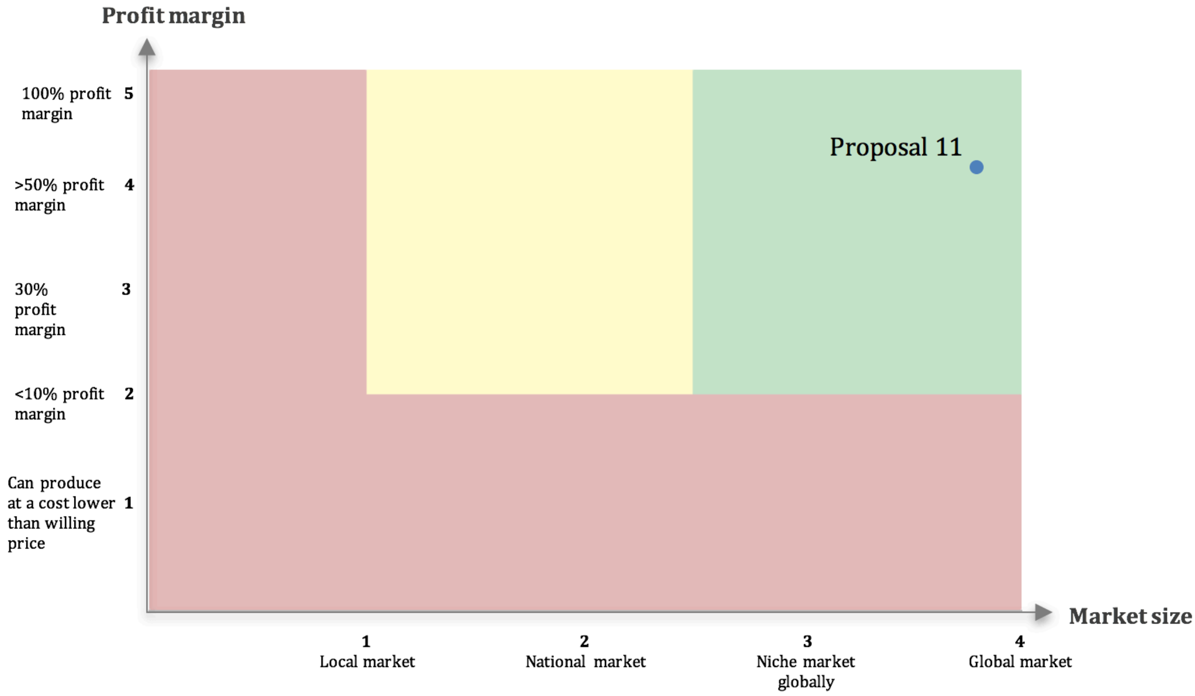

Figure 63: Market size vs profit margin for proposal 11.

5.12 Proposal 12: *Knowledge transfer and with augmented reality*

General

This proposal suggests using smart glasses for documentation of work processes to develop tutorials that are used to train new personnel.
The *German Research Center for Artificial Intelligence (DFKI)* highlights that smart glasses have a huge potential in knowledge transfer of technical operations. In the increasingly flexible job market, with reduced employment time, valuable knowledge is often missed when employees quit. With high-quality documentation on work processes, the transfer of knowledge to new employees may be significantly strengthened. Visual recordings of work processes have proved to be highly effective in the training of new personnel (Quint and Loch, 2015).

A German research paper presented in 2016 at *Mensch und Computer*, a conference that tries to address the interaction between humans and technology, equipped smart glasses to the assembly line- and maintenance personnel in two automotive companies. The purpose was to record processes and to use them for educational, and the results revealed that the smart glasses outperformed the traditional method of documenting this information (Quint and Loch, 2015).

Current method

In general, the way offshore wind technicians are prepared for offshore operations is by traditional training, where they undergo general theoretical education and practical training at a training facility before they are assigned to a live project together with other, more experienced personnel (Windpower-International, 2016). For task-specific projects, the personnel are not required undergo training in advance. The procedure is normally that technicians are familiarized with regulations and high-level information about the site before they are deployed the technician is deployed to the turbine together with personnel with experience from the actual site and problem and is taken through the procedure when located at the turbine (Organisation, 2013). Regarding HSE training, this is highlighted in chapter 5.13, and how technical support of offshore technicians is carried out, is explained in chapter 5.11.

Technical specifications

The video recordings will be done through the use of a device that can be mounted on the protective eyewear, like Olympus *INSIGHT EI – 10* (see figure 64). This is an open-source device that adds additional features to regular glasses. It has a small and lightweight camera that can record work processes and transfer to a cloud through the WLAN network (see figure). If the user wants to record something, he simply presses a button and starts to record (Olympus, 2018).

Figure 64: The Olympus INSIGHT EI - 10 device.

Computer vision technology will enable the device to recognize familiar equipment that belongs to a specific sub-system so that when developing tutorials for a specific sub-system, it can be simply highlighted, like figure 65 is illustrating. The tutorials will be developed by experienced personnel and will contain additional relevant information about the procedure. For instance, if an oil filter should be replaced, the area in which it will be fitted is highlighted, and exact values for bolt torques, dimensions of bolts, nuts and washers will be included. The recorded videos will be stored and managed by a software, that structures them into certain information-specific folders, for instance, “oil filter replacement”.

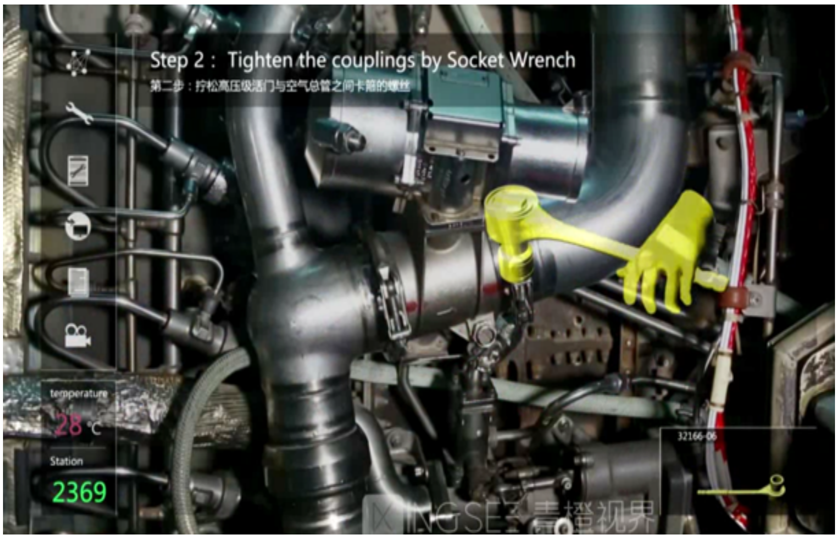

Figure 65: Computer vision recognizing familiar equipment and AR that displays the procedures (Kingsee, 2016).

Challenges
As explained, this system is dependent on a wireless communication system, like WLAN or 5G. This, together with hardware costs and development costs, could cause a quite high investment cost. An alternative approach could be to connect the glasses to a carry-on hard disk, that contains all the data, and where the recorded videos could be stored. Since the time aspect of communicating the files to the cloud is not so critical, this could be a solution, though it will increase the amount of hardware needed and thus hamper the simplicity of the user experience. In order to have such a system that actually works, it should be easy to use, and feel like a natural part of the other equipment.
The recorded files must be processed and further developed to become a tutorial. This may be a time-consuming process, but the computer vision features will ease this process, as it makes the visual expression clearer, reducing the need for additional text.

5.12.1 Screening

Quality and problem size
Technicians that are not familiar with the actual on-site equipment before they are deployed is a recognized challenge (Siemens, 2016), although many believe that the best way to learn is to be "thrown" into a project with limited experience on the actual task. They may also argue that this system hinders effective learning, as it may be quite time-consuming to watch the tutorials. It is nevertheless a known fact that various industries experience too much lost knowledge when experienced personnel leaves, and that documentation practices are unsatisfactory (Quint and Loch, 2015). These points lead to the score given in figure 66.

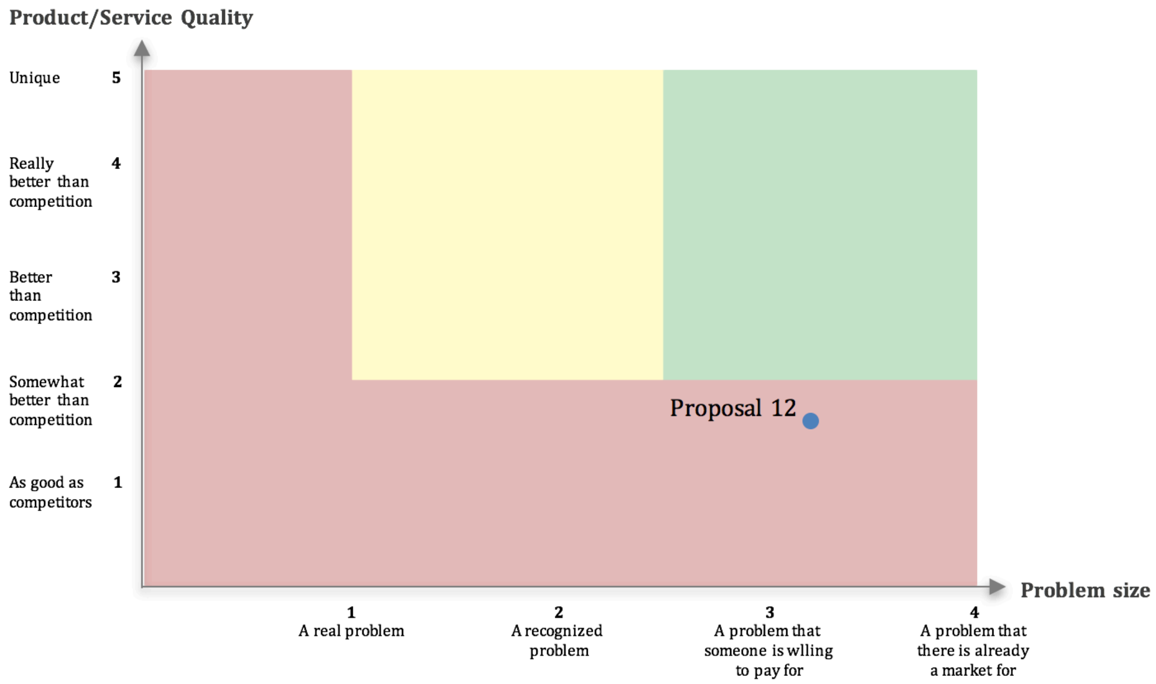

Figure 66: Problem size vs product/service quality for proposal 12.

Profitability, market size, and IPR

This proposal could have a potential for reaching out globally, as it could cut training costs quite by a significant share. Since the proposal is based on using an already existing product, a patent is out of the picture. However, creating a trademark and deliver the solution through a brand name that hopefully gets increased recognition after being launched, could be a viable solution to protecting it. Nevertheless, the number of sales remains uncertain. Taking the predicted investments, cash flows and profit into account, this proposal is likely to reach a profit margin of 20%. See the result in figure 67.

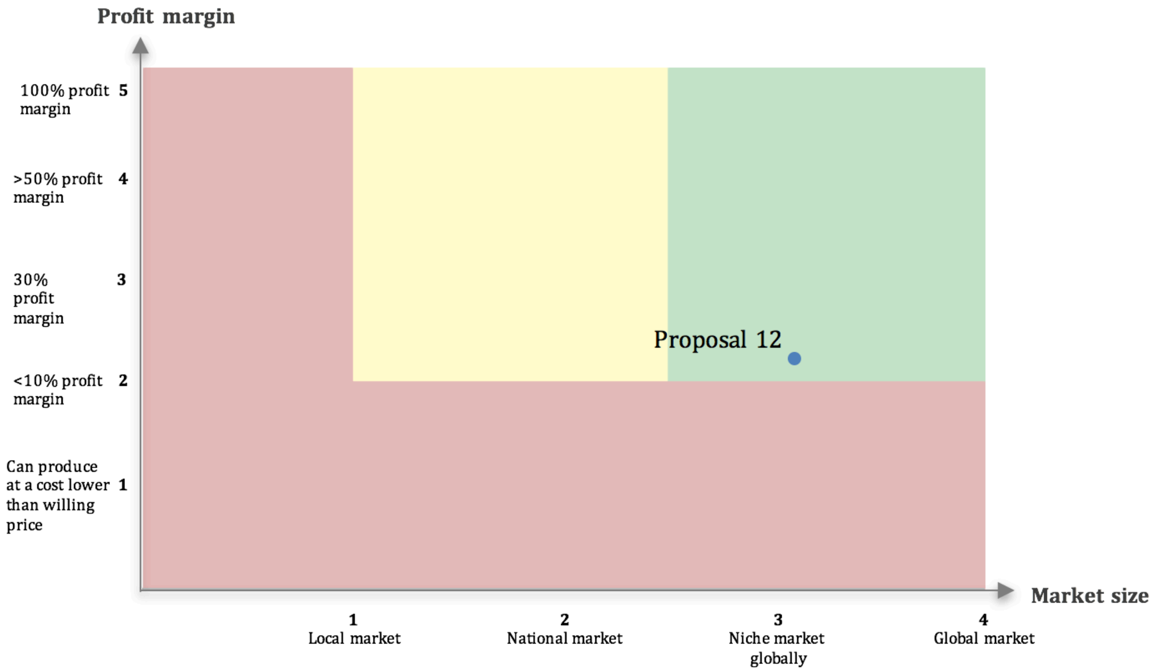

Figure 67: Market size vs profit margin for proposal 12.

5.13 Proposal 13: *Training of personnel with virtual reality*

General
To train technicians on a live project is far from ideal, as it puts both the project and the HSE concerns at risk. Having technicians that are trained in operating the actual equipment in advance, will enhance the overall quality of the operations and thus the production.

Applying VR technology into the training of personnel has through a pilot project carried out by Siemens, already proven to be a viable and effective solution for installation of OWTs (Siemens, 2016).

Current method
Procedures for operations training of personnel (not HSE) is explained in chapter 5.12. For this specific area, it is worth to note that HSE training and education, which is a crucial aspect of offshore operations, has to be done according to certain standards. These vary from country to country. One example is the *working at-height standard* from *RenewableUK* (Windpower-International, 2016).

Technical specifications
A complete 3D model displaying a true copy of the actual turbine has to be in place for this system. A VR solution containing VR glasses, as well as handheld controls will be used. The hardware is provided by an open source VR equipment provider, like *SENSICS,* which delivers customizable VR solutions (Sensics, 2018). In addition to the virtual environment, certain scenarios that the personnel need to be trained on will also be developed. For instance, the climbing procedures that is simulated has to be done according to the applicable standard. The controls will enable the personnel to virtually grasp the equipment (see figure 69). Since the person using the VR equipment is actually walking around, an area of a few m^2 has to be marked and designated to the person. Figure 68 shows how a similar system is used to enhance the production line operation at Volkswagen.

Figure 68: A similar VR solution (Volkswagen, 2017).

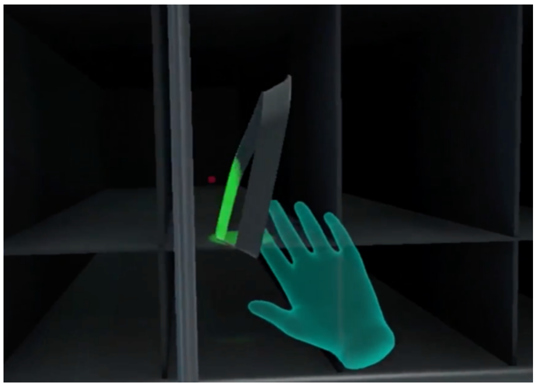

Figure 69: The user is grasping an object (Volkswagen, 2017)

Challenges
It will probably take some time before the personnel is used to the artificial environment. Even though the virtual environment looks and feels real, it will still not be the same as actually being there. The system will also require significant investment in the development of the 3D model of the turbine and in the necessary equipment.

5.13.1 Screening

Quality and problem size
Regarding the problem size, training of personnel on real projects or at least in a real environment introduces HSE risks are significantly larger than by doing it in a virtual environment, and incidents that may damage equipment or increase downtime may also occur, causing unnecessary costs. Siemens Gamesa emphasizes that VR-training for installation operations is beneficial for up-time and HSE areas (Siemens, 2016). Compared with the current methods, this proposal has a good potential for improving the current training. The result is displayed in figure 70.

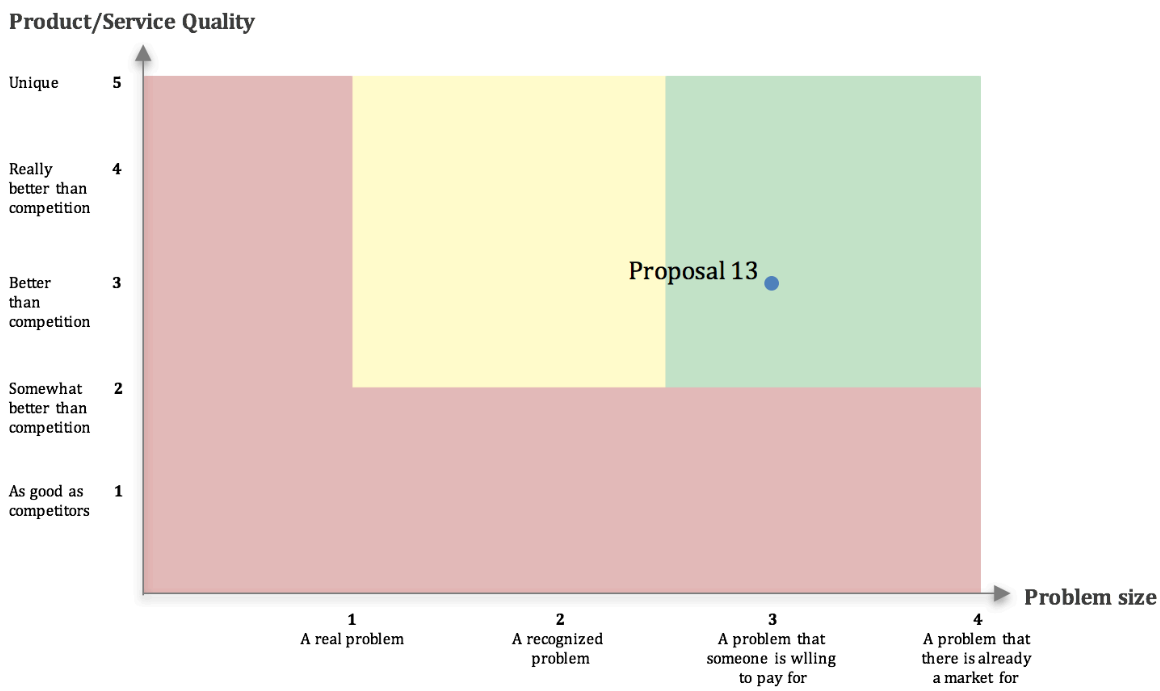

Figure 70: Problem size vs product/service quality for proposal 13.

Profitability, market size, and IPR
Every employee with offshore roles in the offshore wind industry has to go through some kind of training. Whether this training is narrowed to one specific task or a more general training depends on the role. Anyway, whoever that is in physical contact with the turbine, is required to undergo basic safety training (GWO, 2018). Hence, the market for a beneficial solution within this field is on a global scale. A profit margin of around 30% is suitable, as it reflects the investment costs, expected cash flows and profit of such a solution. Since similar solutions already exist in other industries (*EON* has a similar

solution for the oil & gas industry (EON, 2018)), it could be delivered through a trademarked name. The score is given in figure 71.

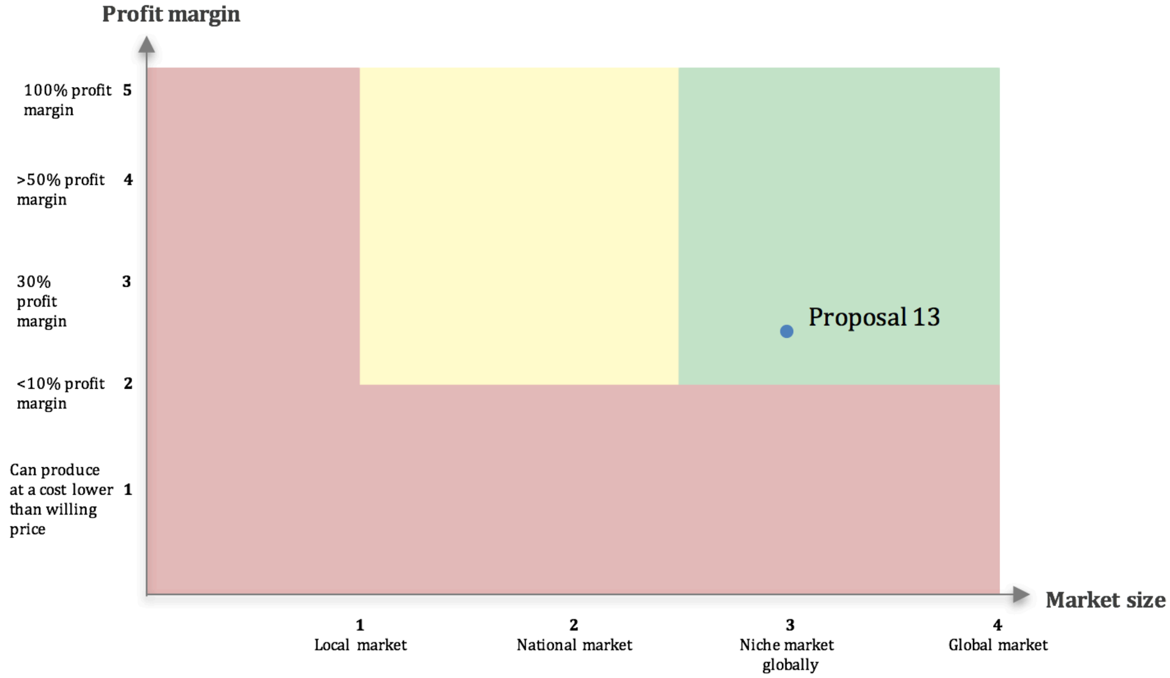

Figure 71: Market size vs profit margin for proposal 13.

5.14 Proposal 14: *Condition- and performance management software platform using Big Data technology and machine learning*

General

This is a proposal trying to undertake the Big Data challenges. It aims to provide a holistic overview of the key performance indicators (KPIs) of the portfolio of wind turbines so that operation managers can be provided with real-time updates. A basis for any Big Data related solution is to have access to large and multi-source data sets. Secondly, the data needs to be processed, stored, and integrated into a holistic overview. An objective should thus be to develop a scheme that focuses on gathering more data and to visualize it with a holistic approach. This proposal will present specific measures that must be taken in order to achieve this. However, this will require a considerable change in the mindset of the OWF stakeholders, and could, therefore, be seen as a strategy as well as a specific measure.

Current method

OWF operators usually use *SCADA* (*Supervisory Control And Data Acquisition*) for remote data monitoring and acquisition an control. This is a system which enables the operators to access the performance data from their OWF and to control the operation. The data is usually acquired at certain time intervals, typically 10-15 minutes, and the measurements consist of wind speed and direction, power output, yaw and pitch angles (Mittelmeier et al., 2016). SCADA has proven to be reliable and robust, though it has several drawbacks. The traditional SCADA solutions focus on the real-time and historical data, and give good insights into the current status. However, it has limited capabilities in providing "intelligent" information like proactive measures, future analytics, device-distributed information (Dvorak, 2016). In the increasingly complex industrial systems, some parties mean that SCADA struggles with adapting to the complex and large datasets, and hence additional compatible software that handles these issues is recommended as necessary (Lange, 2007).

Technical specifications

The purpose of this proposal is to develop a software that will be compatible with the current SCADA solutions. In order to obtain an increased and continuous data stream from the OWF, highly sophisticated sensors must be installed at a range of locations. Areas to monitor will be separated into:

- **Performance** - Power output and power curves, wind speed and direction, turbulence flow measurements, etc.
- **Condition data** - Gearbox, generator, brakes, yaw and pitch drive, bearings, low- and high-speed shafts, controllers. Structural health data from blades, tower, transition piece, foundation, tower stability.

The information will be displayed visually through a customized software architecture that shows the real-time performance and condition of every asset, in a visual way. The visual dashboards displayed on the screen can be customized, depending on the background of the user. Typically, it will contain the geographical map of the turbine fleet, showing real-time KPIs like power output (MW), availability (%), capacity ratio (%) and weather data. Historical data can be displayed next to the real-time data. Data from several OWFs, a single OWF, or even from a single OWT can be displayed if necessary. The system will be set up as in figure 72. Data is collected, and transferred to the cloud, where it is stored. Complex machine learning programs will give prognostics and analysis, as well as suggested measure to the user.

The longer the system is used, the more robust it grows, meaning that the knowledge used in the machine learning features will increase in size and hence quality. This data will also be highly valuable to the developer for further turbine-expansions and developments of new OWFs.

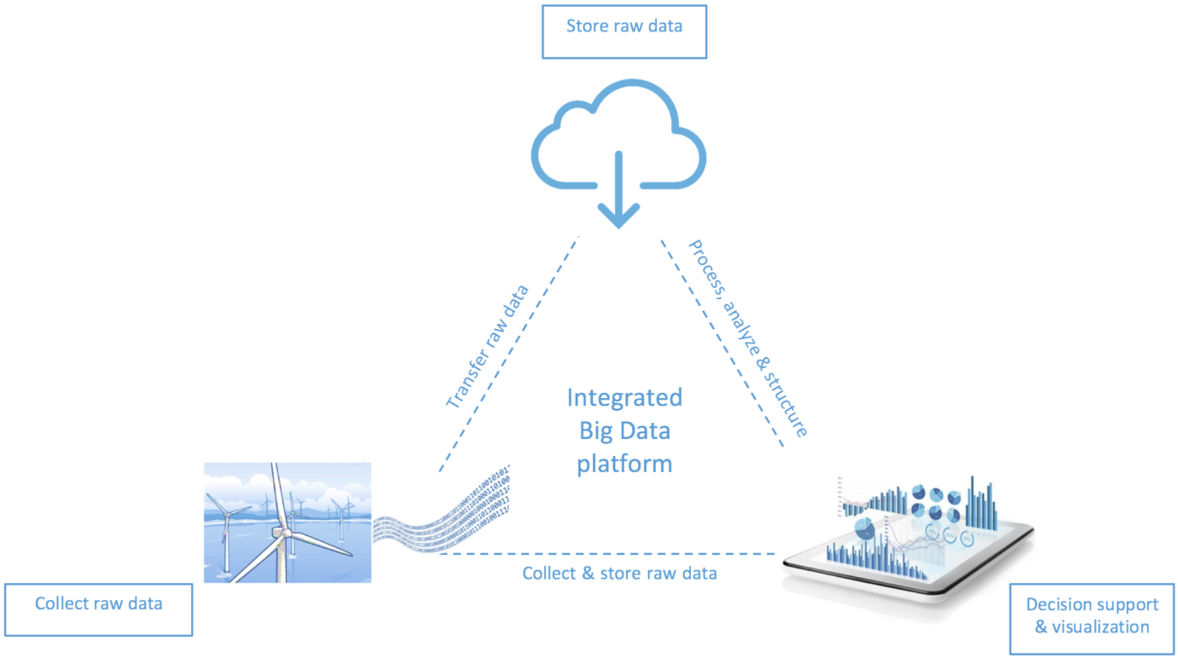

Figure 72: An illustration of the build-up of the proposal.

Due to the enormous amounts of data that will make up this solution, the data transfer architecture is an important factor. In this proposal, *edge computing* will be the communication solution. The edge computing architecture for this proposal is illustrated in figure 73. Rather than having a fiber optic cable going from every single turbine to the cloud at the onshore facility, the data is processed on a remote server before it is transferred to shore.

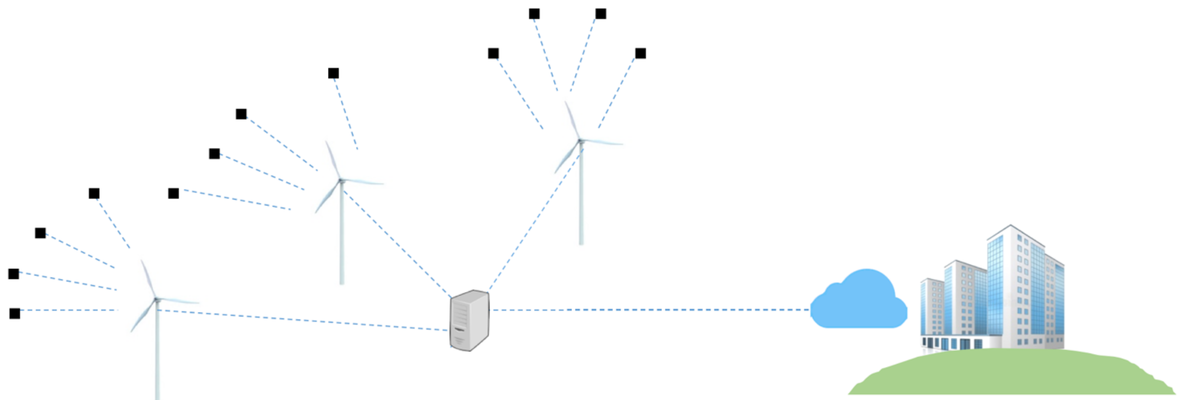

Figure 73: The edge computing logic.

Challenges
This proposal introduces a complete shift in how the management of the OWF is to be performed. To make the platform valuable and robust, and to obtain the *volume, velocity, variety and veracity* (chapter 4.4.3) it must have access to enormous datasets, meaning that the number of sensors installed must be increased considerably, as well as significant investments in communication infrastructure and processing capacity in order to handle the data. All this calls for a major shift in the data management strategy. Another issue that has to be considered is the data security. The huge amounts of data must be handled in a proper way through barriers avoiding leaks of data to happen.

5.14.1 Screening

Quality and problem size
A comprehensive platform that integrates multisource data is needed in the offshore wind industry. The current solutions are too fragmented and does not cooperate. Numerous research projects try to address the topic. Existing Big Data platforms are completely generic platforms that are not developed particularly for industry-specific purposes, like the proposed one.

A project following the *12th International Conference on Damage Assessment of Structures* tries to develop a Big Data approach to predict failures on OWT components through obtaining continuous data sets flowing from all the turbines, which is analyzed and used in a decision support framework (Helsen et al., 2017). Furthermore, there are platforms that integrate and process huge amounts of data by utilizing the open-source *Apache Hadoop* software to split files and process them in parallel. Examples are *Cloudera* and *IBM BigInsights.* A solution which has some similarities to the proposed solution, developed by The Canadian company *Enbridge,* is implemented on 11 of their OWFs. It is called *PASA* and aims to gather and analyze data for maintenance planning. The solution is recently commissioned, so it is yet to prove its worth (Enbridge, 2018). The final score is given in figure 74.

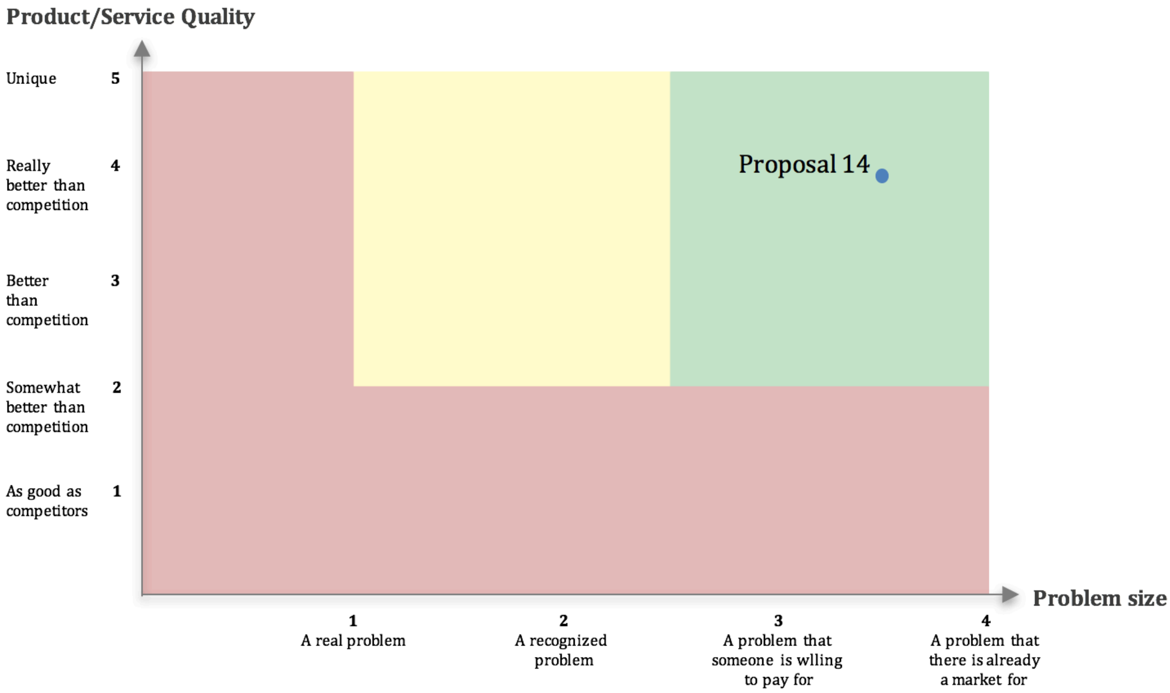

Figure 74: Problem size vs product/service quality for proposal 14.

Profitability, market size, and IPR

Since the number of sensors installed at new OWTs is likely to increase significantly, the market for this software has a potential to be global. Since this proposal is based around a software platform rather than specific components and tangible assets, applying for a patent would probably be inadvisable, as the algorithms in this software are unlikely to have the required degree of originality. Since there are systems that already covers the task of interpreting data and display it visually to the manager, protecting this idea through a copyright could be a good solution. In fact, copyright is the most common IPR used for software (ESA, 2018). Since this idea requires enormous investments, but potential cash flows are quite high, a suitable profit margin is around 40%. See figure 75 for the final score.

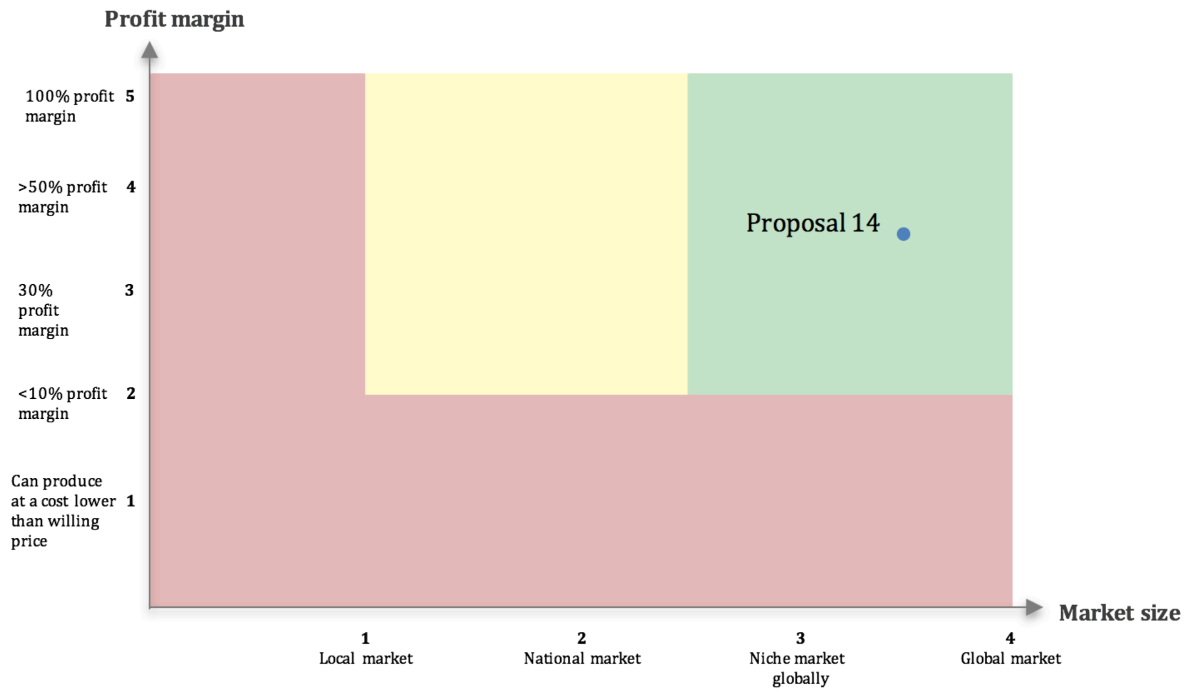

Figure 75: Market size vs profit margin for proposal 14.

5.15 Screening overview

Figure 76 provides an overview of how all of the proposals and their score with respect to problem size and quality in solving the problem compared.

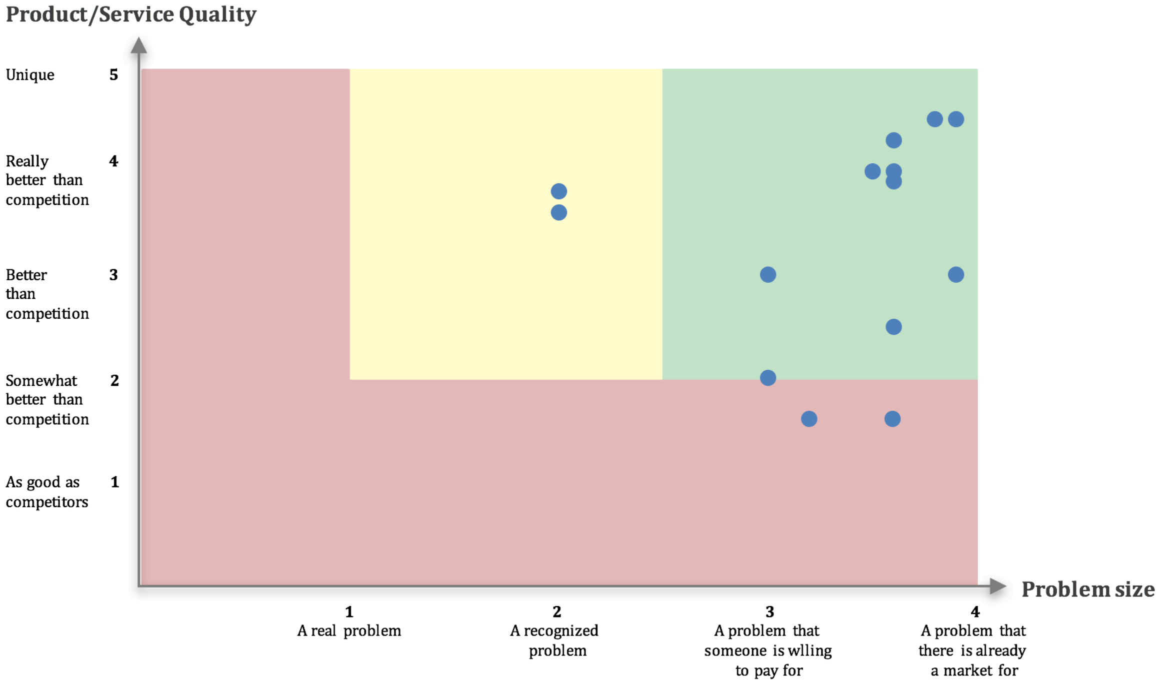

Figure 76: Overview of all proposals with respect to problem size vs product/service quality.

The proposals that are highlighted with a red circle in figure 77, are the most promising proposals with respect to problem size and their quality in solving the problem.

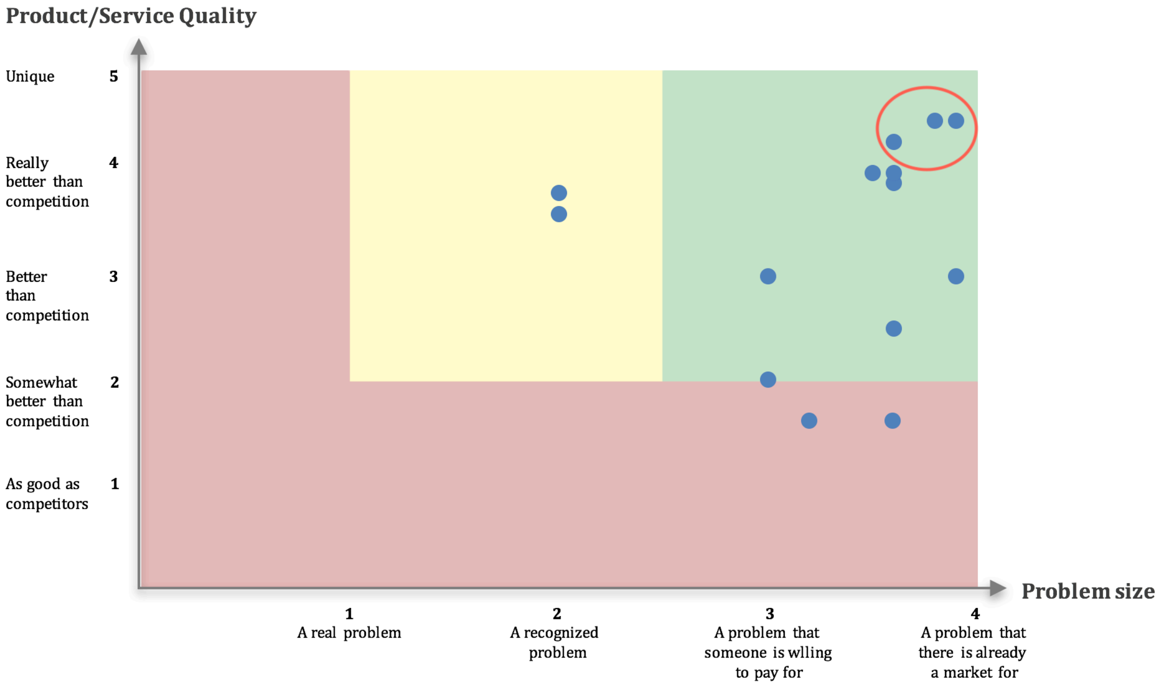

Figure 77: Most promising proposals with respect to problem size vs product/service quality.

Figure 78 provides an overview of how all of the proposals and their score with respect to market size and profit margin compared.

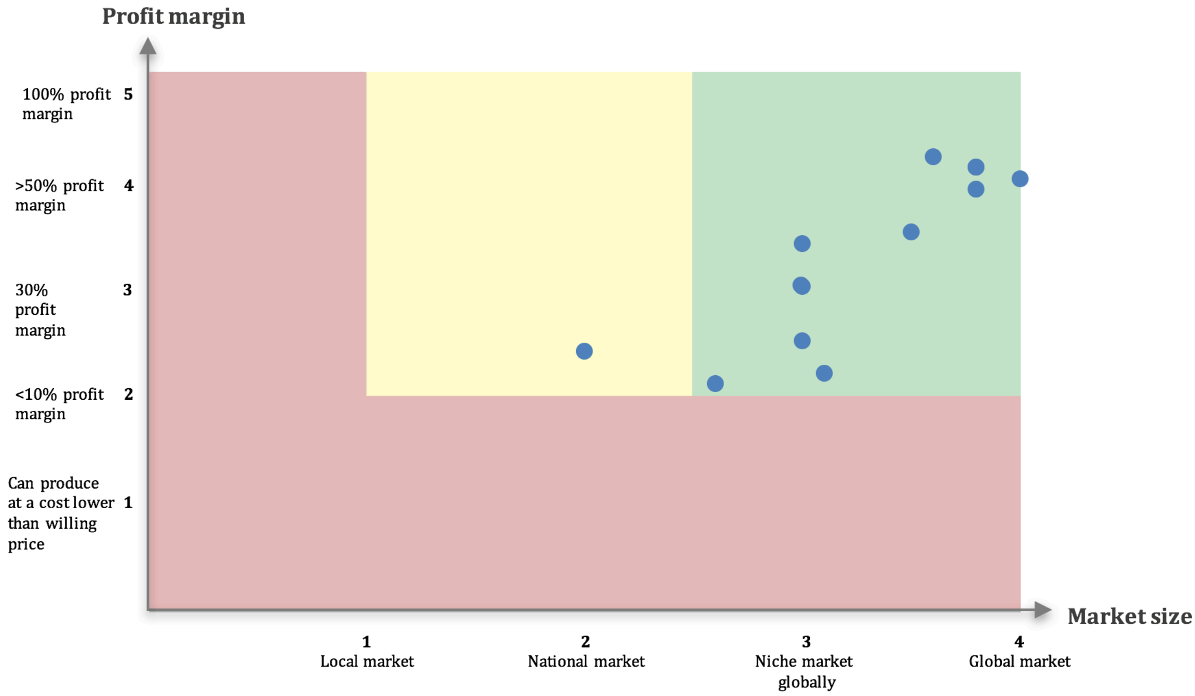

Figure 78: Overview of all proposals with respect to market size vs profit margin.

The proposals that are highlighted with a red circle in figure 79, are the most promising proposals with respect to market size and profit margin.

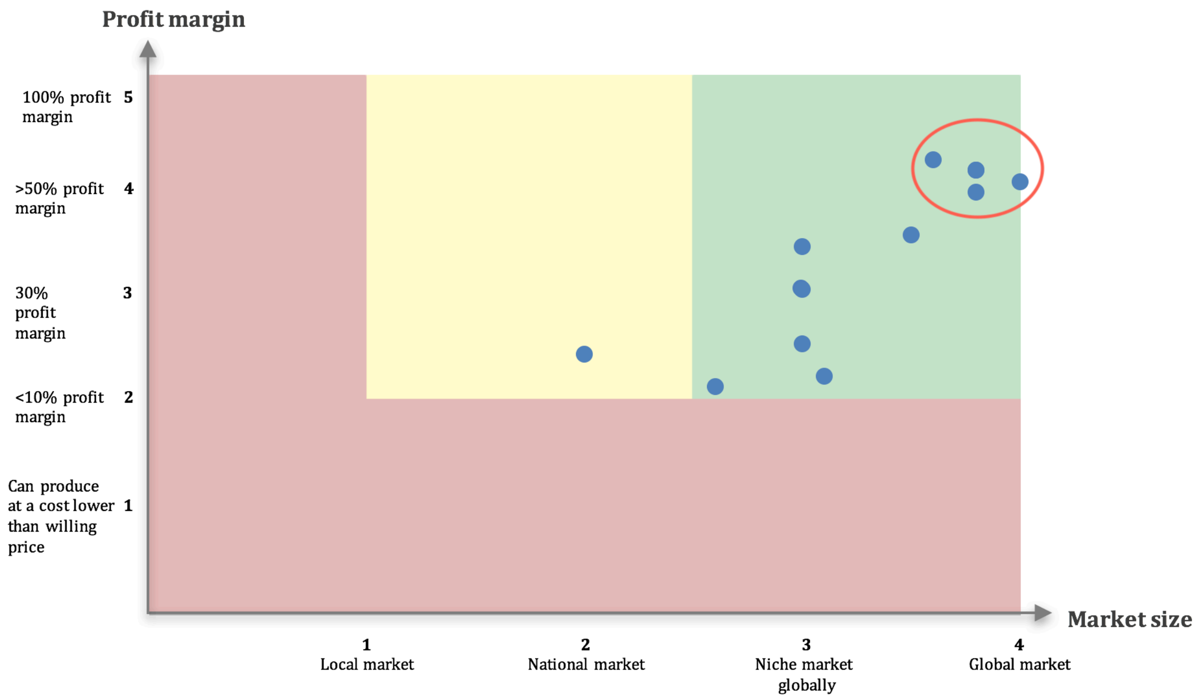

Figure 79: Most promising proposals with respect to market size vs profit margin.

The highlighted proposals from figure 77 and 79 are displayed with their associated numbers in figure 80. It is clear that proposal 2, 9 and 11 stands out in both of the screenings. Therefore, these three proposals will be further explained in chapter 6.

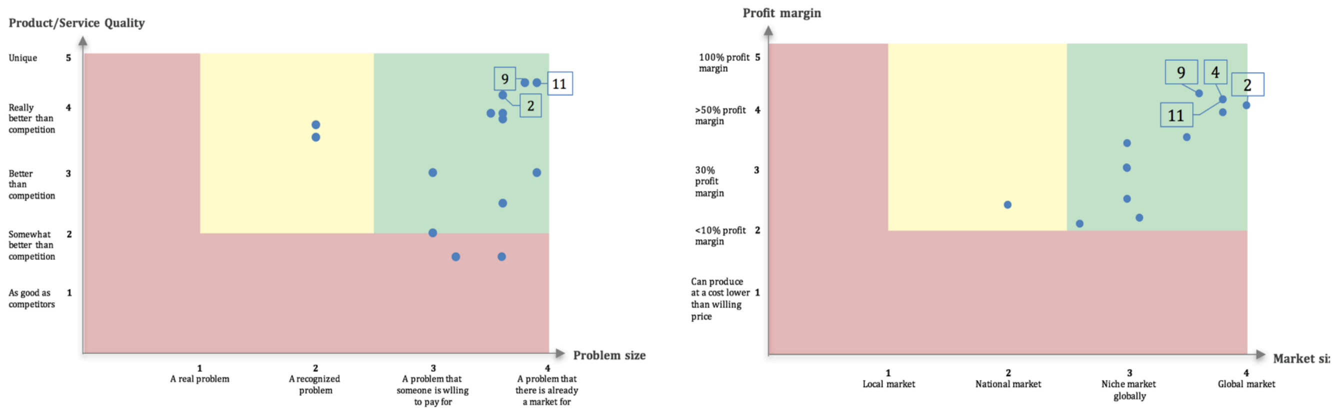

Figure 80: Overall most promising proposals

6 Business model canvas

A BMC is a tool that helps visualize a company's business model. It explains the business model through nine different areas, defined by (Ødegård, 2016);

- *Value propositions* – What do they offer?
- *Customer segments* – Who are the customers?
- *Channels* – How are the customers reached?
- *Customer relationships* – How are the customer relationships maintained?
- *Revenue streams* – From where and when do the revenues come?
- *Key activities* – What are the key activities in developing and delivering the product/service?
- *Key resources* – What resources are necessary?
- *Key partners* – Who are the key partners in developing and delivering the product/service?
- *Cost structures* – What are the main cost drivers and what are their size?

6.1 Real-time scour monitoring with fiber optic sensors

An engineering company can develop this solution, and deliver it as a complete service. Since it is highly original, they can apply for a patent. If they get it patented, they are assured that no one else is allowed to profit on the solution. In order to deliver a more complete service, the company should contract a subsea service/ROV company that can carry out the installation of the system and regular inspections and marine growth removal. Regular service of the system every second year or so, performing functional tests, and investigating structural damages, possible cracks and clean the marine growth. Manufacturing should be outsourced to a company specialized in composite materials. The OWF operator will pay for the initial investment, and a smaller fee after each of the services.

Value propositions

- *Accurate scour data acquisition* - Generates highly precise data sets.
- *Cost-effective scour monitoring* – Extremely low power consumption and is has a significantly lower cost than the existing method.
- *Real-time scour monitoring* – As it is based on fiber optic sensors, data will be received instantly.

Customer segments

- *OWF owners and operators*
- *Bridge construction companies*

Channels

- *In-house sales representatives* – Due to the technical complexity of the system, sales personnel will need to have a deep technical knowledge about the system, and will thus be done by in-house engineers, preferably with some sales knowledge. They will arrange meetings with customers in order to go through the specifications and develop a plan of how to carry out the installation and connect it to the current sensor data infrastructure.
- *Exhibitions and seminars* – Representatives from the engineering company will be present at conferences and seminars for the offshore- and construction industries.

Customer relationships
- *Long-term spare part agreement* – Spare parts can be ordered at any time
- *Warranty* – A 3-year warranty ensuring the customer about the functionality for this period.

Revenue streams
- *Sales of the scour-monitoring service* – The customer pays a one-time fee for the equipment.
- *Sales of spare parts* – Sales of spare parts will ensure a small cash flow.

Key activities
- *Design and manufacturing*
- *R&D* – Continuous research will be done to optimize the solution.
- *B2B marketing* – Relevant customers will be localized and approached

Key resources
- *Fiber optic cables with FBG sensors* – This must be ordered from an external supplier.
- *Highly specialized personnel*
- *Patent* – Will ensure that no others profit on the idea.

Key partners
- *The subsea service/ROV company* – This is the partner that will perform the installation of the system, and is thus a vital partner.
- *OWF operators* – The operator provides valuable experience and knowledge in which the engineering company uses to optimize their technology and service.
- *Raw material suppliers*
- *Manufacturer*

Cost structures
- *Cost of services from the subsea service/ROV company*
- *Cost of manufacturing*
- *Cost of fiber optic, composites, and steel foundations*

From the BMC, it is identified that the proposal can be applied to the bridge construction industry as well, as they struggle with the scour problem in bridges that crosses waters.

6.2 *Asset data- and documentation control with a digital twin software platform*

In order to develop such a system, broad experience and insight in ICT have to be combined with technical and operational knowledge from OWFs. An ICT company with data engineers and some experienced operational engineers preferably from the offshore wind industry is therefore a likely player to do so.

They will develop the software platform, and be responsible for implementation and training. In the software development phase, an extensive mapping of the offshore equipment has to be carried out, so that the computer vision feature will have enough material to be developed. The OWF owner or operator will pay a subscription fee for a predefined period. The ICT company can copyright the software so that others have to pay for the solution if they want to utilize it. After some period, revenues will rise and investment costs will start to pay off. Break-even will be reached, and the ICT company will earn a stable cash flows.

Value propositions

- *A holistic overview of assets* – Multisource data will be integrated on a common platform
- *Better decision support for remote technicians* – Since the digital twin is accessible from mobile screens, technicians can easily access system-specific information on-site.
- *Reduces time* – Time spent on looking for the right information is significantly reduced.
- *Forecasting and simulating* – A simulation engine will use historical data combined with current conditions to forecast future outputs.

Customer segments

- *OWF owners, and operators*
- *Vessel owners*
- *Manufacturing, construction and process industry*

Channels

- *In-house sales representatives* – Experience personnel will be engaged with sales
- *Hired sales consultants* – High-level non-technical sales functions will be outsourced to specialized sales personnel. These will cooperate with in-house sales representatives.
- *Exhibitions and seminars* – Marketing personnel will be present at forums in which representatives from different industries are located. Innovation and technology conferences and digitalization gatherings are also relevant arenas.
- *Websites* – Web sites for information and ordering.
- *Call-center* – A call center where customers can ask specific questions.
- *Targeted advertising* – Advertisements will be sent to locations and platforms where potential customers are located.

Customer relationships

- *Long-term subscription* - Subscription periods for 6 months, 1 and 3 years will be offered.
- *Technical support consultants* - Consultants that can be deployed offshore if necessary can be hired by the customer
- *Customer service functions* - 24/7 helpdesk and live chat will be available for the customer, free of charge.
- *Training and update-programs* - Technicians and managers will be offered training routines for the existing solution and as new features and updates are added

Revenue streams

- *Sales of the software package* – Subscriptions will ensure long-term stable cash flows.
- *Training operations* – Programs for training the technicians in using the software will be offered, giving additional incomes.

Key activities

- *B2B marketing* – Relevant customers will be localized and approached.
- *Software developing* – Data engineers will continuously optimize the existing software, and add new features.

Key resources

- *Software engineers* – Software developers will continuously work with front- and back-end processes.
- *Operational engineers* – Personnel with hands-on experience from the offshore wind industry will use their knowledge to ensure the quality of the software.

Key partners

- *OWF developers that encourage innovation* – Owners, operators and external engineers that have worked with developing of the OWF will have relevant inputs.
- *OWF owners and operators* – They will provide vital information in the optimization of the solution.

Cost structures

- *Employee salaries*
- *Marketing*

From the BMC, it is identified that a potential new customer segment is the manufacturing-, construction-, and process industry.

6.3 Remote maintenance support with augmented reality and computer vision

The ICT company that delivers this solution will use its broad technical ICT experience to develop it to become as good as possible for its purpose. They will receive continuous inputs from OWF operators about how the functionality should be designed. By offering subscription periods of 6 months, 1 or 3 years, the operator will have the possibility to try out the solution and see if it fits their needs. After the subscription period, the ICT company can offer a full handover to the operator, letting them be fully responsible for the solution. If additional support from the ICT company is needed after this, a fee can be paid. Updates of the software, spare parts, and additional equipment are also offered by the ICT company.

Value propositions

- *Real-time support for technicians* – Expert support can be reached with real-time communication.
- *Clear user-interface* – Technicians can clearly understand how to use the solution.

Customer segments

- *OWF operators*
- *Marine and construction industries, utilities, assembly line etc.*
- *Automotive producers* – can sell them as part of an extended deal where the driver can reach expert support

Channels

- *In-house sales representatives and hired sales consultants* – Sales functions can be done by experienced personnel, or be outsources to external sales personnel.
- *Exhibitions and seminars* – Marketing personnel will be present at forums in which representatives from different industries are located. Innovation and technology conferences and digitalization gatherings are also relevant arenas.
- *Websites* – A website for information and ordering.

Customer relationships

- *Warranty* – 2-year warranty period for service and repair of the smart glasses equipment.
- *Software updates* – The ICT engineering company will offer an update program every 3 years so that additional software features are added.
- *Computer vision update* – Any new equipment which is installed at the turbine that the operator wants to include in the computer vision feature, can be added if necessary. The ICT engineering company will, therefore, offer this as an additional service.

Revenue streams

- *Sales of the complete package* – The customer pays a one-time fee for the software and the smart glasses equipment.
- *Additional equipment* – Sales of additional smart glasses and spare parts.
- *Computer vision update* – Sales of the update services.

Key activities

- *Software developing* – The software will be continuously updated, with new versions being launched frequently.
- *Offshore deployments* – Offshore trips have to be done to gather visual material for the computer vision feature.
- *B2B marketing* – Relevant customers will be localized and approached

Key resources

- *Software engineers* - Software developers will continuously work with front- and back-end processes.
- *Design engineers* – Technical design engineers will be responsible for the additional tangible features of the smart glasses.
- *Smart glasses* – The smart glasses are procured from an external supplier, making them a vital resource.
- *Trademark* – The trademark will enable the ICT engineering company to grow a high market share.

Key partners

- *Smart glasses supplier*
- *OWF owners and operators* – They will provide vital information in the optimization of the solution.

Cost structures

- *Employee salaries*
- *Smart glasses equipment*

From the BMC, it is identified that the proposal has a potential in the marine-, construction-, utility-, and assembly line industry, as well as the automotive industry.

7 Discussion

This research applies a model for identification and evaluation of innovation opportunities from technology trends in the offshore wind O&M segment. The paper aims to prove that in order to keep up with the staggering pace of technological innovations, today's businesses can benefit from a model-based approach in the pursuit after technological advancements.

The model

Several institutions try to address the challenge of keeping pace with advances in technology. The *Enterprise Innovation Model* at Singularity University stresses that innovation is achieved through four steps: *Educate* – gaining knowledge about the current technological advances, *Ideate* – identify new opportunity spaces, *Incubate* – build and test a portfolio of innovations, and *Leap* – become an agile, adaptable company for the future (SingularityUniversity, 2018). Another approach is the *Eight Pillars of Innovation* by Google, which explains how their business model encourages innovation (Wojcicki, 2011). Even though these concepts are developed and adopted by highly successful enterprises, they have little to offer with regards to specific measures that should be taken when pursuing technological innovation. Generic models and step-wise procedures for how the average tech company can achieve innovation are arguably non-existing. The applied model is thus an answer to this gap.

The three resulting opportunities which are presented in the BMC has gone through a comprehensive screening and evaluation. They are also cross-checked with relevant research and similar practices to validate their viability. From this, it is fair to say that they have a big potential of succeeding in the offshore wind industry. One may thus conclude that the applied model is a well-functioning tool for its purpose.

O&M in offshore wind

It is a broad underlying agreement among enterprises in the offshore wind industry that the industry is depending on an accelerating innovation in the coming years. However, limited work is done in the development of a strategy for achieving this. It is still a fragmented industry, with many companies that deliver services mainly to other industries, with the offshore wind as some sort of additional area of interest. In order to grow strong and independent, the industry needs to develop its own practices, instead of solely relying on traditional practices which have proven functionalities in other industries. Nevertheless, this is a movement which is slowly happening as we speak. The future prospects for the industry are looking very bright.

Main challenges with the research

The technology trends that are chosen when using the applied model has to be thoroughly evaluated. Some trends may just have a higher potential than others, and a prioritization of a range of technology trends should, therefore, be done. There may be other technologies that some would have argued to be relevant for the studied industry segment. This is currently an area where one's personal opinions can have big implications for the final result.

The innovation opportunities that are identified in this report are compared with existing research on similar solutions applied in other areas and evaluated against existing procedures. This was done in order to double check the ideas using a critical judgment.

When using standardized procedures, it may be easy to have a tunnel vision that hinders critical thinking.

Future research

Even though the model is developed to be completely generic, it is still uncertain whether it would be useful for other industries as well. Therefore, it would be highly interesting to see additional studies using the same model for new industries. Also, a follow-up on the presented opportunities with prototypes and real tests would most likely give a more evidence-based answer to whether the model is working or not.

A common issue with many of the proposals is communication. Methods for improved communication in remote offshore areas would be of high value for future OWFs.

8 Conclusion

Following an increased demand for stable electrical power and a more united global effort to the decarbonize the energy sector, the offshore wind industry has emerged as one of the most promising renewable energy sources of the future. There is, however, a big need for further cost reductions to make it competitive with other renewables. Thus, new and innovative solutions, especially in the operations & maintenance segment is needed. A method for assessing how offshore wind companies (and companies in general) can develop innovative solutions from the rapidly developing technology trends it, therefore, needed to cope with the key challenges.

This research applies a state-of-the-art model in order to identify and evaluate innovation opportunities emerging from recent technology trends. The proposed opportunities are screened, before the most promising ones are presented in a BMC. Some key findings are:

- Operations & maintenance in the offshore wind industry is a highly fragmented segment, relying on many, unestablished practices.
- Generic models and frameworks containing specific and step-wise procedures for aiding companies in developing innovative solutions are hard to locate.
- Several new technologies have proven to have a good potential in offshore wind. These are Fiber optic- and MEMS sensors, floating LiDAR, robotic crawlers, drones, AUVs, digital twin technology, DLT, virtual- and AR, computer vision, and Big Data.
- Three final proposals that fulfilled the most requirements for commercial purposes were presented in a BMC. These were: (1) a method for measuring foundation scour with fiber optic sensors, (2) using smart glasses to support remote inspections, and (3) a digital twin software platform for easily storing and accessing asset-specific information.

The applied model showed good results in creating a holistic overview of the potential use cases of the technology trends. Some refinements can, however, be done, even though it proved to be highly effective in achieving its objective.

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Appendix A

A1 Effect on "Condition monitoring" of technology trends

Service		-Cloud migration, -Increased processing- and storage capacity -Quantum computing?	-Smaller sensors - Embedded sensor networks	-IoT - Increased network capability (5G?)	-Big data -Cyber security -Distributed ledger technology (blockchain)	-Digital twins -Virtual reality	- Intelligent apps -Smart devices -Displays
Value creation flow	**Changes to process flow** – Are there possible improvements from this technology trend to the process flow?				-Eliminates the duration of data transfer	-Introduces a supervisory visualization possibility to the process flow	-Merging of data treatment processes -Software that gives recommended actions
	Changes to required skills – Are there possible changes to the required skills from this technology trend?					-Engineers with IT and CM knowledge	
Service delivery	**Changes to software** – Are there possible improvements from this technology trend to the programming?	-More powerful softwares -Integration of softwares -Process data on site -Computation of more complex algorithms -Access to more input	-Increased software scope (integrate more data) -More holistic software coverage		-Higher server capacity	-Must integrate a solution for VR and digital twins -Simulation software -Common platform for different systems (CM, PM, logistics)	-Intelligent software that makes decisions based on sensor data
	Changes to service delivery method – Are there possible changes to the service delivery from this technology trend?	-Software that integrates manual processes (instead of graphs, it gives recommended actions) -Interpretation of data is done by algorithms (not humans) -Specialized processing actors can receive data from more clients -Real-time monitoring instead of monitoring intervals	-More seamless and less time consuming installing process -More holistic service delivery -OEMs can get a competitive advantage	-Less physical inspections -Supervision can be done more remotely		-Integrate simulation in the planning process	-Interpretation of data is done by the software
	Changes to costs – Are the service delivery costs changing from this technology trend?	-Reduction of manual processes may reduce costs -Increase in initial investment -Reduction in storage capacity investments	-Sensor cost reduction -Standardization = cost reduction	-Reduce need of local servers for storage	-Increased security investments	-Increased investments in software -Potential decreases in planning and supervision costs	-Increased investments in software and hardware -Potential decreases in planning and supervision costs

							-Reduces the need for personnel within analytics, diagnosis and prognosis
Market	**Increased functionality** – Can the technology trend contribute to increased functionality?	-Give recommended actions rather than data overview -Increased reliability of results as bigger data bases are generated -Can interpret more complex data -More accurate predictions -Can install more sensors for more data	-Integrate CM and PM (performance monitoring) -Can monitor more components (smaller size)		-Market opportunity for sales of data -Facilitates digital twins, autonomous decision making, machine learning	-Integrate sensor data in a complete virtual wind farm -Simulation	-Facilitates for PM -Real-time information
	New needs covered – Can this technology trend contribute to covering potential new needs?	-Real-time decision information -Decentralized processing -Possession of historical data (don't have to buy) -Facilitates a new autonomous CM system	-PM -Increased monitoring possibilities (more sensor types)	-Higher speed of data transfer -Real-time monitoring	-Increased data transfer security -Can trace data ownership	-Enhanced testing, training, forecasting, visualization -Performance planning	
	New customer groups – Can this technology trend make the service attractive for other customer groups?	-Contractors and third party vendors -Creates a new market on sales of data	-OEMs, service providers, scientific organizations, educational institutes	-OEMs, service providers, scientific organizations, educational institutes	-OEMs, service providers, scientific organizations, educational institutes	-OEMs, service providers, scientific organizations,	-Owners, service providers
Key	**Solving key challenges** - Can the technology trend help solve one of the key challenges?	-Better cost-benefit understanding Increased reliability of measured data due to better filtering of corrupt data -Better diagnosis -Can facilitate earlier predictions -Increasing the amount of historical data -Increased significance of trends and historical data	-Eliminates problems regarding mounting that affects data -Contribute to cost benefit justification -Contributes to more holistic and reliable integration with SCADA	-More accurate reliability of data (bigger data files) -False alarms -Facilitates for early predictions and better logistics planning	-More accurate reliability of data (bigger data files) -Facilitates for early predictions and better logistics planning -Trustworthy digital contracts and data transfer helps complying with documentation commitments from insurers and OEMS, as well as trans-national legislations	-Contribute to cost benefit justification -More trust in prediction capabilities	-Eliminates the need for qualified data treatment personnel -Facilitates for early predictions and better logistics planning -Automatization of maintenance processes -A common scalable platform that integrates the whole wind farm
	Increased intangibility – Can the technology trend contribute to making the product less tangible/more of a service?	-Yes, because manual processes may be eliminated -Reduced need for physical storage capacity	-Less cables and material	-Less cables	-Reduces paperwork -Increased transparency within stakeholders -	-Virtual simulations and testing rather than physical testing	-Visualization rather than physical testing
Other	**Other factors**						

A2 Effect on “Inspection” of technology trends

Segment		-Drones -UAVs -ROVs -AUVs -AGVs	-Smaller sensors -Embedded sensor networks -New camera technology	-Increased network capability (5G?)	-Digital twins -Virtual reality	-Augmented reality -Intelligent apps -Smart devices -Displays
Value creation flow	**Changes to process flow** – Are there possible improvements from this technology trend to the process flow?	-Reduces need for transport -Eases access operation -Facilitates for a shift from manual inspection to remote monitoring -From calendar-based inspection to be based on demand	-Facilitates for a shift from manual inspection to remote monitoring	-Faster data transfer	-Facilitates simulation of inspection scenarios -Facilitates remote/autonomous access	-Potential for huge decreases in planning duration -Smoothens transferring and processing of data
	Changes to required skills – Are there possible changes to the required skills from this technology trend?	-Will not necessarily need access skills -Skills in maneuvering drones				-May reduce the required inspection skills (AR) -May reduce the required data processing skills (IA)
	Changes to costs – Are the service delivery costs changing from this technology trend?	-Reduced/eliminated logistics and transport costs -Reduced need for access equipment	-Reduced/eliminated logistics and transport costs -Reduced need for access equipment	-Facilitates for enhanced responsiveness -Quicker responses	-Reduced planning costs	-Increased quality on inspection operations -Reductions in planning time
Service delivery	**Changes to software** – Are there possible improvements from this technology trend to the programming?		-Software that integrates solutions for these new data sources	-Compatible with 5G -Increased data capacity	-Digital twin and VR software	-Software with more complex algorithms and data processing capacity
	Changes to service delivery method – Are there possible changes to the service delivery from this technology trend?					
Market	**Increased functionality** – Can the technology trend contribute to increased functionality?	-Inspection demand (real-time) -Scalable -Less weather dependent	-Facilitates for 24/7 monitoring/inspection -Measuring of more complex parameters	-Real-time operational support	-Can be used for training purposes	-Facilitates for additional input (real-time information) to operations
	New needs covered – Can this technology trend contribute to covering potential new needs?	-Can inspect in bad weather conditions -Potential for inspecting more components		-Facilitates for remote real-time inspections -Facilitates for remote	-Reliable testing -Forecasting workloads	-Holistic visualization platform -Complete and systematic overview

		-Subsurface inspection		operations of ROVs		
	New customer groups – Can this technology trend make the service attractive for other customer groups?	-Oil & gas industry -Shipping industry -Border control -Coast guard -Etc.			-Training supplier	
Key	**Solving key challenges** - Can the technology trend help solve one of the key challenges?	-Increased safety -Less time consuming inspection -Less weather dependent -Eases planning of operation	-Increased safety -Less time consuming inspection -Less weather dependent -Eases planning of operation	-Less time consuming planning -Decreases in communication costs -Remote operation of ROVs	-Less time consuming planning -Increased safety	-Less time consuming planning -Increased safety
	Increased intangibility – Can the technology trend contribute to making the product less tangible/more of a service?	-Less vessels -Less human interaction	-Less vessels -Less human interaction	-Facilitates for remote operations	-Simulations rather than physical inspections	-Less paperwork
Other	**Other factors**					