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Defining the path to implement predictive maintenance on an offshore drilling business

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Affidavit

I, **GIUSEPPE BATTISTA ABBATE, MSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "DEFINING THE PATH TO IMPLEMENT PREDICTIVE MAINTENANCE ON AN OFFSHORE DRILLING BUSINESS", 60 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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1 Abstract

The text aims at presenting how to implement a predictive maintenance strategy based on machine learning techniques in an offshore drilling company.

Results are related to the execution of the innovation management strategy for an offshore drilling company where the author is employed.

After a brief introduction on technology management and different maintenance strategies, the paper focuses on the predictive maintenance topic, in particular on those related to predictive maintenance strategies made available by the Industry 4.0 and technologies such as machine learning.

An industry analysis is performed to picture the scenarios within the digital innovation environment in the Oil & Gas, with specific focus on the predictive maintenance and Industry 4.0. A competitor analysis on the digital strategy of the top drilling contractors is then presented.

Considering the peculiarities of the Oil and Gas industry, a stakeholder analysis has been carried out in order to allow the reader to understand how the implementation of predictive maintenance strategies can impact the various actors of the business.

The methodology used in the subject company to investigate the predictive maintenance technology trend is then presented.

The most relevant parameters to implement the predictive maintenance in an offshore drilling contractor, including topics such as supplier selection, technical challenges and potentialities, have been evidenced.

Finally, the most relevant parameters to build a business case to justify expenditures on such projects are introduced.

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4 List of abbreviations

CMMS	Computerized Maintenance Management System
DMS	Document Management System
ERP	Enterprise Resource Planner
HQ	Head Quarters
HSE	Health, Safety and Environment
IIoT	Industrial Internet of Things
IoT	Internet of Things
IT	Information Technology
O&G	Oil and Gas
OEM	Original Equipment Manufacturer
PoC	Proof of Concept

5 Introduction

Cost reduction and safety improvement in the drilling industry can be reached through predictive maintenance, based on the ability to forecast equipment faults to avoid unexpected nonproductive time and to maximize supply chain efficiency accordingly.

Two forces are currently shaping the Oil & Gas industry: high efficiency is required to survive, as drilling market is still under consolidation (Tippee, 2019); renewable energy is a threaten, and lowering drilling costs could make oil still more profitable than alternative energy sources. Considering these two forces acting on the market, a successful implementation of predictive maintenance may have a massive strategic impact in the industry.

Of course, predictive maintenance trends are crossing over various industries, and many businesses are making their moves to find the most suitable options to implement their strategies chosen among the available studies. The drilling market benefits from cross-business researches, but a specific drilling-related discussion on the topic is worth if we consider the following specificities of the business: automation lack, harsh conditions of operations and industry push towards innovation to mark O&G as competitive.

Over the last 30 years, most part of the industries have gradually moved from man-operated hydraulic systems to fully-automated electronic machines: facilities which 30 years ago needed 200 workers are now even more productive with a small number of workers. Conversely, the Oil and Gas (and, in particular the drilling) machines and equipment have not faced the same level of automation: as a consequence - the road to set up predictive maintenance seems even more difficult.

A second challenge is the fact that the market of predictive maintenance platforms is mainly focused in serving typical manufacturing industries such as Automotive, FMCG, Telco etc, and suppliers are not used to deal with the technical needs specifically needed in the Oil & Gas to produce a concrete business-related offer.

Predictive maintenance is just one of the many technology trends which drilling companies can implement to minimize time, human resources and costs.

Therefore the current work's objectives are the following: to briefly present a framework to effectively manage technology trends which impacts the drilling industry; to present the results of applying such framework in the predictive maintenance technology trend case.

The latter objective will be accomplished by defining the so called "dimensions of predictive maintenance" for an offshore drilling company: these fundamental parameters which characterize the topic will allow the drilling company management to define a short term strategy (which coincides with the definition of the specifications to be required to suppliers) and a long term strategy which will support the human resources management and specific know how to be generated.

The thesis work is the result of the author's experience while working as innovation manager in one offshore drilling company, where the methodology has been introduced and applied on the predictive maintenance case with positive results.

To fully elaborate on the predictive maintenance application in the upstream oil and gas industry, a literature review on the innovation and digitalization efforts of the industry will be presented. A stakeholder analysis and key element to build the business case will be furthermore presented to allow an implications evaluation of implementing new maintenance policies.

5.1 Technology management

Literature typically refers to two main clusters of technological innovation: market pull and technology push (Dolfsma, 2005). In the first case, the innovation is driven by a market need which instills an effort into businesses to satisfy the need through innovative solutions. In the latter case, the one that will be mostly considered in the following chapters, the business efforts are dedicated to understand how a new technological discovery can be used to create an innovative product or service.

Managing a new technology is becoming more and more important in a digitalized world. In the past, long time passed between two consecutive breakthrough technology able to radically change the way a certain business is conducted. Furthermore, the rate of diffusion of such technology was lower. The rise of information technology brought to a higher pace of innovation rate, with new algorithms and software able to radically change a business. At the same time, less barriers are featuring this digital world: once a "new discovery" is accomplished, it can be deployed (potentially) immediately to many different companies, operating in different industries and worldwide. It is therefore important for companies, and especially for big corporations, to develop methods and tools in order to correctly map these new disruptive technologies, but also to be able to extract value from these technologies reducing resources (time, money and personnel). Managing a technology trend can guarantee several advantages, among which (referenceforbusiness.com, 2019):

- Operational and maintenance cost reduction
- New product and market creation
- Increased flexibility in adapting to evolving market needs

As new technology can shape the way the business will be conducted in the years to come, managing a technology typically will impact the strategy of a company. For this reason, it is important to define a strategic management of technological innovation. The process is well described in (Shilling, 2017) and can be summarized as follows:

- Understanding the specific dynamics of innovation of the company's industry
- Formulating a technological innovation strategy by defining a mapping system, a project selection framework and proper collaboration strategies as well as intellectual property strategies
- Implementing a technological innovation strategy, which includes defining an organization of human resources involved in innovation, managing the innovative projects and a deployment strategy.

5.2 Predictive maintenance

Maintenance is needed in order to guarantee functionality and efficiency of every plant. At increasing levels of capital needed to run a business, maintenance becomes more and more important.

Different maintenance strategies have been developed over the years, and can be summarized as follows (Mobley, 2002):

- Run-to-failure strategy: once the plant is in place and working, the maintenance team will be fully dedicated at quickly detecting a fault in one of the equipment. If a fault is detected, equipment will need to be repaired. Of course, during repair time the production might be stopped, and the costs associated to the repair might become very high. Furthermore, it requires to have a high stock level and to have all spare parts which might be needed in order to repair all faults as fast as possible. Nonetheless, the main backside of this strategy is the unpredictability side: manufacturing management cannot anticipate any breakout and therefore the production capacity of the periods to come.
- Preventive maintenance: the basic concept of this strategy is to substitute the equipment which are going to break just before they break, based on a statistical study. Ideally, OEM of every component installed on the plant have done tests to evaluate the useful life of such components. Providing these data to the plant management, the maintenance team will take care of the substitution of components which are going to break according to the statistics provided by the OEM. The backside of this approach is that this is based on a general statistic, and it usually doesn't take care of the specific utilization of that component in the specific plant. In that case therefore, it might happen that even by preventively substituting the component according to the OEM instructions, the assembly breaks out causing non-productive time. Or, it could happen that the maintenance team substitute components which could have worked for long time more. Nonetheless, this approach let the manufacturing plant manager incredibly reduce the unpredictability of the capacity. But, maintenance costs could turn out to be higher compared to the run-to-failure strategy (without considering the loss time production impact).
- Predictive maintenance: as for the preventive maintenance, the concept is to substitute the component which is going to break just before the breakout. The difference is that this substitution is not determined by statistical methods, but by some sort of measurements. For rotating equipment for example, it is quite common to periodically perform a vibration

analysis to prevent eventual malfunctioning of some of the components. If the measurements detect a suspicious malfunctioning of the components, the maintenance team will substitute it, ideally without impacting on the production. This approach let the manufacturing management reduce even further the unpredictability related to the non-productive time and allows a maintenance costs reduction compared to preventive maintenance, since equipment are most likely to be substituted only when needed.

In this thesis a special type of predictive maintenance is going to be presented, strictly connected to the concept of Industry 4.0. The framework under which the maintenance strategy of the future will relate refers to a hyperconnected world where every machine will send and receive data from every other equipment of the plant, or even of the supply chain (including therefore suppliers and clients' data). Returning to the vibration analysis example, instead of having periodical vibration analyses, the vibration sensors will be constantly installed on the machine and an algorithm will automatically detect the potential fault and send a signal to buy the related spare part to make it available just before the rupture of the component. Furthermore, every sensor and actuator currently installed on the machine will be now available in real time to perform analyses, allowing the availability of these data (before used only to control the motion of the equipment) also for fault detection. The following thesis is related to the application of such type of predictive maintenance, where machine data (already existing in the machine controllers or coming from new dedicated sensors) are available for fault detection. Being these new technologies, the management of activities related to such topics lies under the technology management field.

It is worth mentioning that the above presented Industry 4.0 approach on predictive maintenance can be considered the first step of what is considered to be the next generation of maintenance strategy, which some (Osservatorio Tecnologie e Servizi per la Manutenzione, 2018) refer as to Maintenance 4.0. This paradigm states that the quantity of data available thanks to the application of Industry 4.0 framework will allow not only to predict faults in a more efficient way to reduce maintenance costs, but also to impact quality performance of the plant itself, as well as to allow a better integration between the operations and maintenance teams.

6 Industry Analysis

6.1 Innovation in the Oil and Gas

In the past, the Oil and Gas (O&G) industry has driven technology and innovation efforts also on behalf of other industries, setting their trends too. For instance, O&G business has been one of the first to install sensors and actuators, as well as to introduce wireless technology communication or even to apply machine learning in seismic surveys.

In more recent times, the digital revolution has been guided by other industries, such as the automotive, and as a consequence O&G moved from being the trend-setter to a follower position. Lots of data are available though, thanks to the long history of the oil industry (early 1900s) but can't be properly used due to the fact that are strongly unstructured. Prior to the latest oil crisis, O&G has guaranteed great profits at every level of the supply chain, so that all digitalization efforts have not been boosted: the main reason has to be found in the fact that digital transformation could only guarantee long-term return on investments.

The latest downturn of the oil price and the related challenges imposed by the consequences of 2008 financial crisis are now forcing O&G to change, in order to remain competitive in the energy markets.

As stated by the World Economic Forum (WEF, 2017), the digital transformation of O&G can be organized in the following four streams:

1. Digital asset lifecycle (creating the digital twin of wells and equipment will reduce costs of operations);
2. Circular collaborative ecosystem (applying the principles of the circular economy will reduce the impact of the industry on the environment);
3. Beyond the barrel (updating the business model to customer service and assistance instead of purely selling oil barrels);
4. Energizing new energies (integrating the tradition with new energy sources which will be available in the future).

Reports from (EY, 2016) and (Deloitte Center for Energy Solutions, 2017) further elaborate on the WEF streams.
As stated, the digital asset lifecycle is strictly related to the digital twin concept, which can be further divided in the following sub-streams (as partially suggested in (EY, 2016)):

1. Integration of unstructured real time data, on two dimensions: within the discipline silos inside the company and within the supply chain (oil companies, drilling contractors and suppliers);
2. Back office automation and digitalization;
3. Predictive maintenance;
4. Operational excellence;
5. 3D virtualization.

In order to achieve maturity on the above streams, (Deloitte Center for Energy Solutions, 2017) states that ten steps have to be taken into consideration in the O&G industry.

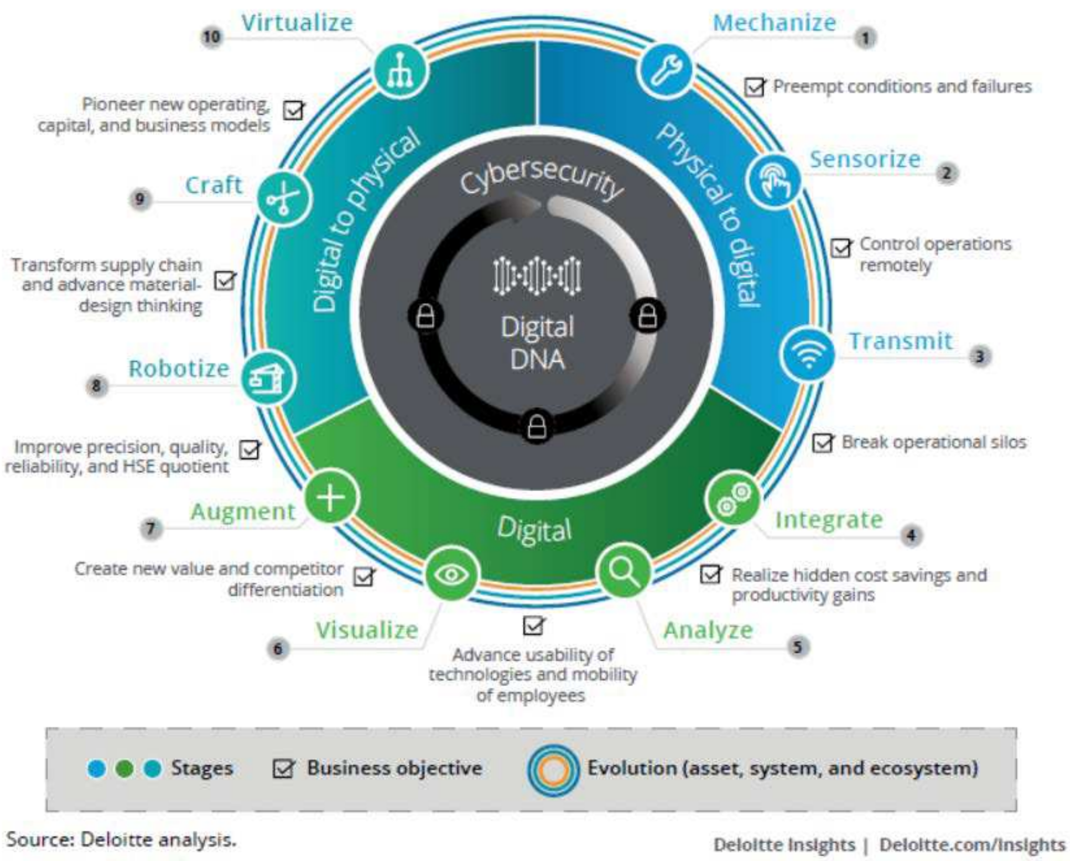

Figure 1 – Digital Operation Transformation framework designed by (Deloitte Center for Energy Solutions, 2017)

Among the ten steps, mechanization is the key as O&G equipment (especially in the upstream exploration and production) are heavily relying on not fully automated machines, still requiring human commands and without numerous sensors. This concept will be further explored in the current thesis.

Also, Deloitte states that the supply chain entities in O&G are at various maturity levels of digitization of their business:

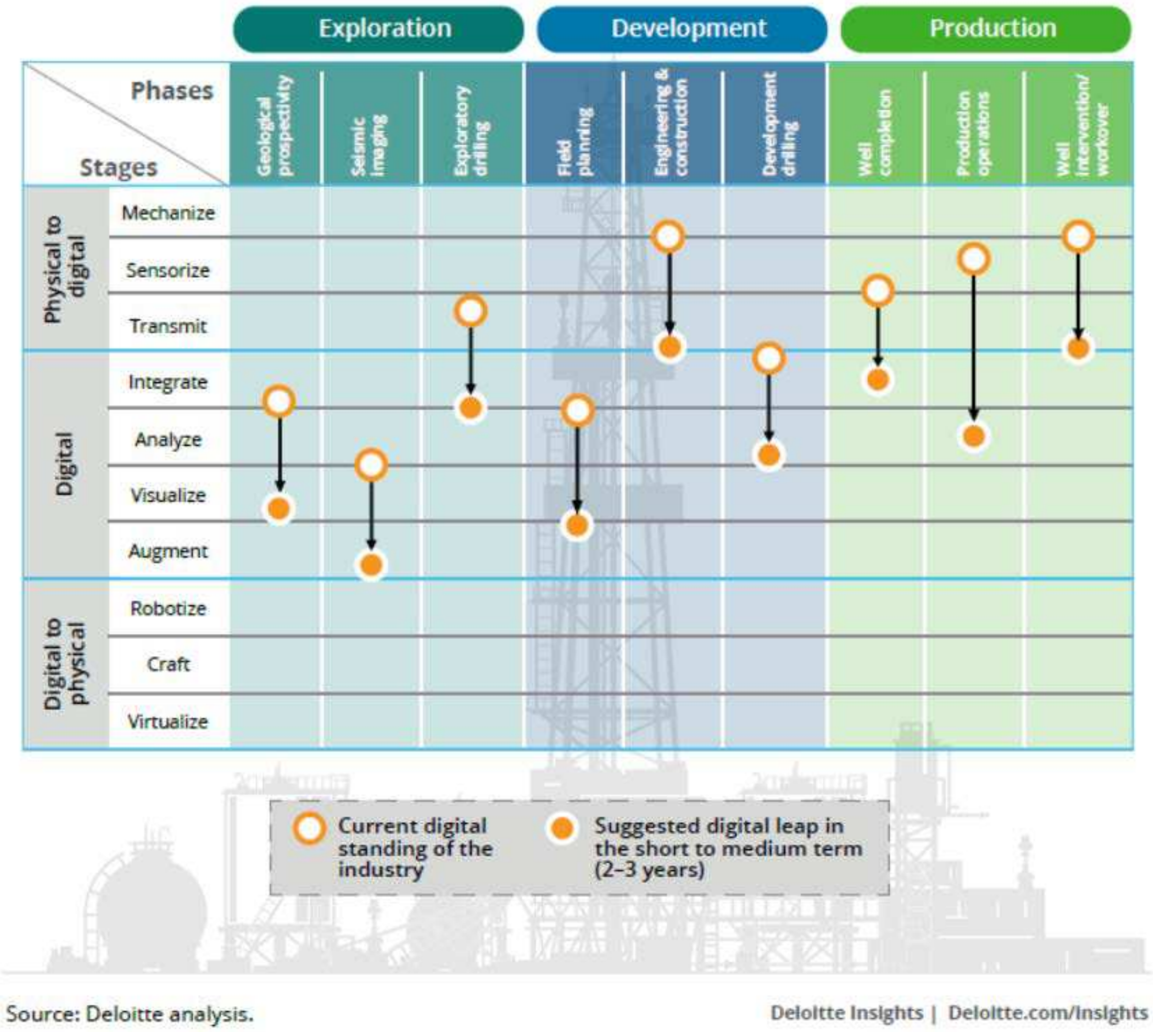

Figure 2 – maturity status of digital technologies by industry segment. In this thesis, the segment under examination is the "exploratory drilling". (Deloitte Center for Energy Solutions, 2017)

As described in the above figure, the exploratory drilling companies (subject of this thesis) are currently facing the effort of transmitting and integrating data, after a slow mechanization process which is still not fully concluded. Data are available in a non-structured way (hand- and machine-written text stored in history station[1] of each equipment) and now need to be interconnected and sent to a central database. This journey requires lots of investments, but the industry finally is able

[1] History stations are server where data related to some equipment are stored for long term. Similar to the flight recorder (or flight black box) history stations are used in case of emergency to evaluate the cause of incidents, or simply for troubleshooting and analyses.

to see advantages in the long run for the O&G digitalization, and therefore these are now considered “justified” investments (EY, 2016).

According to (Biscardini, 2018), at the end of the digital transformation journey of the upstream, the business would look like as follows:

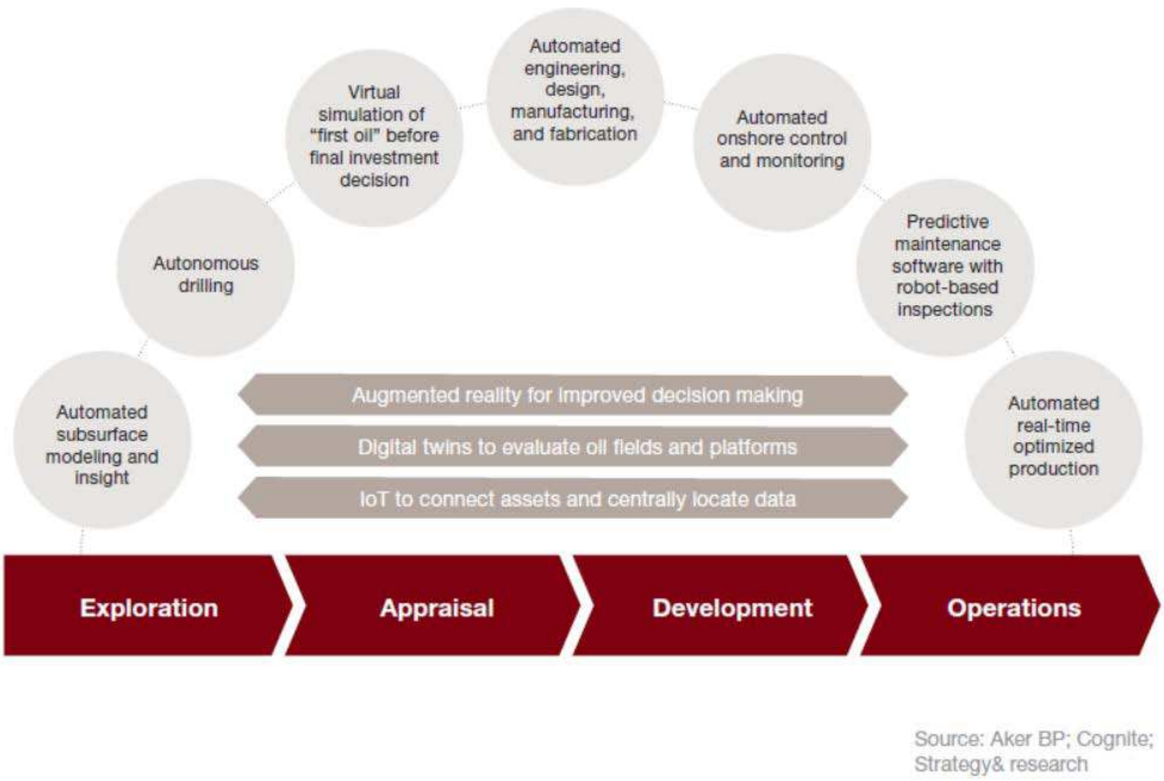

Figure 3 – representation of how a digital upstream business would look like according to (Biscardini, 2018), citing AkerBP and Cognite.

6.2 The O&G digitalization

According to (EY, 2016) and Oxford Economics, “Internet of Everything (IoE) adoption by the O&G industry has the potential to increase global GDP by up to 0.8 %” within the next five to ten years (CISCO, 2019).

According to (WEF, 2017), “digital transformation in the O&G industry could unlock $1.6 trillion of value for the industry, its customers and wider society”. This can be brought up to $2.5 trillion if truly advanced digital technologies (such as natural language processing) will be considered and current operational constraints are relaxed as well. The potential value that digitalization could create for O&G Firms is worth $1 trillion.

A (MacKenzie, 2018) report indicates that the "upstream sector could see annual cost savings of $75 billion per year from digitalization by 2023" and that offshore facilities CAPEX reduction targeted by Equinor is up to 30%.

Finally, according to (Marie-Hélène Ben Samoun, 2019), digital transformation of the oil and gas could bring up to 60% reduction in data understanding timing during exploration, up to 70% less engineering hours for field development, 30% faster well delivery and up to 40% less maintenance costs in production.

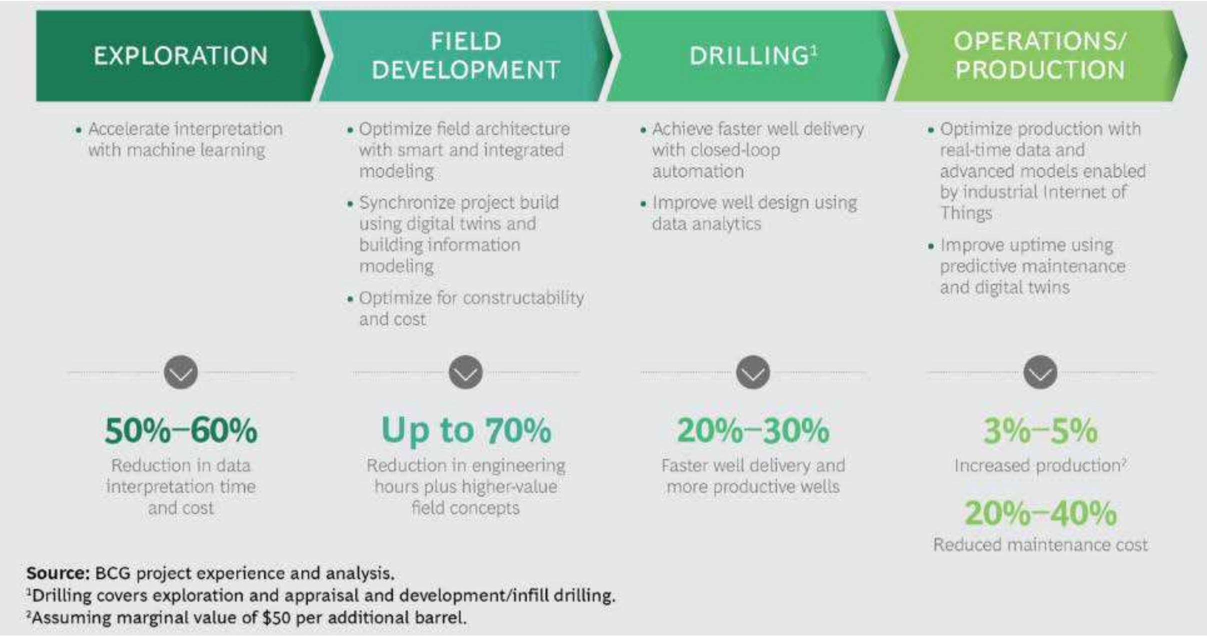

Figure 4 – value potentially unlocked by digital transformation in all O&G industry segments, (Marie-Hélène Ben Samoun, 2019) citing Boston Consulting Group analysis.

From an environmental point of view, the digitalization will strongly support the path to sustainability of O&G industry (WEF, 2017) reducing the CO_2 emissions of 1,300 million tons, reducing water consumption of 800 million gallons and contributing to fight oil spills.

6.3 Predictive maintenance for drilling contractors

Out of all the digitization initiatives for the O&G suggested by literature, in this thesis the predictive maintenance has been selected. The reason for this choice is that, compared to other streams, this is to be considered the most urgent technology which needs to be implemented by the drilling contractors, according to the following two main factors.

First of all, predictive maintenance objective is to reduce maintenance costs: in this cyclic financial downturn of the drilling industry, the importance of the cost optimization is constantly growing.

Secondly, most oil companies are striving to digitalize their businesses with great vigor: most customers are in fact starting to add to their bidding documents some requirements related to predictive maintenance tools in place in the drilling contractor. Predictive maintenance is therefore considered in the scoring phase of rigs, and needs to be properly addressed by drilling contractors.

Relying totally on OEM to produce a predictive maintenance solution for their equipment would be not efficient enough, for two reasons mainly.

The first is that OEM would typically require high costs for such a service. One of the aim of the predictive maintenance tools is that they allow non-engineering knowledge expert entities to rely on statistical models of the equipment in order to predict faults. This is of course an opportunity for drilling contractors, which are system integrators. By avoiding to rely uniquely on OEM for maintenance, they can manage to reduce maintenance costs through such systems.

The second reason is that each OEM will always predict faults on their own equipment, not considering the equipment around their system. On a longer term though, predictive maintenance objective is to discover dependencies between different systems' OEM which are currently unknown. Therefore, the drilling company has to develop some sort of predictive maintenance tools in order to be able to relate all different equipment which are installed on its rigs, and reduce downtime and maintenance costs thanks to improved knowledge on its installations.

6.4 Literature Review of predictive analytics

Considering the application of machine learning on the upstream industry, it is possible to identify six main clusters of scientific articles related to the upstream O&G drilling.

The first important pillar is related to application of machine learning to prevent unwanted events during the drilling phases. The most important topic in this sector are the prediction of stuck pipe event (Ali Chamkalani, 2013), automatic oil spill identification (Fengli Zhang, 2008) and prediction of well control events (Sean Unrau, 2017).

The second pillar is related to fault prediction of drilling equipment (drill bit and inside-the-well equipment) and support equipment (such as generators, pumps and compressors). In the first case the main objective is to avoid drilling interruption and therefore machine learning is used to detect faults and minimize effects on drilling efficiency (E. Mendel, 2009). In the latter, the objective is to predict fault of equipment and a better planning of the logistic and the supply chain (Samuel Telford,

2011) and (Estefhan Dazzi Wandekokem, 2009). This thesis work can be considered part of the latter stream.

The third pillar is related to the operational excellence: automatic detection of operations stage (Esmael, Fruhwirth, Arnaout, & Thonhauser, 2012) as well as a decision support system for data decision making (Odd Erik Gundersen, 2013) are two of the most important topic in this field of study.

Risk management interest is highly recognized in the upstream industry, mainly on the oil company point of view. Financial as well as environmental risks are being mitigated through the use of machine learning algorithms (Bigliani, 2013).

Natural Language Processing is being used in many ways to retrieve valuable information from the great amount of unstructured data available to oil companies, such as in (Quantum Reservoir Impact, 2018).

Finally, lots of oil companies and related service companies are taking advantage of augmented and virtual reality technologies relying on machine learning algorithms in order to improve safety of operations, such as in (S. Burrafato, 2019) and (Piergiorgio Gallerati, 2019).

6.5 Competitor Analysis

Restricting the analysis to the upstream drilling market is of course very important to evaluate what competitors are doing in the digital transformation field, and especially in the predictive maintenance topic.

The following analysis will be done considering the largest drilling rig owners (Offshore Energy Today, 2019).

Since it is an important part of the strategy, this section will be heavily based on the information provided by the companies themselves to the media. Information might be therefore biased or not fully representing the truth.

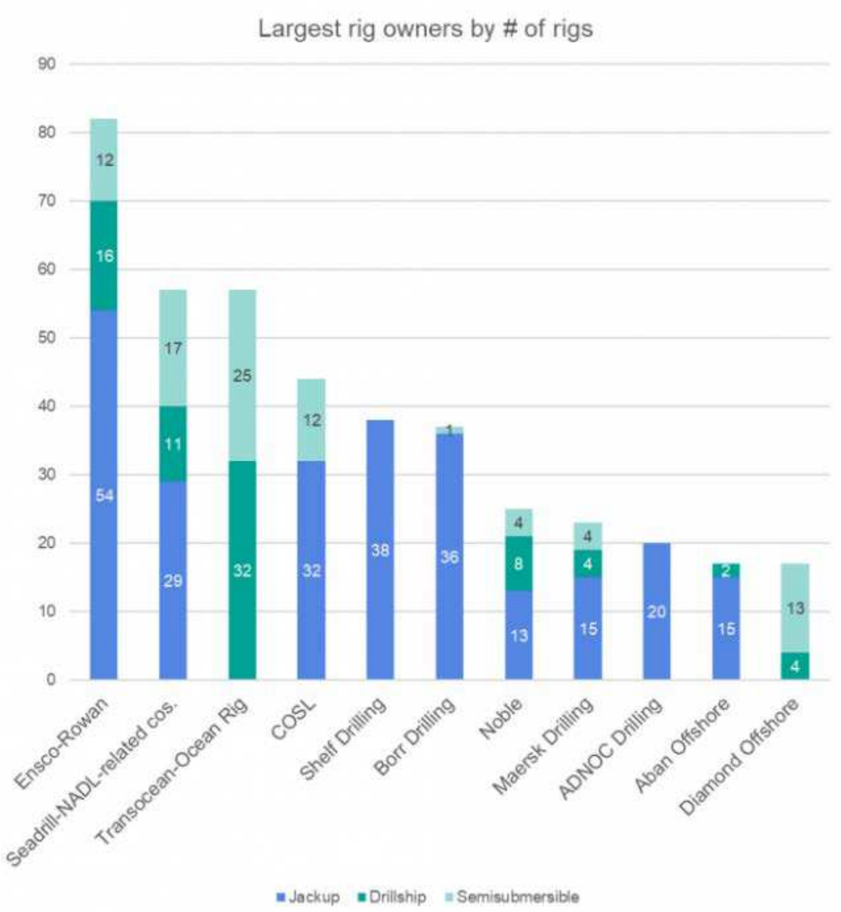

Figure 5 – largest rig owners by number of rigs, by rig type (jackup, drillship and semisubmersible), according to (Offshore Energy Today, 2019), citing Bassoe Analytics data.

The largest offshore drilling company by number of floaters, Transocean, has recognized as well the importance of the digital transformation in the drilling industry. For this reason they launched the program "Transocean 4.0". As stated by the Head of Digital Transformation (Gutierrez, 2019), its strategy is to develop a version based incremental analytics. Out of the 14.000 tags available on board, analysts found that they could start delivering value to the business with only 100 tags. In the nearest future, Transocean plans to develop more detailed models using all tags, but this has to be considered as a vision and not something which could be concretely achieved as per the current status of technology. In the meanwhile, tags are used to improve processes in two ways: first, through simple dashboards; second, through AI business intelligence. It is very clear that the strategy is to partner with other entities of the IoT supply chain: in fact, Transocean appears to have very strict relations with OsiSoft for the data management and with GE for the transition to condition based maintenance (Boman, 2019). In 2016, Transocean defined its IIoT and Big Data roadmap (DrillingContractor.com, 2019). By end of 2017 all rigs were equipped with IoT enabled equipment. (Worldoil, 2019) suggests how Transocean took steps in order to add sensors on its assets and implement the most advanced Automated Drilling Control which take advantage of the sensors.

For Seadrill, the pillars of the digital transformation (SeaDrill, 2019) are presented as follows: data driven decision making and performance management (under the operational excellence cluster), safety, and rig integrity (asset management and predictive maintenance). Regarding the IT and machine learning infrastructure, it seems that a partnership has been closed with Microsoft (SeaDrill2, 2019). Concerning the data infrastructure off-shore and on-shore, Tata Consulting Group has been selected as contractor (ArabianBusiness, 2019). Further efforts have been made in order to enable transmission of data retrieved through industrial wireless communication (EnergyVoice, 2019).

ENSCO-Rowan detailed a high level digital transformation strategy on (Mercadal, 2019). Pillars of the strategy are safety, operational excellence and asset management and, among the three, operations efficiency maximization is considered the most important. Data infrastructure is provided by OsiSoft, but ENSCO appears to manage the data analytics internally to improve those pillars. In fact, an Ensco Predictive Intelligence Center (EPIC) has been created with the specific purpose of building internal capabilities.

Noble Drilling is relying on an external partner, GE. Being provider of both maritime and drilling equipment, as well as of its analytics and IIoT platform Predix, GE managed to close the deal with Noble to start creating a digital twin of selected equipment of the rigs. Starting by an anomaly detection, Noble and GE aim to reduce maintenance costs. Through dashboards, they plan to improve efficiency of the operations (including technical improvements processing and better personnel management). The focus appears to be on the asset management efficiency improvements (OffshoreEnergyToday, 2019).

A very similar approach to Noble Drilling is followed by Maersk Drilling, which partnered with GE (GE, 2019) on the operational excellence and predictive maintenance topics. Conversely to others, Maersk Drilling is already highly interested in mixed reality application and partnered with Microsoft (MicrosoftReporter, 2019) to develop collaboration tools.

ADNOC, the Abu Dhabi National Oil Company, has a branch dedicated to onshore and offshore drilling divisions which is on its digital transformation journey on its own. Whilst the parent oil company relies on IBM for the digitalization of operations (OffshoreTechnology, 2019), its drilling branch secured a strong partnership with Baker Hughes, a GE Company (DrillingContractor.com, 2019), the latter acquiring 5% minor stakes in ADNOC Drilling. By taking advantages of the drilling services knowhow of Baker Hughes (WorldOil.com, 2019), as well as of the digital expertise of its parent company GE, ADNOC Drilling targets 30% faster drilling operations (Dartnell, 2019). According to the news, the main scope of the digital transformation is to improve operations efficiency.

Bourbon Drilling followed a similar approach, establishing a partnership with Kongsberg (instead of GE). Being Kongsberg an historical provider of dynamic positioning and vessel automation management systems, Bourbon started by replicating data available on board on the cloud. The vision is to connect drilling equipment in the same Kongsberg platform to enable analytics on the operations side. Safety and operations efficiency are main pillars of this program (MyNewDesk, 2019).

Diamond Drilling developed a blockchain technology to maximize efficiency of well construction activities (JWN Energy, 2019), with a focus on operational excellence and better logistic and warehouse management.

Other competitors are not announcing any specific digital transformation projects.

7 Stakeholder analysis

Implementing a predictive maintenance strategy implies not only a definition of a strategy for the technology. An analysis of the impacts that such maintenance policy can have on the industry has to be taken into consideration as well, in order to define a comprehensive strategy to apply such maintenance policy.

Most relevant stakeholder will be therefore briefly discussed in the following sections.

7.1 Clients – Oil Companies

The final objectives of implementing a predictive maintenance are the cost reduction and HSE improvement. Of course, these objectives are set because the market is clearly demanding them.

Starting from an HSE perspective, historically all oil companies have put lots of attention of HSE management practices of their contractors. Implementing predictive maintenance could allow to predict unexpected faults which could lead to severe consequences: in this regards, it is important to note how predictive maintenance could become a relevant competitive advantage in the bidding phase. Proposing a rig with predictive maintenance policies could improve HSE statistics and therefore improve the ranking of the rig itself.

Regarding the cost reduction effect of the predictive maintenance, the oil companies are clearly impacted, both on short term and in the long term.

When, as in current economic cycle, market demands for low rig daily rates, contractors are requested to lower their costs on an important dimension. Drilling contractors, in order to propose competitive rig rates, have to reduce operation and maintenance costs. The latter can be reduced adopting the latest technologies available such as machine learning, digital tools and more automated equipment. As briefly shown in the business case chapter, predictive maintenance is one of the technologies which allows a relatively quick cost reduction with small investment.

But predictive maintenance will most probably have several implication also in long term relationship with customer. One of the trend which might occur in the drilling industry follows the so called “servitization” stream. As drilling contractors are currently paid on a daily rate basis with some performance bonus/malus system, the industry is slowly moving to a “pay-per-drilled-meters” basis. This of course implies that all contractors are able to estimate costs related to the well constructions with higher precision to develop a correct pricing strategy: in this sense, predictive maintenance is crucial to better estimate maintenance costs.

An additional long term advantage of implementing such strategies are related to the pressure that clients are putting on subcontractors to take care of costs which were historically always managed by the client. Fuel for drilling rigs can be considered one typical example, always been provided at the oil company expenses. For this reason, the drilling contractors had the only objective of reducing the maintenance cost of the generators, without caring about the fuel consumption efficiency. But performing an optimal maintenance on generators implies also better efficiency of them and therefore less fuel consumption. As long as clients paid for it, drillers were not interested in such efficiency, causing higher costs to the clients. As this is going to change in the nearest future, it is important to note that a predictive maintenance strategy could be very useful in order to set up the best balance between maintenance costs reduction and fuel consumption. Another example is related to the logistics of equipment during operations: in the past, cost sharing policies were in place but as costs are being shifted more and more to drilling contractors, building a predictive maintenance technology allows a better logistic planning, and once again a cost reduction.

7.2 Original Equipment Manufacturer

Whilst contractors can coincide with the OEM of operational equipment in the offshore construction business, in the drilling industry rig owners integrate equipment provided by third party OEM. As a consequence, it would be unreasonable to implement a predictive maintenance strategy without partnering with the equipment suppliers. In fact, suppliers are currently based on a planned preventive maintenance model with some emergency calls which are done in case of critical faults which stops operations. On the same basis, suppliers typically guarantee emergency stocks of spare parts in order to let drilling contractors never stop operations. Of course, such level of emergency management has a high cost. By implementing innovative maintenance policies, it would be possible to reduce the emergency calls and to better plan each maintenance activity. Suppliers will need therefore less emergency response capabilities, and in turns this should lead to lower cost of maintenance services.

On a longer term period, it could be reasonable to think about a close partnership between OEM and drilling contractors, where data are gathered from the rigs, analyzed by OEM and the results are sent back to the rig for a wider evaluation of consequences on other equipment. In order to achieve this vision though, it is important to start as soon as possible by partnering with suppliers in defining the infrastructure needed: input and output of the algorithms shall be clearly defined as well as the algorithms to be used.

7.3 Third party institutions

The drilling industry relies on different third parties to guarantee safe operations: regulatory institutions (API, NORSOK), certification entities (ABS, DNV) and insurances. The balance between them determines most of the decisions of OEMs, drillers and oil companies and will be therefore treated together.

Because of potential catastrophic events, drilling contractors usually rely on insurances to reduce operative risks. In order to evaluate if valid processes and methods are in place, insurances heavily rely on certifications provided by entities such as ABS and DNV. If a drilling rig is certified to perform drilling operations, insurances are most likely to provide services to the drilling rig.

Certification entities impose some rules on how maintenance has to be organized on a rig and how operation can be considered safe. The rules usually heavily suggested to follow OEM procedures as a guarantee of correct maintenance. Drilling companies have been therefore obliged to contract the maintenance to OEM (and not to cheaper competitors), creating de facto a lock in effect for drillers.

The predictive maintenance can be considered a way to reduce these costs, since maintenance responsibility can slightly shifts to the drillers, as they now have methods to evaluate the status of equipment. But if policies of insurances and third party certifications rules do not adequate to such maintenance infrastructure, efforts to implement a predictive maintenance policy might be ineffective. Lately, some changes have been noticed in the third party certification institutions, allowing non OEM and system integrator to take responsibility of the maintenance of equipment. Nonetheless, changes in insurance industry will require more time.

8 A framework to manage technology trends

As presented in the above chapters, the O&G industry is putting a lot of effort to increase digitalization in various ways. Many technological trends have to be taken into consideration because they most probably impact the drilling companies, both directly and indirectly. Therefore, one of the objectives of the innovation management office of the drilling contractor subject of this thesis is to understand how these technology trends could impact the business.

Complexities are on multiple dimensions. Variability of the technologies is one of the most important to consider. The most currently interesting technologies are machine learning, predictive maintenance and visualization. In the nearest future, 3D printing will be increasingly important and, afterwards, quantum computing will be among the protagonists. As well known, innovation cycles are getting shorter and shorter and asset intensive companies struggles in understanding how to manage these almost-simultaneous trends, without spending too many resources (economic and human) on a failing technology trend, which might always occur.

A second dimension of complexity is related to the diversified offerings which a growing market generates. As the next chapters will further explain, if we consider the predictive maintenance market as it was four years ago, the IT giant companies (such as SAS, Microsoft, IBM) were directly addressing industrial companies as predictive maintenance services companies. After a couple of years, industrial IT companies' proposition (such as Siemens, Dassault, PTC, GE, …) was to be considered as service providers in the field of artificial intelligence for the industry. In most recent times though, new service providers totally dedicated to the O&G market emerged with digital services to cover the specific industry's needs. All of this happened in less than 4 years.

A third dimension of complexity is related to the limited resources available in a company. Every technology trend can be very diverse and therefore a specific knowledge on the subject shall be acquired. However, it would definitely not be reasonable to hire an expert for every single technology trend which could ever impact the business. The number of resources dedicated to innovation department cannot be higher than the ones dedicated to operations. A minimum set of knowledge has to be acquired by the innovation department until the technology trend is mature enough to justify the hiring of an expert.

A fourth complexity dimension is related to the fact that technology trend might be just a hype and therefore might be not relevant anymore after a while. A mechanism to better evaluate the maturity and the potentiality of a technology shall be in place.

In order to manage emerging technology trends, it is important to define an innovation strategy able to overcome the above complexities. The suggested framework relies on the following steps:

1. All relevant macro technology trends for the drilling industry are to be systematically tracked (e.g. predictive maintenance, operation automation, 3D printing, …);
2. All relevant macro technology trends for the drilling industry are to be evaluated on a 2x2 matrix based on maturity level for the O&G industry (e.g. considering the 3D printing, it is a mature technology for manufacturing but it is just not ready for the offshore environment) and the impact it could have on the business (reliable 3D printing could dramatically decrease operation costs);

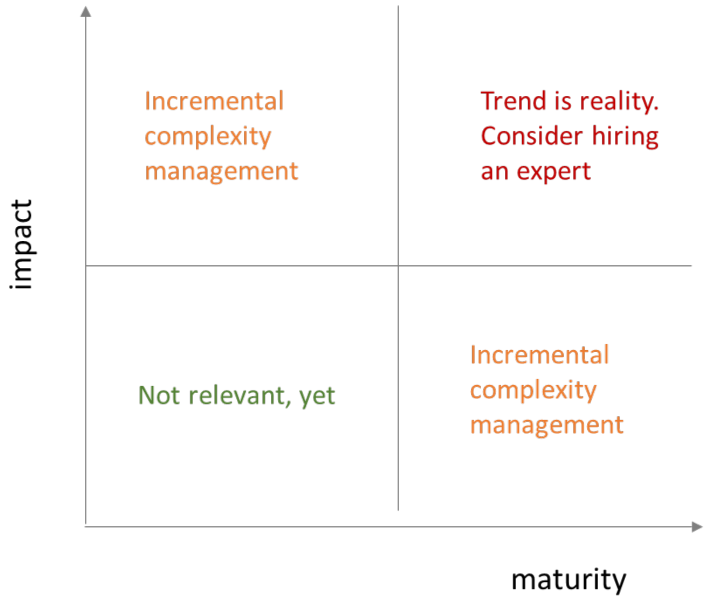

Figure 6 – framework used by the company under examination to define the correct technology management strategy according to maturity and impact.

3. As evident it is not necessary to manage technology trends in the green box, but once a technology trend becomes relevant in terms of maturity or impact on the business, it is the case to start managing the technology trend. The objective is therefore to build internal capabilities and discover in deep the potential of the technology. To minimize required resources, the incremental complexity approach (described in the next lines) is suggested;
4. In order to ensure a quick return on investment, it is finally important to build a backlog of many relevant use cases which could be solved by using the new technology trend.

The incremental complexity process relies on some of the Agile principles, but it's specific for the technology trend management in the drilling industry. The concept is to perform several projects related to the technology trend, instead of starting with a massive (and expensive) project. Starting from very quick and cheap projects, it will be possible to explore potentialities and criticalities of every technology trend and reiterate increasing the complexity and resources at every cycle.

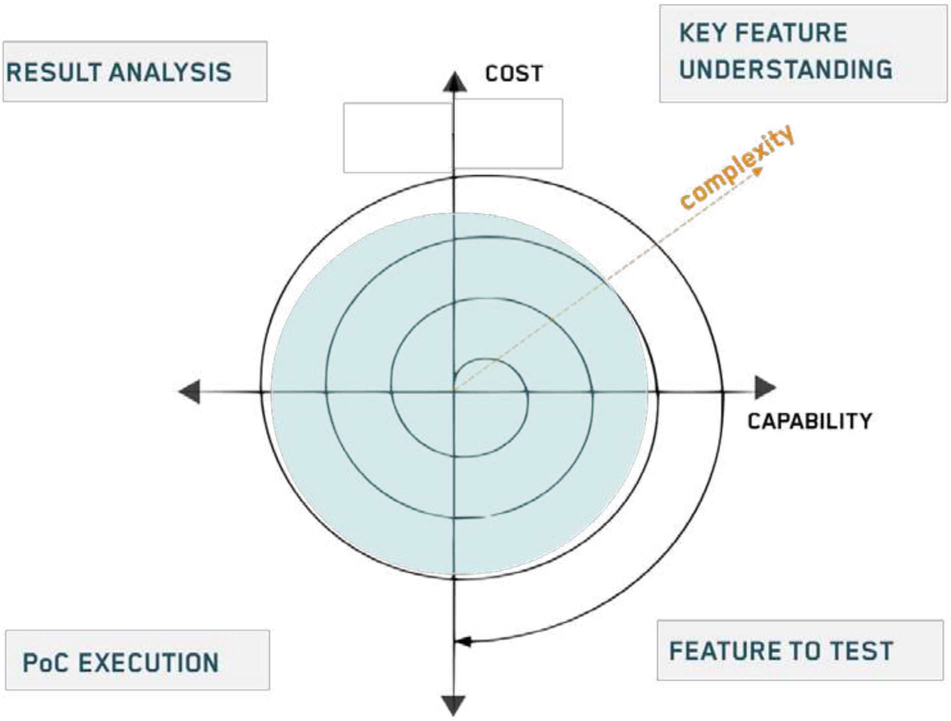

Figure 7 – graphical representation of the methodology (increasing complexity approach) used by the examined company in order to efficiently manage technology trends.

The O&G industry heavily relied on the classical linear project management tools, very typical of the constructions projects; therefore, applying Agile methodologies in this field of innovation management can be considered original. If we consider the complexity dimensions highlighted above, the classical linear project management tools would require many more resources at disposal, as well as accepting that these resources might become worthless if the technology trend appears not to be relevant in the long run. As the Agile methodology is born in the software development environment, where several code-test cycles occur, a similar methodology can be considered valuable in the technology trend management, where the innovation department needs to get a "minimum understanding" of the technology in order to set up a proof of concept (POC) as quickly as possible. The first POC should be minimal in terms of time and resources (max two-three weeks and three human resources involved), in order to gain confidence in the technology, understand the complexities and the potential of the trend. Once the POC proves positive results, it will be possible to reiterate the cycle; at this point, two moments will be crucial: testing the difficulties experienced during the previous cycle; embarking more employees from the business lines to get them to know the technology trend and be part of the innovation effort. It is of particular importance that for innovation related to asset and operations, the related personnel will be embarked as soon as possible in the project. This is a specific requirement for the drilling and in general for the offshore industry. As vessels are geographically far away from the head quarter, typically there might be a clear separation between the offshore teams and the headquarter employees. Of course, innovation management will most probably sit on the headquarters and to avoid a rejection phase of the technology once deployed on the vessels, it is important to collaborate with crew as soon as possible. Due to physical distance this will most probably slow down the innovation effort but will definitely support the technology adoption.

Every cycle is composed of four phases:

1. Understanding the key features: in the first cycle, it means a brainstorming process managed together by the business knowledge owner, the technology trend knowledge-owner and one or more innovation champions of the impacted offices. The scope is to understand which are the basic features marking the technology itself;
2. Deciding which is the feature to be tested: once the key features are clear, it is necessary to understand which one among them is crucial to test. This phase coincide with the proof of concept design and the definition of expected results:
3. Executing the Proof of Concept;
4. Analyzing the results, which implies a comparison with the expected results, a formalization of the complexities faced while performing the POC and eventually an acknowledgement of the new features of the technology which were not clear when starting the cycle. These results will be the input of the new iteration, embarking more and more people from the business.

The adoption of the incremental complexity approach allows to evaluate various technology trend simultaneously and to downsize economic and human resources volumes, while creating internal knowledge. Furthermore, adding more people from the business (who will actually be the ones to use the technology) at every cycle will allow a good balance between two factors: ensuring that business employees will not lose too much time on ineffective technology trends; allowing employees to be part of the technology exploration, which in turn will help in the adoption once the technology will be fully implemented in the business.

Conducting this innovation management practice should guarantee that all relevant technology trends are taken into consideration, and should help to define the short and long term strategy for every single technology trend.

Another result of this approach is that a specific set of desired features of the technology trend will be clearly formalized at the end of the exploration, and could be written in a technical specification. This is very important when managing emerging technologies: the normal process of buying an equipment (e.g. a valve) requires an engineering office setting the value of every parameter, well described in the internal best practices and regulations (e.g. temperature, material, pressure rating …). When it comes to emerging technologies, these parameters are not known yet: the incremental complexity approach allows to find out the parameters to build a technical specification in a reasonable time. With the technical specification, the drilling company can go to the market, avoid to entirely trust external suppliers and minimize expenditure.

Furthermore, we need to consider that - at the beginning of a technology trend exploration - it is impossible to create a solid business case to justify the investment. With such approach, it is possible to incrementally build the cost structure and the potential economic benefit that the technology could bring to the company.

Finally, an important result is that the approach allows to formalize the know-how related to a new technology linking the expertise to the specific use: the know-how will be therefore strictly connected to the business, and will not be a general report on a new technology.

8.1 Application to the predictive maintenance technology trend

In the following dissertation we'll consider the application of the framework into a case study of an offshore drilling company.

As said, predictive maintenance was at the time of starting the project already a mature topic. Therefore, the company decided to better investigate this trend through the increasing complexity methodology.

8.1.1 Phase 1 – Key feature understanding

As the scope was to define the key feature of such technology, it was very important especially in the first iteration to define the objective of the predictive maintenance, i.e. the guardrails.

A brainstorming has been therefore conducted with an asset maintenance manager (the business knowledge expert), one junior knowledge owner of the predictive maintenance technology and one employee with experience in finance (the outlier). The task was to find the main goals that predictive maintenance could bring specifically to the offshore drilling, and the key features needed to implement the technology.

Out of the many advantages that predictive maintenance can bring to various businesses, for the drilling offshore the following have been highlighted:

- Decrease maintenance costs, by means for example of reduction of stock level of offshore warehouse and last-minute call of service OEM
- Reduce unexpected downtimes: if one can anticipate a failure, remedial action can be taken in order to avoid the rupture of the equipment while continuing the operations
- Set the basis for new business models: by having great confidence on the status of the equipment, it might get convenient to change the business model to a pay-by-drilled-meters basis (Deloitte Center for Energy Solutions, 2017).

Regarding the key feature of the technology, the brainstorming evidenced that to implement predictive maintenance three things were of particular importance:

- Data
- Fault history
- Data science capabilities

8.1.2 Phase 2 – Feature to test, define a valuable POC

The definition of these three features has been key in order to define a valuable PoC. An analysis of available data has been conducted: conversely to what happens on other industries, having data for the drilling was not a problem. All systems related to drilling systems and marine equipment had installed history stations as required by regulations[2]. These systems are also the most critical ones, and therefore a predictive maintenance program would most probably involve these equipment. Data were available for the PoC, and it was possible to define the next steps.

Concerning the fault history, an investigation has been performed. Fault history were present but in a very unstructured way. Faults were recorded in mails, notes and computerized maintenance

[2] As occurs in the aviation industry, most critical systems on an offshore rig have to install a sort of flight recorder (black box) for investigation in case of disasters.

management system (CMMS), but not clearly and it was difficult to understand what the problem was. As a result of this, a systematic fault recording system has been proposed to the asset management for the future predictive maintenance system upgrades. For the first PoC, a dataset where also a fault history was available has been selected.

Regarding the data science capabilities, in the drilling offshore division there were none but it appeared that other divisions had just hired data scientist which “needed to practice” on real cases. One months of data scientist was therefore offered by the other division.

The basic feature for the PoC have been investigated and therefore it has been possible to define a valuable PoC. On one of the offshore drilling platform there was a recurrent need of substituting one sensor of the tensioner system, but early investigation brought to no results. It is important to note how this real case has been brought up by the business knowledge owner. Data related to the tensioner system had to be therefore retrieved and sent to the data scientist for analysis. The scope was to detect any pattern which could explain or at least anticipate the failure of the sensor.

8.1.3 Phase 3 – PoC execution

Retrieving the data has been the starting point for this project and, at first, this could be considered the easiest part of the research because of the large availability of information, as already mentioned. As history proved later on, the research team underestimated the fact that data availability includes both data presence and data accessibility. Data were present in big quantities (2 Gigabyte for the PoC), but stored in history stations and encrypted in order to occupy as little space as possible. A third party company had to be contacted in order to parse the data. Furthermore, another underestimated complexity was related to the connectivity. Parsed data, readable with data scientist tools such as Python or R, were available onboard the rig. The transmission to headquarter proved to be very complicated due to the very low bandwidth (4 Mbps) which relies on satellite technologies.

The whole data retrieving process required almost 3 months. Once data were finally available at the HQ and could be used by data scientists, the team managed to get the results in four weeks, and this proved the potentiality of the technology. Before technology, an OEM service engineer had to be sent onboard to better investigate the reasons of recurrent failures, now a data scientist managed to get to the same results without even having detailed engineering knowledge on the tensioner system.

8.1.4 Phase 4 – Results analysis

It is important to evaluate if the potentiality of the technology is well understood in this phase. As known, the potential of such technologies is high in terms of budget savings for asset maintenance. If such system could be available for critical equipment, the money saved could be even higher. Furthermore, the PoC also proved that even the limited capabilities in data science available at the time were enough to bring value to the company.

Concerning the data, it has been evident that improvements had to be made in order to retrieve the data from the black box onboard. This part of the project could not be managed through the increased complexity approach. A more traditional approach, including market scouting, technical specification and supplier selection, was needed in order to implement such services. The selection has been performed in parallel with the predictive maintenance project. Nonetheless, it is here important to note that this part of the project highlighted that a true data management strategy had to be taken into consideration for all digital transformation aspects.

Another key result of this first iteration was that it proved the necessity to define a "predictive maintenance infrastructure" to better scope the project. The same infrastructure could be used also for secondary digital transformation projects. The pillars are the following:

- Data integration onboard the vessel: several systems are installed on the rig, and those may have different history station and data policy. All data will need to be connected to a central hub (to be selected) in a structured and common platform;
- Data connectivity: data stored on the rig will need to be available for analyses of the data scientist. Connectivity of the rig has to be taken into consideration;
- Industrial IoT platform: an industrial IoT platform needs to interface to the upper level of data of the rig, release the data to the predictive maintenance app (and all other apps), and show the results of the app on a dashboard;
- Predictive maintenance app to retrieve the data from the rig: this app shall predict faults and anomalies;
- User interface with asset managers: it shall be able to give valuable insight to the asset manager without impacting their daily job.

The fourth phase objective is to understand if continuing the investigation of the technology trend is worth it, and if yes how to continue. The results of this first iterations are therefore that:

- Data strategy is needed for all digital programs;

- Technology has potential.

It was therefore clear that it was the case to start with another iteration.

8.1.5 Second iteration

As one iteration has been completed, the team has been increased including other asset maintenance engineer. The complexity had to be increased as well, and therefore the team decided to test the technology on a critical equipment (diesel generators). These systems are known for being much more complex than the tensioner system, and to produce a lot more data (1 TB for four month, for each generator) as a consequence. The features to be tested were:

- Big amount of data;
- No fault history, which imposes the use of unsupervised methods;
- Data science capabilities available in the market, compared to internal.

The team therefore decided to perform a PoC with several contractors and compare the results between each others.

The selected dataset included at least two major faults, but root cause analyses did not identify the reason for the fault. The objective of the multiple PoC was to verify if the use of statistical methods would have allowed to automatically detect the anomaly (i.e. the fault) before its occurrence, and also to possibly show which was the wrong-behaving variable.

The same dataset related to the diesel generator have been provided to the suppliers with a high level description of the objectives.

The scope was also to verify who could be a good partner for such services in the market. As said, being a growing market, almost every supplier was proposing a predictive maintenance solution, so that for the drilling contractor it was difficult to understand who to partner with.

Subject of this thesis is the evaluation of the results derived from the second PoC execution. The expected results were to build enough internal know-how to design a technical specification for a third iteration, a pilot project, which would have been a full scale project integrating all the predictive maintenance infrastructure above mentioned.

9 Dimensions of predictive maintenance in the offshore drilling industry

As briefly introduced, the following chapter aims at presenting the results derived from the application of the framework above examined. Results can be identified in the definition of the most important features of the predictive maintenance, which allow the reader to set a short and long term strategy for implementing predictive maintenance in an offshore drilling company.

Dimensions will guide the innovation manager or the asset manager to the definition of the desired predictive maintenance solution to bring value to the business.

Before setting the strategy, it is important to make some preliminary considerations.

9.1 Preliminary consideration 1 - Scope of the predictive maintenance

As typical of data science projects, it is very important to set the goal first. As anticipated in the literature review, the predictive maintenance in the upstream industry can be used for two main purposes:

- Well construction equipment failure (e.g. drill bits);
- Drilling contractor equipment failure (e.g. top drives and diesel generators).

The first purpose includes all statistical techniques meant to anticipate the failure of an equipment used to perform the well (drill bit, inside valves, …). The failure anticipation is not therefore related to the optimization of the supply chain, but to the improvement of the well construction quality. For example, a major failure in the drill bit, or a stack pipe event, might cause unexpected consequences undermining the good quality of the well, which can easily be transposed in economic value: good quality well means better production. This goal of the predictive maintenance is usually more interesting for the clients, the oil companies. Depending on the contracts stipulated with drilling contractors though, there might be interest also for the rig owner to dedicate investment for the inside-well drilling equipment failure.

The second class of goals includes a more typical approach, related to the anticipation of the asset failure in order to reduce the costs related to the supply chain. Predicting a failure of these equipment with a reasonable time of advance, can bring to the following advantages:

- Avoiding unexpected non productive time: if the failure can be predicted, a redundant equipment can be used or, if not available, the equipment can be used at lower performance in order to postpone the breakout;

- Reducing the costs related to the emergency call to the OEM service: when a fault is predicted, it is possible to have a better planning of the service and to reduce the costs. This can be considered a very specific purpose for the offshore environment, where the service costs gets substantial due to the transportation on the vessel. Furthermore, in the offshore drilling industry, the service personnel is required to have special trainings and certifications to perform operations onboard and therefore the service price is even higher;
- Reducing the impact of maintenance intervention by avoiding the troubleshooting phase, and perform it when most convenient.

For the company object of the case study, the latter goals were more impelling and therefore they have been targeted for the pilot project. Nonetheless, a possible integration with the oil company for the inside-well equipment failure prediction has been considered.

9.2 Preliminary consideration 2- Mapping the automation level of your asset

The O&G is a capital intensive business, and therefore investments are made with a long term horizon, so that very old assets are currently present in the industry. Considering the industry subject of this thesis, the upstream drilling, it is possible to have assets from 1970 or even earlier in some cases.

Performing predictive maintenance on old equipments brings many complexities, and has to be therefore taken into consideration. By no means trying to be exhaustive, the following complexities arise when trying to implement predictive maintenance on old equipments:

- old equipments most probably have little or no automation and it is therefore difficult to retrieve information about the system itself. In case they have sensors, they are most probably not precise enough to bring value with statistical tools (are they just pressure switch, or pressure sensors? If pressure sensors, are they analog or digital already? How many samplings per second? Which accuracy?);
- if available, PLCs and industrial controllers have been designed before the internet era. At the time, the scope of the PLCs was to read values from sensors and power actuators. Connectivity with other PLCs was just about to start and there was no internet. As a consequence, the old PLCs have no built-in protocol to transmit data to the predictive maintenance app. A retrofit has to be taken into consideration;

- in case they have connectivity, how well protected are these PLCs from cyber attacks? As well known, cyber crime is now targeting the industrial PC and the easiest target are the old PLCs which have no built-in cyber protection.

Before starting the path to predictive maintenance, a mapping of the technology status of the assets has to be completed. It is important to provide answers to the following questions:

- Do your assets have sensors? If so, are they precise enough to perform predictive analytics?
- Do your assets have PLCs connectivity?
- Is any industrial cybersecurity policy available and structured within your company? If not, you better take care of that first.

Considering the company subject of this thesis, its fleet is composed by one third of the rigs with technologically advanced equipment, with relatively new PLCs able to interconnect to an onboard data integrator.

The suggested approach would be therefore to test the predictive maintenance tools on the most advanced rigs, in order to minimize the test costs (no need of retrofit). Once the technology has been developed, it might be the case to extend the program also to older rigs.

9.3 Preliminary consideration 3 - Availability of historical data

As clearly identified in the preliminary phases of the project, data are crucial to proceed on predictive maintenance projects. When setting up the strategy for this kind of projects, it is therefore important to start with understanding if data retrieval activities have to be included in the scope of supplier.

This is important because, if data are available before starting the model construction, the supplier has already a basis which can use right away to start building the statistical model. Unfortunately, this kind of approach might lead to wrong data modeling, and therefore the data scientist might be forced to develop a model using the wrong variables. Nevertheless, this approach allows to dramatically reduce the deployment time.

If data are not immediately available, the supplier will most probably need to guide the company to set up a data retrieval strategy. Ideally the supplier would first guide the company in the variables-to-store selection and in defining the automation data infrastructure. In this case, the company shall be aware that a data strategy has to be included in the bid for the predictive maintenance provider.

As it often occurs, for the company considered in this project the status of data availability was not the same for all equipment. Basically three main groups could be defined.

The maritime equipment (generators, thrusters, etc.) generally have great availability of data for historical reasons. As anticipated, these equipment had to store the data in history stations to investigate failure causes in case of incidents. The same provider of the equipment allows to mirror these data on the cloud with a small upgrade of the software system making them easily accessible.

For the second group of equipment, typically the ones related to drilling machines, a very similar black box system is in place, but there is no effective accessibility to these data.

Finally, for the last group (non critical equipment), no valuable data have been stored in the past. Considering the availability of data, the company decided therefore to start the pilot with the maritime equipment and to adequate the infrastructure for the drilling equipment. For non critical equipment, the company decided to wait and see if updates will be available in the market to allow storage reduction and to mirror the costs of old equipment.

Having in mind the above preliminary considerations, it is now possible to go through the "dimensions" of the predictive maintenance.

9.4 IT infrastructure

One of the greatest PoC result has been the one helping the technician to define the data infrastructure needed to implement a scalable and reliable solution for the predictive maintenance. Being a new software, the whole infrastructure was not clear and had to be organized through a framework. Of course, each element of the framework requires a decision, which has strategical consequences. Each element will be quickly described hereunder.

In summary, data from equipment have to be retrieved onboard through a lower automation level, integrated and transmitted to an IIoT platform. Data are retrieved on this platform by an analytics app, which will produce predictions to be sent to the CMMS in order to become actionable.

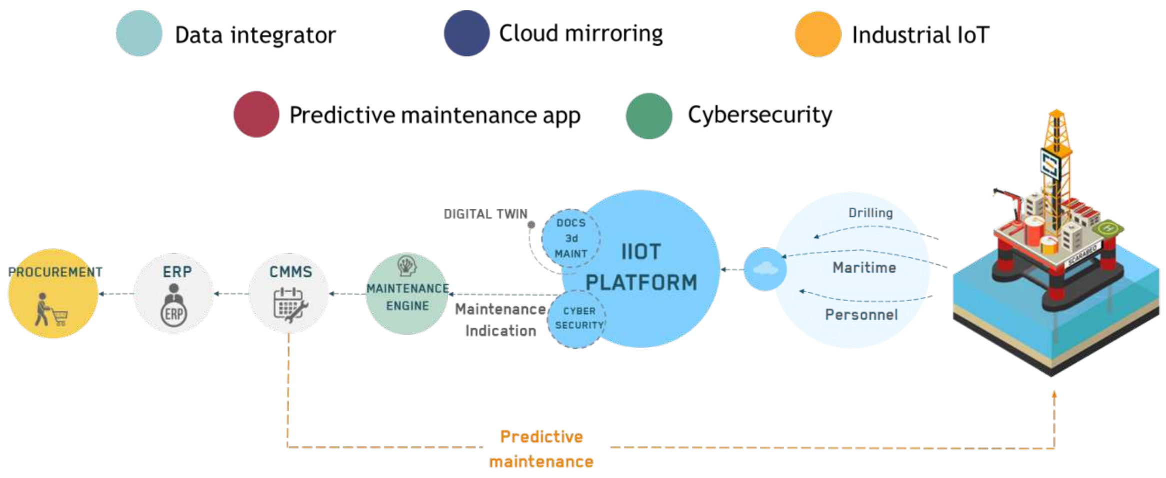

Figure 8 – graphical representation of the building blocks composing the predictive maintenance for the company under examination.

9.4.1 PLCs data, or new sensors?

Based on the results described in the preliminary considerations, the decision maker has to define if it is enough to use the sensors data already available in the automated equipment or if it is the case to install new dedicated sensors. Whilst the first approach would "only" require an integration between the equipment and the mirroring system, installing new sensors would require the installation of a totally new system onboard. The latter would cause higher costs and longer times to deploy, in order to adequate the data infrastructure with the new systems.

9.4.2 Connectivity and data mirroring

Once data are retrieved from the selected equipment (ref. to the dimension "critical equipment or all equipment"), they have to be transferred to an IIoT platform. As offshore drilling rigs are typically in remote areas, connectivity and data mirroring has to be taken in serious consideration while building the infrastructure.

Considering current technologies, internet bandwidth onboard usually relies on satellite technologies (with a typical bandwidth of 4 Mbps) and has to be shared with operations and clients to guarantee safe and efficient well construction. It is therefore important to scout the market in order to select a good data mirroring service which has the specific objective of minimizing data transmission.

Nonetheless, this dimension is strictly related to the vision on rig connectivity. The decision on data mirroring (as well as on edge or cloud storage and computing power which will be later on described) is to be taken considering the availability of a great interesting number of research programs (above all mid-range satellite and 5G technologies for harsh environment) that have the objective to improve the connectivity of remote devices. If these projects prove to be effective, they will definitely change the way business is conducted in the offshore drilling industry. Among other major consequences, access to greater speed will allow to remove the reduced bandwidth limitation and therefore the data mirroring could be chosen according to other factors (latency for example).

9.4.3 IIoT Platform

Once data are successfully transmitted, the industrial internet of things (IIoT) platform will need to be defined.

As a common definition of this platform does not exist, the company will need to define its own definition. The most important features that could be included in an IIoT platform and could be required during its selection are described below.

First of all, the platform will need to relate data extracted from the equipment, considering both live stream data coming from PLCs, new sensors installed to retrieve high frequency data or data from OEM history stations. Of course, high quality predictions cannot be performed without interconnecting data of an equipment coming from different sources.

A second objective of the IIoT platform could be to act as operating system for the predictive maintenance, including all the necessary statistical libraries which are the building blocks when building predictive maintenance model.

Finally, the IIoT platform could also perform the UX platform for the development of the algorithm and to show results of predictions (dashboarding interface).

9.4.4 Edge or cloud?

The storage and the computing power necessary to produce the predictions are other relevant dimensions to select the IT infrastructure.

Once data are retrieved from equipment and related to each other, they will need to be stored for immediate access. The deployment of a central headquarter server for the CMMS, ERP and DMS including all rigs has been a typical approach for IT systems onboard, mirroring the relevant data onboard the rig to guarantee quick and reliable access to operating personnel also in case of unstable internet connection.

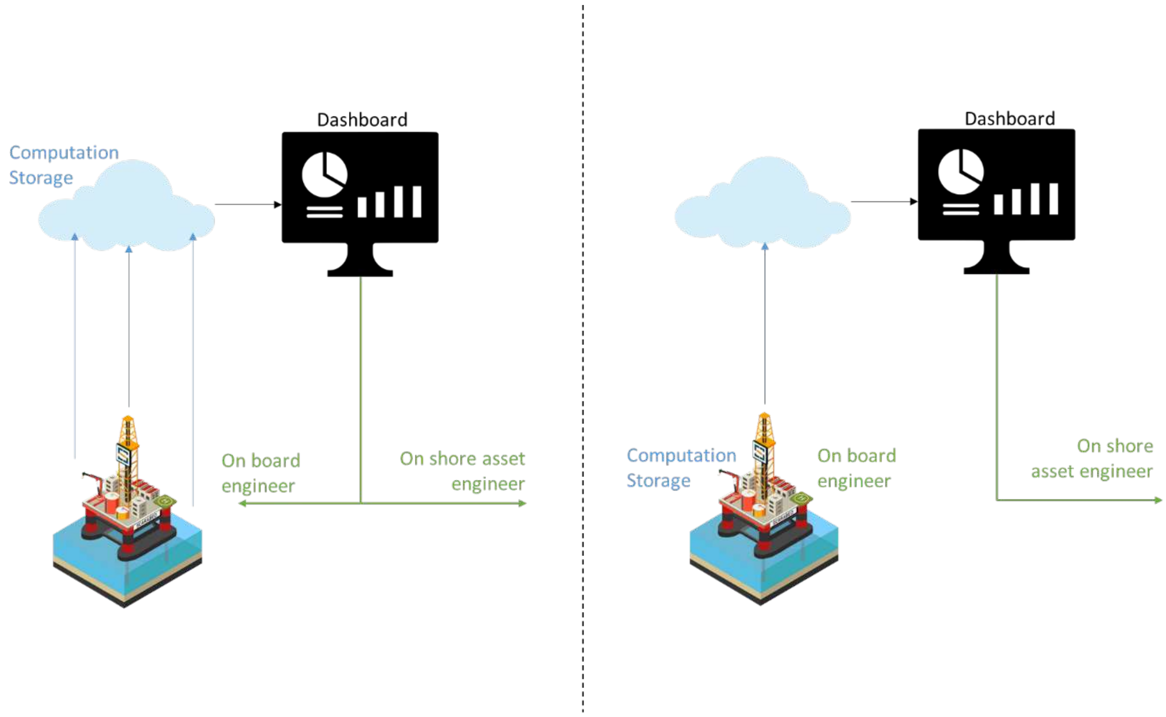

Figure 9 – conceptualization of the data flow in totally cloud (left) vs edge (right) architecture. In the cloud case, all data are sent to the cloud, processed and visualized by people onboard and onshore. In the right case, only relevant data are sent to the cloud for onshore evaluation.

For the predictive maintenance infrastructure the same approach could be applied: data storage could rely entirely on cloud capabilities, as well as the statistical models could rely on cloud computing power to perform effective and real time predictions. Results could be then mirrored back to the rig personnel and to the headquarters engineer to manage adequate decisions. This type of infrastructure would show the typical advantages of the cloud services, for instance flexibility based on real need of the predictive maintenance tool and consequent avoidance of installing a new server onboard. Nonetheless, the risk is to congestion the internet connection. As these data are primarily important for the onboard personnel, it might not be necessary to transmit these data up to a cloud and then back to the rig again. An edge computing strategy could be envisioned, where algorithms are run on servers available directly on the rig, where the data would also be stored. Then, aggregated results could be sent to the headquarter in order to be evaluated by engineers, with a minimum bandwidth usage. The trade-off to consider is between having an adaptable infrastructure vs reducing the impact of predictive maintenance tools on the connectivity.

9.5 Analytics App

On top of the IIoT platform, what has been defined by the company as "analytics app" or "maintenance engine" will produce relevant predictions, based on data retrieved by the IIoT platform and statistical models provided by the data scientist.

9.5.1 Time of prediction

Since there is almost no case history on predictive maintenance applications based on purely statistical methods, it is important to define what is the expected accuracy of the models.

As briefly anticipated, the time of prediction is incredibly important to build the business case. If the model is able to predict the failure with large anticipation, it has to be accepted that the prediction might not be precise and the remedial actions might be less effective. Conversely, if the model can predict the failure just few minutes before it happens, it can be harsh to take advantage of the prediction itself. Timing of prediction is one of the parameters that the supplier will need to ask to the drilling company as a parameter. The company will need therefore to understand with operations and asset how much time earlier the prediction is needed in order to bring some value.

9.5.2 Type of prediction

It is possible to consider two basic levels of prediction. There might be a model which is able to understand that the system is not behaving as normal, i.e. an anomaly detection, or there might be a model able to predict that a specified part is going to break.

Defining what is reasonable to ask in a technical specification for such model is duty of the drilling company. After a brief market scouting, it will be almost evident that in the future a predictive model able to predict all parts breakout will be available, but at current time it might be harsh to be found in the market.

Predicting an anomaly on a statistical means basis is something more feasible with the industrial technologies currently available. Based on a training period which the engineers sets as "normal", there are several techniques to understand if the recorded variables are behaving in a "normal" way. Different levels of accuracy exist in the case of anomaly detection. Some systems may only recognize that one single variable is not behaving as it should, while more complex systems could understand if variables are not behaving normally compared to each other (multi-variate anomaly detection). There are also different techniques to reach this target, based on classical statistical approaches, other automation techniques or advanced statistical methods based on neural networks.

Predicting that a certain part is going to break can be very tricky. First of all, a distinction has to be made. If there is a frequent break of the part, and data are available to record the variables of the machine before the breakout, it might be possible to create a very specific model to predict that exact break out with a supervised learning model. In this case, it is reasonable that OEM (who have detailed engineering knowledge of their equipment) will propose a dedicated system for detecting such failures: these algorithms will always be better than what a system integrator can provide and therefore it might be the case to rely on OEM solutions for such predictions.

For the company in subject of this thesis, anomaly detection was considered feasible with the available technologies, and therefore it has been included in the technical specification. In this case, it is important to note that onboard engineers already receive lots of alarms from the monitoring systems (e.g. when a temperature exceeds the limits). Adding another anomaly detection system will surely bring even more events to be checked by the engineers; a maximum number of daily anomalies should be therefore set by the drilling contractors. Finally, as a requirement of the anomaly detection model, at least three different mathematical methods has been requested to the algorithms provider. As output, the company reasonably supposed that there would have been a dashboard related to the system connected to the predictive maintenance tool advising the operator that an anomaly was occurring, and ideally an indication on which variable was out of normality will be displayed as well.

Regarding the prediction of specific part failure, no tracking of recurrent failure was present and therefore a program has started with operations in order to trace recurrent failure which would be useful to predict.

9.5.3 Programming language type

As the statistical model is based on algorithms, the type of programming language to be used has lots of implications for the future strategy.

Once again, this dimension has been noted by executing the PoC with different suppliers. All suppliers in fact have a different vision of the future of the predictive maintenance, and therefore use various programming techniques.

Types of programming language for predictive maintenance can be grouped in three main categories: pure coding (such as R or Phyton), block oriented programming (provided by SAS and

Microsoft for example[3]) and more automated machine learning (such as PTC or dedicated startups). Of course, each approach has pros and cons to be evaluated. A pure coding approach allows to design a specific statistical model for the application needed, allowing the data scientist to have full control on algorithm portfolio which can be used, parametrization and eventually the liberty to mix various approaches. By using a block oriented programming, it is possible to maximize efficiency of the data scientists, as algorithms are pre-packed and the interconnection between various sections of the algorithms is automatized. Even more efficiency is possible when automated machine learning is used: by automatically testing several statistical models and scoring the adherence of the models themselves, the system minimizes the effort of the data scientist. This latter approach could be an interesting option since the predictive maintenance cases are usually very similar to each other and can be therefore standardized, especially in the anomaly detection case. Of course, more automation means less control for the data scientist can on the modelling: not all algorithms might be available, especially the ones just released on scientific papers. Furthermore, the developer has to know how to program in the specific automated platform, which is less common. Another implication of the type of the selected programming code is related to the algorithm maintenance. The more the system is automated, the easier the maintenance of the model.

Governing this dimension implies also the definition of the long term strategy for predictive maintenance. In fact, the type of programming requested for the predictive maintenance app will define the future manager of these activities. In fact, if it is very much common to rely on external sources at the beginning, it is then necessary to define who - in a 3-5 years time - is going to create new models and maintain the existing ones. These activities could be handed over to an external specialized firm. In the case of the company subject of this thesis, the know-how related to predictive maintenance development will be kept outside the company and therefore it might be considered a risk.

An alternative could be to build an internal data science team: in this case the expertise could be kept inside the company and the costs might be lower. The risks in this case is related to the fact that an internal team could not have the same expertise which is available within an external firm; also, the team would not be very busy in case the predictive maintenance proves to be not interesting anymore.

[3] Similar to MATLAB Simulink

A more visionary approach is related to the development of automated machine learning systems; if these systems prove to be very effective, ideally the engineers who have expertise in the equipment (the users of the predictive maintenance algorithms) might be able to build their own statistical model of the equipment with little or no support of data scientist. This vision is in line with the idea that predictive maintenance will start bringing real value when massively used by all key decision makers in the maintenance strategies[4].

Depending on the vision that the innovation management has on the employees using the tools, it is possible to request the appropriate type of programming language to the supplier.

To conclude this chapter, it is worth mentioning an approach recently proposed by some of the suppliers. The approach will be defined by the author "blueprint approach", even though no particular definition has been known in the literature so far. Being the predictive maintenance a branch of artificial intelligence specified in understanding possible anomalies in a defined set of equipment (pumps, motors, compressors, etc.), some suppliers are proposing the idea of providing a blueprint of the equipment type, which will self-parametrize according to the data received from the field. This approach can be very effective for two main reasons:

- Instead of creating a custom model from the available data (which can be different from OEM to OEM), the algorithm requires certain variables. For the engineers then, it is clearer how to evaluate the status of the data infrastructure and how much would be required in order to adequate the system in case of need;
- The data science job would be incredibly automated. The engineers, with just few notions of statistics, will be able to create the model of the assets and to start value generation.

The company under examination decided to start with a block oriented programming, which would allow to minimize risks while maximizing efficiency. The workforce will be externalized at first, and then internal capabilities will be developed once the predictive maintenance proves to be a mature technology.

[4] Doing an analogy, some expect that there will be a predictive maintenance tool which will be widely used. As happened with Microsoft Office, whose simplicity allowed even non-expert users to develop quite complicated spreadsheet, some see that there will be a tool for predictive maintenance which will allow the engineers to build their own statistical models and deploy with great autonomy.

9.6 Critical assets or all assets?

As it happens in other industries, some equipment are more critical than others in the offshore drilling, meaning that if one of these equipment fails, the well construction has to stop (non-productive time). In the upstream drilling business, these equipment are called top drives, blow out preventer, drawwork, tensioning system, mud pump, diesel generator and thruster.

This would make the reader think that it would be surely the case to start the implementation of a predictive maintenance program only for the critical equipment to reduce the non-productive time. Nonetheless, as clearly stated in the preliminary consideration 1, it is important to have the goal in mind. If the goal is to reduce only maintenance costs (and not to reduce the non-productive time), it might be the case to consider to address the predictive maintenance of all non-critical equipment (which are more numerous than the critical assets).

Ideally, with a predictive maintenance tool, we would be aware of the failure some time before the actual break. Nonetheless, it would be very difficult (especially at the beginning) to have a prediction with more than two weeks notice. Once again ideally, the system would advise the engineers that a failure is going to occur and therefore the spare part would be requested to the OEM. The real issue here is that these kind of spare parts are very specific and they're usually not kept on stock by the OEMs, with an average production time of almost four months. In this case, a two weeks failure prediction notice wouldn't help the asset management, and the only possibility would be to keep the stock level as currently done. The main advantage would be that the service travel could be better organized, reducing the costs of about 10%.

Furthermore, it is important in this case to evaluate the future development of the supplier market. As one of the macro trend is the servitization of the most relevant equipment (as happened for the Rolls Royce engines in the aviation industry), it could be a risk to invest resources in the development of a predictive maintenance tool which in the nearest future will be managed by the OEM as a service. OEMs are in better position to perform predictive maintenance as they also have the engineering knowledge and therefore it would be senseless to continue on this way.

Alternatively, performing the predictive maintenance on all other semi standard equipment (pumps, electric motors, …) might generate higher return on investment. In this case in fact, the lead time is definitely lower and a failure anticipation of two weeks would be enough. Consequently, a reduction of the stock level for the spare parts of non-critical equipment could occur, reducing the total cost of ownership of such equipment. Furthermore, critical equipment are almost unique and therefore a dedicated predictive model has to be built for each asset, while more standard equipment may allow the implementation of "one-size-fits-all" statistical model which could give good value to the business.

For the company of the case study, the predictive maintenance adoption for the standard equipment would bring value to the company in too much time: stock levels cannot be easily lowered as the spares have to be used first and cannot be just thrown away. Furthermore, non-critical equipments are also the oldest ones on an offshore rig and therefore an upgrade of the data infrastructure would be required, increasing the cost. Adopting the predictive maintenance on the critical equipment would guarantee a quicker return on value instead, but - among all - it would guarantee a continuous experimentation with predictive maintenance, necessary to build an internal know how.

The decision has been taken also considering that, despite some tentative servitization approach proposed by some front-runner OEMs, the suppliers seem not to be ready. The received quotations couldn't justify the leasing option instead of buying; therefore the company decided to start implementing predictive maintenance on the critical equipment and to transfer the lesson learned to non-standard equipment.

The last reason for this decision has been that, according to the literature and the common sense on data science projects, it is better to start on a single asset approach instead of covering all the equipment available in the offshore rig. This is to avoid the efforts dispersion in too many directions and to ensure that one predictive maintenance implementation is totally covered.

9.7 Partner selection

Once again, being the predictive maintenance a hype, it's an evolving market. Over the time different type of suppliers were proposing some sort of predictive maintenance service and at a time it was difficult to understand the differences between each others. As a result of the multiple PoC (second iteration) the company decided therefore to include as dimension of the predictive maintenance also the partner selection, which has many consequences for the full scale predictive maintenance project.

Since this was one of the feature to test on the second iteration (data science capabilities), the team decided to perform a multiple PoC with several potential suppliers. The selection has been carried out according to the type of supplier, as follows:

- Engineering consultancy firm
- IT service company with expertise on ship construction

- Oil and gas well data service provider
- Pure IT company
- Industrial automation electronics supplier
- Startup dedicated to advanced machine learning

As noticeable, companies came from very different background and industry-expertise but were all offering some sort of predictive maintenance services.

An important result is that all of them achieved almost the same results. What really differentiated suppliers from each other has been, therefore, their process knowledge of how a data science project works, if they had any engineering background or had some drilling equipment knowledge, if they could guarantee after-deploy support and if they had complimentary products to offer. For sake of completeness, we are going now to better detail these differentiation.

9.7.1 Having a process in place

One major difference between the companies was related to their experience in managing predictive maintenance projects. Many suppliers managed several PoC or pilot projects already and had a specific process flow in place for the requirement gathering, the data management and the results proposed. In the case study analyzed in this thesis, having a process has proved to be more effective in terms of time and effort required to develop a ready-to-be-implemented solution. Suppliers with no process in place achieved the same results (sometimes even better results) but required much more time in managing their clarification due to randomness of the process flow.

9.7.2 Having an engineering knowledge

Apart from a defined process flow, the engineering expertise of the supplier has generated lots of differences between the PoCs. Being a data science/statistics/IT project, most of the suppliers technicians have an IT or a purely statistics background. In order to apply their knowledge to a predictive maintenance topic, engineering expertise has to be included in the project team. Companies with a strong engineering background (such as the engineering consultancy firm or the industrial automation supplier) eased the interaction required to relate data with physical meanings. Where these expertise were not available, the company had to plan many hours of the asset technical office in order to support the assumptions and evaluate the results of the data scientists.

A special mention has to be made for the particular case of the IT service company with specific knowledge on drilling rigs (due to another division being rig construction company). In this case, the interaction have been minimal and the result was in line with all others.

This is an important dimension to be considered on a strategical level, i.e. for the full scale implementation of the predictive maintenance. If we only consider the PoC execution, the difference in time needed to manage the supplier (both on the project management side and on the engineering knowledge side) is not to be considered an issue. But, for the extension of the program to several equipment, if the supplier needs lots of project management or asset engineers, the total cost of the project would definitely increase.

As a result, an interaction with the asset department as well as with the IT department has to be carried out in order to understand the future staffing on that side. Based on the available personnel, keeping the expertise internally or relying on external sources will be possible options.

9.7.3 Support after deploy

Building a statistical model of the equipment is just the first step to apply a predictive maintenance strategy. As many other software, the algorithm has to be "maintained". As equipment is being used, its behavior will most probably change. The model describing its behavior will be therefore not valid anymore, and the system will need to be trained to adhere to the new normal condition. Risks of not doing such maintenance are that the alarms will be shown by the system even if the equipment is working in normal condition, decreasing the accuracy of the system.

As algorithm maintenance is necessary to have a consistent system, the company shall consider how the supplier can support the maintenance. In this sense, relying on IT or automation companies might be more reasonable as part of their current business is to maintain their products. It is worth mentioning that an industrial partner will most likely not be so fast in applying the latest state of the art algorithms, whilst a startup or dedicated contractor might be faster in implementing these algorithms.

9.7.4 Business model

A great result of performing a parallel PoC with several different contractors has been the verification that diverse business models are being suggested by suppliers. As often occurs with newly created industries (in this case, predictive maintenance software industry), there is not a predominant business model in the market place. The drilling company will need to define which could be the solution theoretically to adapt the most to its need: a brief summary of the business models which have been encountered during the PoC follows hereunder.

It is relevant to define that the price of a predictive maintenance tool can be considered composed by a development fee and a maintenance fee.

The most frequent quotation structure is related to a lump sum model development fee, and a maintenance license costs on a yearly basis. Some providers are open to transfer the development costs on the license fee.

The variability mostly occurs in the license costs: most suppliers are proposing a pay-by-tag model, where the maintenance and dashboarding fee are based on how many tags (i.e. variables) are being used as input and output of the predictive maintenance model. Others, typically the one who rely on automated machine learning solutions, propose a pay-by-asset fee, with a labile definition of how much complexity can a single asset have. Suppliers who propose also IIoT platform in their portfolio, usually rely on a pay-by-platform annual fee, despite of how many equipment are connected to the predictive maintenance tool.

9.7.5 Complimentary offerings

Finally, the supplier complimentary portfolio is to be considered as well. As briefly explained, applying the predictive maintenance in a drilling company requires not only good algorithms but also data infrastructure adaptation (data aggregator, data mirroring, industrial IoT platform, analytics app and user interface).

Managing the same supplier for multiple streams of the predictive maintenance can be really effective in terms of cost reduction due to gained synergies. In the case study proposed for this thesis, the product portfolio of the supplier was very diverse and based on the core business of the supplier itself. If one supplier was able to propose a data aggregator, the analytics app and a valuable user interface already used by engineers onboard, another was able to provide an industrial IoT platform and the data mirroring together with the analytics app.

Evaluating the complimentary services of each supplier can be very subjective for the drilling company and it’s strictly related to the internal capabilities which the company can provide.

For the case study company, it has been decided not to give great importance to the Industrial IoT platform, which can be considered almost a commodity. Once all other streams of predictive maintenance will be ready, the IIoT will be selected based on its ability to interface with existing systems.

10 Business Case for predictive maintenance

Following the process of investigating new technology trends, it can be interesting to correctly quantify the benefits that could be achieved by implementing the innovative solution. In fact, for the predictive maintenance case, a quantitative business case has been possible only after PoC execution: before that, limits of the technology were unclear and the risk of over estimating the benefit could have unnecessarily increased the investment. A qualitative estimation of the benefit can be produced before knowing the possibilities given by technology.

The following analysis has been performed for the examined company, considering results as confidential: as consequence, only qualitative considerations will be here presented.

As briefly introduced in the first chapters of this thesis, the obvious benefits provided by the implementation of a predictive maintenance solution are related to the maintenance cost reduction due to emergency calls to OEM, but also due to unplanned downtime. Thanks to the PoC, it has been possible to recognize that current machine learning tools cannot predict the complete spectrum of faults of an equipment, but could predict anomalies in the system and some very specific faults for which the statistic models have been trained. This has brought to the conclusion that a predictive maintenance will not have, at least at the beginning, a revolutionary effect on maintenance cost reduction. It is possible to split maintenance costs in two main groups:

- ordinary maintenance
- unexpected maintenance

Considering ordinary maintenance, the shift from periodic to predictive maintenance will reduce, according to some literature (Anodot, 2019) and (PwC - Mainnovation, 2018), up to 12% in most advanced industries. After the evaluation of the automation status of the equipment onboard the rigs, the cost reduction estimation should be reasonably cut: since current technology could only validate if an anomaly is occurring in the system and warn the engineers, the full potential of predictive maintenance can not be achievable in the short term for the drilling industry.

As for the unexpected maintenance, the down time costs of the rig have been added to the costs related to emergency calls. In this case, the identification of the exact fault by the algorithm is important, and therefore a specific supervised learning algorithm has to be used. This requires a history of faults to train the models. By performing an analysis on the last faults occurred in two critical equipment of one rig in the examined company, only a small portion of faults (on a total of ten) occurred in the last 5 years on the equipment, could have been predicted because of the specific availability of a case history to train the model. This means that only a small reduction of unplanned maintenance costs could be reasonably achieved thanks to the anomaly detection methods.

In this regards, a specific analysis of contracts signed with oil companies showed that a critical equipment maintenance rate is currently guaranteed to cover drilling contractors from this type of unexpected fault precisely. In the short term business case, there is almost no direct advantage of predicting unexpected faults but, of course, this can be used as long term strategy to be more competitive in the bidding phase.

On the same stream, it is important to consider the increase in brand reputation in the business case: a more innovative drilling company, especially in the more recent time, can better serve oil companies in their innovation path and therefore is more likely to be selected in the bidding phase.

In the business case, it has to be considered that some literature states that asset life would be increased if a predictive maintenance tool is adopted. In fact, implementing a preventive maintenance requires the substitution of components even when not necessary: when such components are substituted, particular operating and stress/test mode of equipment have to be run to verify correct installation, and this tends to decrease the total life of the asset. By substituting components only when and if necessary, it would be possible to increase asset lifetime up to 20%.

Another factor to be included in the business case is related to a more efficient third party certification processes. As more intelligent tools are installed onboard, it would be easier for the certification tools to investigate if proper maintenance instructions are realized. On the same stream, insurance costs would be reduced because risks of insuring an equipment or safe operations would be reduced as well by the implementation of predictive maintenance tools.

Finally, the costs related to HSE should be included in the business case. The risk reduction related to unexpected faults could prevent injuries of personnel, by improving safety (which is incredibly valuable) and the costs related to the injury itself.

11 Conclusion and Future Prospects

The thesis approached a methodology to better investigate new technology trends and presented the successful results of the application of such methodology for the predictive maintenance case study. As a result, short- and long-term strategy has been set for the predictive maintenance by the examined offshore drilling contractor subject of this thesis, and the methodology has been set as recommended practice for the technology trend related projects.

As future prospects, the author would suggest to better investigate proper agile methodologies to perform project management of every single iteration of the increasing complexity methodology.

Furthermore, it would be interesting to verify the application of such methodology also to other types of projects. Further to the technology trend management, the innovation management of the drilling contractor had to manage the so-called “makers projects”, where the scope was to build a prototype using fast prototyping electronics boards and sensors (Wikimedia Foundations2, 2019). The project management of such project should follow a more linear approach compared to the technology trend ones, and therefore it is suggested to develop a dedicated methodology.

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