University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization : **Industrial Asset Management**	**Spring Semester 2019** **Open**
Author : **EL HIMER Malak**	Author's Signature : ……………………Malak……………
Faculty Supervisor : **Professor Jayantha Prasanna Liyanage, PhD**	
Title of master's thesis : **Innovation in Condition Monitoring and Predictive Maintenance solutions in Industrial Contexts**	
Credits (ECTS): **30**	
Key Words: **Innovation, Condition Monitoring, Predictive Maintenance, Industry**	Number of pages: 204 Place and date: **Stavanger, 15/06/2019**

Innovation in Condition Monitoring and Predictive Maintenance Solutions in Industrial Contexts

By
EL HIMER Malak

A Thesis
Presented to the Faculty of Science and Technology
University of Stavanger

In Fulfillment of the Requirements for the degree of
Master of Science
(MSc)

Universitetet
i Stavanger

Faculty of Science and Technology
Spring 2019

Abstract

Innovation has become during the last decades the ultimate focal point to the majority of academics, managers and industrial market players due to the enlarged competition and the accentuated need to improve business performance. Industrial institutions around the world were for centuries concentrating mainly on the innovation of their products and processes through emerging technological manufacturing courses leading them to gain remarkable competitive advantages. However, the interactions between these inventive approaches and their surrounding dynamic environments appear to be quite complex and misleading in many cases. This has induced increased levels of uncertainty and unpredictability as well as a continuously variation of the relevant circumstances which are therefore inciting companies on discovering and implementing innovation furthermore in the monitoring, evaluation and maintenance in their related activities.

Companies have come to the conclusion that by adopting innovation into their monitoring and predictive maintenance processes, their systems are likely to become more flexible than usual and capable to adapt to multiple situations either they are unexpected or not. The set objectives are still about achieving the best performance with respect to the imposed limitations of cost and time under the full integrated respect of the safety and environmental standards. These inventive programs have already brought a significant interest to the development processes in various programs by enabling frequent testing of new strategies and theories allowing firms to absorb more relevant data and conclude by that better supervision and evaluation in terms of efficiency and accuracy. Over and above, it will convey significant measures on the prognostic and prediction of failures and unsought courses of action. This will permit to acquire better results, more effective policies and improved assets.

This thesis seeks to discuss the possible alliances between innovation, monitoring and maintenance solutions chiefly the predictive ones in industrial contexts and the way they are able to operate harmoniously all together. The project has the goal first of all to reveal to what extent monitoring and predictive maintenance as two of the most valuable processes in any given industrial establishment can be highly impacted by the introduction of ingenious tools and how these instruments can allow their analogous activities to reach the necessary outputs with the desired quality and performance targets. This thesis will also illustrate the exiting connections between condition monitoring, predictive maintenance and innovation and how the latter can be perceived as a business concept. The presented discourse will consequently identify some of the most currently breaking through innovative concepts following some study cases and examples in the accordant fields. It will describe additionally some of the primary factors to be taken into account by organizations while implementing such new strategies in monitoring and maintaining their assets that can maximize their utilization and profits. This thesis will finally display some viable enhancement potentials and recommendations for further studies in the matter.

This thesis is aimed consequently at providing practical insight on how the application of novel technological practices associated to monitoring and predictive maintenance can provide ameliorated usage of assets in multiple industrial settings and what are the most suited means to achieve so.

Acknowledgements

The following thesis that you are about to review concludes my Master of Science Degree in Industrial Asset Management specialization at the faculty of Science and technology at the University of Stavanger.

The past two years have been both challenging and remarkably delightful for me. I had the privilege of learning along with my classmates interesting subjects under the supervision of extremely sharp and experienced professors. I have spent long and tiring hours preparing for exams, projects and various presentations, written and oral ones, to finally deduce that it was all worth it. This journey was without a single doubt the most fruitful one in my entire academic life and I am beyond grateful that I have shared it with incredibly talented and amazing people.

I have to say that the writing of this thesis wouldn't have been possible without the aid of my family and friends and I would like therefore to take this opportunity to thank them from the bottom of my heart for their unconditional love and support.

I would like also to express my sincere gratitude for my professor, faculty supervisor and mentor Jayantha Prasanna Liyanage for his patient guidance, encouragement and advice. Professor Liyanage has been continuously supportive, comprehensive and involved during my master period. He has shared with us, students, during our studies and his interesting courses, extensive knowledge and brilliant ideas through his solid commitment and far reaching standards by teaching us diverse segments of the engineering sciences. I consider myself truly lucky to have a supervisor who cared so much about my work, and who responded to my interrogations and queries so promptly. His insightful comments as well as his professional instructions have been greatly helpful to the progression of my work and a primary factor to the achievement of my thesis. They have allowed me to face and sort out many of the challenges I have encountered during the preparation of this project.

I would like also to thank my fellow students with whom I shared this agreeable experience. I have arrived to Norway two years ago. I was the "New girl" to this new country, new city, new faculty and new culture. I had the chance to meet friendly and nice people who made me feel that Stavanger can be a second home to me. I felt that I wasn't alone anymore nor should I be scared of this big change in my life and for that I am forever grateful.

Thank you Mom, Dad, Emma my beautiful sister. Thank you for always believing in me and making me believe in me. I could never thank you enough for your love and kindness. You guys are my rock and couldn't ask for a better family. I love you more than anything.

Table of content

Table of figures

List of Tables

List of abbreviations

ACARS: Aircraft Communications Addressing and Reporting Systems
ACMS: Airplane Condition Monitoring Systems AMS: The Analysis and Measurement services
AF: Asset Framework
AGSS: Aircraft Ground Support System
AHM: Aircraft Health Monitoring/ Airplane Health Monitoring
AHMS: Aircraft Health Monitoring System/ Aircraft Health Management System
AHTMS: Aircraft Health and Trend Monitoring System
APM: Airplane Performance Monitoring/ Asset Performance Management
ASDP: Automated Stimulation Delivery Platform
BHGE: Baker Hughes
CCTV: Closed-circuit television
CES: Consumer Electronics Show
CIO: Chief Information Officer
CM: Condition Monitoring
CMMS: Computerized Maintenance Managed System
COGS: the cost of goods sold
CPS: Cyber Physical Systems
CPU: Central Processing Unit
CTO: Chief Technology Officer
DBuV: Decibel per microvolt
EBITDA: Earnings before interest, tax, depreciation and amortization
ENOC: Emirates National Oil Company
ERP: Enterprise Resource Planning
ESPs: Electric Submersible Pumps
EV: Electric Vehicles
E&P: Energy and Production
FMC: Flight Management Computer
GCP: Google Cloud Platform
GE: General Electric
GPU: Graphics Processing Unit
HDFS: Hadoop Disk Filing System
HDP: Hortonworks Data Platform
HPC: High Performance Computing
HTM: Health and Trend Monitoring
IBM: International Business Machines
ICE: Internal Combustion Engine
ICMS: Intelligent condition monitoring system
ICT: Information and Communication Technologies
IFS: Industrial and Financial Systems
IIoT: Industrial Internet of things

IoT: Internet of Things
IT/OT: Information technology/ Operational technology
LCR: Inductance, capacitance and resistance
LCSR: Loop current step response
LIDAR: Light Detection and Ranging
M2M: Machine to Machine
MES: Manufacturing Execution System
MRO: Maintenance, Repair and Overhaul
MTBF: Mean Time between failures
NASDAQ: National Association of Securities Dealers Automated Quotations
NEAA: North East Automotive Alliance
NPTA: Non-Productive Time Availability
OECD: Organization for Economic Cooperation and Development
OEM: Original Equipment Manufacturer
OS: Operating System
OT: Operational technologies
OTA: Over-The-Air
PdM: Predictive Maintenance
RFID: Radio Frequency Identification
RTD: Resistance temperature detectors
R&D: Research and Development
SAS: Statistical Analysis System
SPdM: Smart Predictive Maintenance
SPSS: Statistical Package for the Social Sciences
SQL: Structured Query Language
TB: Terabyte
TDR: Time-domain reflectrometry
WSN: Wireless Sensor Network

PART 1: BACKGROUND AND OBJECTIVES

Figure 1: Word cloud generation of the most commonly used words in the thesis (EdWordle, 2019)

1.1 Background

Elaborating efficient procedures and strategies to manage the increasing complexity of the industrial operations has become an ongoing concern for managers and researchers in all engineering areas. It is crucial to comprehend the true meaning of complexity and the exact segment it has affected in the relevant institution before taking any steps ahead. Indeed, complexity can be a logistical one that is the result of expanded volumes of transactions, tasks or products leading to a significant rise of operations' interactions adding to the complexity level. It can also be linked to the organization where multiple organizational forms and structures turning the various departments and their connections into a puzzling establishment. Complexity is also a technological one by its systems and complex programs either related to the products or the processes. *(Khurana, 1999)*. However, most enterprises are usually concerned by the logistical complexity that involves more technical and managerial issues. This type of complexity generates usually several complications when it comes to the monitoring activities and the maintenance tasks. Thus, costs are more likely to go up decreasing by that the profit margins and creating some serious problems to the production and delivery schedules. Firms have therefore a tendency to arrange for cross-functional problem solving and to resolve the presented challenges by employing more technically oriented managers to come up with better efficient plans and multiskilled workers to manage the diversity of operations and their complex linkages. Nevertheless, these actions do not deal with the true origin of the imposed complexity not does introduce viable solutions for the heightened competition in all industrial markets. This has made stakeholders become more open-minded to new possibilities in order to identify how their operations can be performed efficiently, with lower costs and higher benefits.

There's only one possibility that manages to offer the competitive advantage that companies call for and the solution to overcome the complexity in their structures. They need to assimilate that old-fashioned schemes for operating, monitoring, evaluating and maintaining their equipment and procedures can no longer ensure the earnings long desired by them. They must look beyond the limits they have surrounded themselves with and choose innovation as the new policy for improvement. During the last decades, this has been a momentous break point for every major player in the industrial business. Firms have finally come to the conclusion that they need to adopt novel ways of thinking but also apply them in their framework. We are witnessing today multiple entities investing millions of dollars into inventive technological systems and financing tech-startups that can provide and develop intelligent setups for their assets management. In the latest news, Starbucks Corporation is investing $100 million in a newly established fund that will be handled by Tesla Inc investor Valor Equity Partners in order to endorse companies creating novel technologies and products for the food and retail business. The fund, Valor Siren Ventures Fund, will later aim to raise an additional $300 million, the world's largest coffee chain confirmed ahead of its annual shareholder meeting. *"We are inspired by, and want to support the creative, entrepreneurial businesses of tomorrow with whom we may explore commercial relationships down the road,"* Starbucks Chief Executive Officer, Kevin Johnson, have stated. *(Business News REUTERS Website, 2019).*

As a result, we have chosen to discuss in this thesis innovation in relation to monitoring activities and predictive maintenance tasks as a great factor for improving their performance and effectiveness. It would be imperative in this case to examine to what extent innovation can enhance decision making processes and upgrade data sharing policies into the various departments of the relevant organization enabling a much improved communication among the key stakeholders. This will facilitate the achievement of operational excellence of the diverse industrial disciplines. Therefore, in order to draw carefully the complete picture and obtain a better perspective on the matter, it is crucial to identify the multiple possibilities in today's markets. Indeed, with the substantial technological progresses occurring from the manufacturing sector till the subsea fields, new opportunities have arisen in relation to the continuous monitoring of the industrial equipment and transmission of the information in real time regardless of the physical location and other limitations. As the competition between innovative systems owners and manufactures goes stronger, the urge for more efficient and less costly programs increases. It has become essential for companies to gain the strongest competitive advantage, to win the innovation race. Indeed, between 2007 and 2016, the number of patents registered in China increased by 700%, this is versus the rise of 19% in the US, 22% in France, 6% in the UK and 8% in Germany. In this worldwide battle for technological and economic power, we have on one side of the ring the Unites States of America defending their leadership position and on the other side China, who is working hard to pass from the image of the imitator to acquire the title of an original innovator; China's president Xi Jinping's 'Chinese Dream' has set China's objective to be a world-class innovator by 2050. *(Gouilliard, 2018).* This pressing demand for product and process development is an imminent outcome of the elevated need for maintainability, availability, accuracy, reliability, performance and safety with higher benefits and reduced operation and maintenance costs of the assets in question.

It is often believed that investing in high technological solutions in condition monitoring practices goes in the opposite direction with doing so when it comes to proactive measures in the form of preventive maintenance or even reactive procedures such as corrective maintenance. It is true that condition monitoring when applied correctly and carefully might lead in many cases to prevent from unexpected failures and avoid by that extraneous maintenance tasks that will only elevate the total bill eventually. However, maintenance and condition monitoring aren't adverse entities of the industrial institution. Therefore, considering both of them as two parallel paths to achieve the same goal can revolutionize the way that assets are managed today. Hence, it is imperative to comprehend that innovation is greatly needed in both areas. Condition monitoring is already starting today to be improved by the novel intelligent tools allowing for better supervision of the operations and advanced versions of the diagnostic and prognostic tasks. On the other side, maintenance activities are having more trouble to be enhanced and innovated due the expanded clichés believing that maintenance is another burden on production and other operational segments, others go even to the extent of confirming that maintenance is quite the enemy of innovation. This was in a way the opinion of Andrew Russell, Professor and Dean of Arts & Sciences at SUNY Polytechnic Institute in Utica, New York, and his colleague Lee Vinsel, who expressed that "innovation is usually overvalued and that maintenance matters a lot more". *(The AgilityEffect Website, 2019).* This vision isn't always right and maintenance mainly the predictive one has to adopt novel characteristics towards a cleaner and a more efficient discipline; innovation shouldn't be regarded as the enemy but as the supporting friend.

This thesis will consequently clarify how innovation can be the question and the answer to many issues in today's markets. Innovation is definitely a leverage that companies can easily gain if they decide to invest in the right area with the right amount of resources and potential. It is also the eventual key for making asset management attain its excellence and lead to better results.

1.2 Problem definition

Based on the above, this thesis has been chosen to study the subject of innovation in relation to condition monitoring and predictive maintenance in industrial contexts with the aim of discussing the importance of innovation in both of the previously mentioned disciplines. Even if innovation seemed to have sometimes a bad reputation due to the fact that a number of executives had in the past unsuccessful experiences in implementing innovation into their structures, the majority of companies today show an intensive interest in innovative concepts as they lead to a greater growth and more profits. Indeed, Booz & Co 2011 Global Innovation 1000 report have found a clear difference in both revenue (11%) and EBIDTA (22%) growth in favor of the most innovative corporations. According to McKinsey, 80% of executives consider that their current business models are at risk to be disrupted in the near future. Additionally, 84% of executives express that innovation is highly crucial to their growth strategy. The Accenture 2015 US Innovation Survey confirmed as well that 84% of executives regarded their future success to be extremely or very dependent on innovation. *(Nieminen, 2018)*. It is therefore essential to illustrate firstly what current obstacles that condition monitoring and proactive maintenance measures are facing today in any given industrial environment, mainly the ones that are still using traditional and old-fashioned procedures. This will provide the means to comprehend the degree of significance and impact of inventive systems in the progress of supervision and maintenance tasks and how they can allow these activities to reach their full potential in the performance scale. It is also the goal to recognize how these key concepts of innovation, condition monitoring and predictive maintenance are interacting so as to understand better their connections. Moreover, it would be essential to underline how innovation has progressed through various generations and revolutions and most importantly how it is regarded today as a vital business concept.

In order to acquire the right answers for these interrogations, it seems logical to search into the existing inventive systems and approaches and even the ones that are being currently developed or expected to be introduced to the market in the future. For that, this thesis will elaborate the most known and expanded technological solutions for condition monitoring and maintenance for systems and processes. It will as well demonstrate some examples of companies that have chosen to insert these novel tools into their structures to be able to observe in a concrete manner their influence on their operations' performance and effectiveness and in a broader way on society as well. For instance, according to a study established by the PR agency Edelman, 9 in 10 customers agree that innovation needs to impact society and that 69% of these clients expect innovation to actually improve society. *(Claveria, 2019)*. In fact, to see the difference that these new strategies and structures have provoked in the organization in question will enable us to solve multiple questions about the interactions between innovation, monitoring and maintenance and thereupon amass the needed information on the matter.

By establishing such comparisons and studying the relevant examples of innovative systems and companies adopting them, we can further put in place the most suited strategies and approaches to follow by different industrial players all markets to create a revolutionary culture based on innovation and creativity. As there's always a reminder that innovation doesn't always come easy and isn't always successful. According to a study established by Harvard Business School, 95% of the new products fail. *(Claveria, 2019)*. These plans can be regarded as beneficial recommendations to take into account by any given enterprise regardless of its sector and size so that they can succeed in enhancing their assets utilization.

1.3 Scope of work and objectives

The major scope of this thesis is to provide a much clearer insight on how the interactions between innovation, condition monitoring (CM) and predictive maintenance (PdM) have grown during the last decades within the remarkable technological advancements that have occurred in various sectors. Moreover, it aims to emphasize the benefits that can be drawn from the implementation of innovation related to the technological advancements, the fourth industrial revolution (industry 4.0), artificial intelligence, the Internet of Things and digitalization, as a crucial pillar in the industrial culture for the achievement of better outcomes.

The first objective of this thesis will be to describe the state of the condition monitoring and predictive maintenance systems and procedures before the implementation of inventive programs by describing the challenges they face and how they have developed after their establishment. A general study of the emerging technological trends in relation to condition monitoring and predictive maintenance will be carried out in this thesis in order to acquire a wide-ranging vision on the current innovative methods and approaches in industrial institutions.

This project focuses as well on highlighting the necessity of innovative implementations in today's market as the most advantageous solution for obtaining optimal utilization of assets throughout a lifecycle perspective by showing the importance of innovation in predictive maintenance and condition monitoring systems. To further accentuate innovation's value, its impact on the organizational structures and strategies in terms of its advantages connected to the most crucial aspects including cost, quality, reliability, safety and maintainability on the short and long terms will be exhibited in detail.

Another goal is to determine innovation's evolvement through the various industrial revolutions and distinct generations. In order to better comprehend innovation in our established context, it would be essential to show the existing connections and interactions between innovation, condition monitoring and predictive maintenance and how innovation can be perceived as a business concept in today's markets.

Presenting study cases of enterprises that have chosen to invest in new technological solutions or finance start-ups that are doing so will permit to scrutinize closely the progress that has been made in their respective structures. To accomplish so, this project will explain in what ways exactly the developing trends related to the new technical solutions for installing advanced diagnostics and prognostics will yield the opportunity of improved monitoring operations. Furthermore, it will grant the possibility of examining the old maintenance management strategies versus the inventive ones and the types of tools that have been added for maintaining the studied assets. The latter study will allow to perceive the difference that implementation of these systems has made in the overall performance of the relevant companies and the significant rise of their market share after the application of these novel practices. The goal of this description is to reveal the substantial benefits and grasp an idea on how companies can insert innovation into their organization successfully.

Another objective is to open to view a conceptual model on how to implement innovation in the condition monitoring and predictive maintenance tasks by introducing some actionable steps that can be followed by companies of different characteristics to achieve an optimal level of performance. A discussion of the areas that should be the main focus of the organization when putting in place these developments will be provided additionally to their eventual interactions with the organizational and structural policies of the institutions in question. This discourse will ease the way towards understanding the kind of challenges that companies will be experiencing while scoring such huge progress in their asset management and conclude constructive and litigable solutions to overcome the identified obstacles in order to reach improved value making progression through their framework.
The final scope of this thesis will be to perform an evaluation of the work that has been accomplished. Therefore, the targets are to sum up the total findings during this project and the benefits behind the discussions that have been made as well as the challenges that have been faced throughout the advancement of the study. Following that, some recommendations of other topics in relation to the subject of this thesis will be conferred to look into for those who might find it compelling. At last, a brief conclusion will be presented to summarize what has been written in an informative manner.

Thusly, the result of engaging the work on this thesis is not only to show the importance of innovation in today's markets or the ways companies are using it in their businesses, but goes further into starting the conversation about the interactions between innovation, maintenance and monitoring and that companies aren't obliged to make the choice between them any longer but it has been proven today that they can innovate, monitor, maintain and repair all at once and still make the best profits out of it.

1.4 Delimitations

The objective of this thesis is not to display any scientific analytical results but instead create a discussion about the existing and possible connections between innovative technological concepts, monitoring practices and predictive maintenance activities per se. Subsequently, the study will focus more on an overall qualitative reasoning of the introduction of inventive trends in the organizational culture. Thus, it won't present a huge amount of quantitative data or detailed information on the novel technical tools especially those that are currently in a development phase. This limitation of information could be unfolded due to confidentiality and disclosure reasons when it comes to sharing private reports and statistics. However, as clarified heretofore, the point of this study is to knuckle down the methodology of inserting innovation in the industrial practices while figures and technically elaborated designs of novel systems can be replaced by more or less summarized schemes of the programs or devices in question.

It is in the same manner imperative to mention that the firms that will be subject of study, mainly the ones that have been and still are working on testing and adopting new technological solutions in their businesses, will be chosen according to the availability of information concerning their inventive equipment and procedures. These companies will be elected moreover on the basis of the importance of the innovative tools they are utilizing and how this can be employed to establish the improved value making of their relevant assets. In other terms the choice made to suggest these concrete models of innovation wouldn't be related to the market share of the said company, its reputation, its capital, its size or any other publicity purposes. These aspects will be also applied on the presented innovative concepts. It implies that the study will be chiefly illustrating some of the currently most known and expanded technological solutions despite by whom they were invented, introduced into the market or by which entities they are operated.

During the study cases, it will be noticed that inventive condition monitoring activities and novel predictive maintenance tasks won't be continuously equally detailed and that can be explained by the amount of data available on the matter.

1.5 Methodology

This project will be based on the analysis and assessment of information collected from multiple sources primarily from articles, reports, surveys, international standards, newspapers and online publications. These diversified sources have each their own proper ways of treating the subject of innovative condition monitoring and predictive maintenance solutions in industrial contexts, still they have shown themselves extremely useful and succeeded by that to create a complete image that the thesis required. In the part where models and examples of firms; working on inventive systems, are introduced, data has been gathered principally from documents and open-access reports of the institutions in question.

Suitable lecture notes and presentations communicated by lectures at the University of Stavanger or other international faculties as well as similar academic resources have been accordingly brought into play to add a clearer perspective on the eventual connections among different aspects of the studied subject.

Furthermore, the discussion with the thesis supervisor have helped to boost the advancement of the work, to enlighten some undervalued aspects of this project and fulfill thoroughly the section of recommendations towards other relevant and quite interesting topics.

1.6 Structure of the thesis

The most convenient manner to organize this project was considered to break it down into six major parts. These six parts have been divided into fourteen sections where each section was branched into subsections. It was regarded more beneficial for the readers to keep an acceptable number of subsections; not too high nor too restricted in order to obtain a much user friendly table of content and a comfortable organization of the work.

The first part includes the sections associated to the background, the problem definition, scope of work and objectives, delimitations, methodology and the thesis structure.

The second part consists of three sections; the first one cites some definitions of the concepts in question while the second one presents the technological advancements in relation to condition monitoring and predictive maintenance that we are interested in. The third section on the other hand adduces the need of innovation in condition monitoring and predictive maintenance tasks as well as the influence of the introduction of innovation on asset usage and management.

As for the third part, it was divided into three major sections; section four is about the progression and development of innovation throughout the multiple industrial revolutions and generation models. The next section shows in detail the existing connections and interactions between innovation, condition monitoring and predictive maintenance. Subsequently, the following section demonstrates how innovation can be represented as a business concept.

Concerning the fourth part, it contains two sections. Section seven illustrates some of the top current inventive approaches related to condition monitoring and predictive maintenance practices. Latterly, the eighth section will illustrate the technical, financial, organizational and strategic improvements that have been observed after the implementation of the technological innovations in some of the mentioned industrial companies presented as study cases on the seventh section.

Furthermore, the fifth part includes three major sections. Section nine indicates the mistakes that ought to be avoided while implementing industrial innovation. Oppositely, the tenth section demonstrates the actionable steps to adopt when introducing innovative measures in relation to monitoring and maintenance. Both of these sections would be the foundation for the following one in order to construct a general conceptual model on innovation's introduction and establishment in any given industrial context.

Finally, the sixth and last part will comprise three sections. Section twelve will display a detailed discussion on the thesis. Section thirteen will cover the recommendations for related topics and further studies on the matter. A conclusion will be presented in section fourteen in order to sum up the work that has been performed throughout this thesis in a concise manner followed at last by the bibliography.

PART 2: The need for innovation in Condition Monitoring and Predictive Maintenance and its impact on their practices

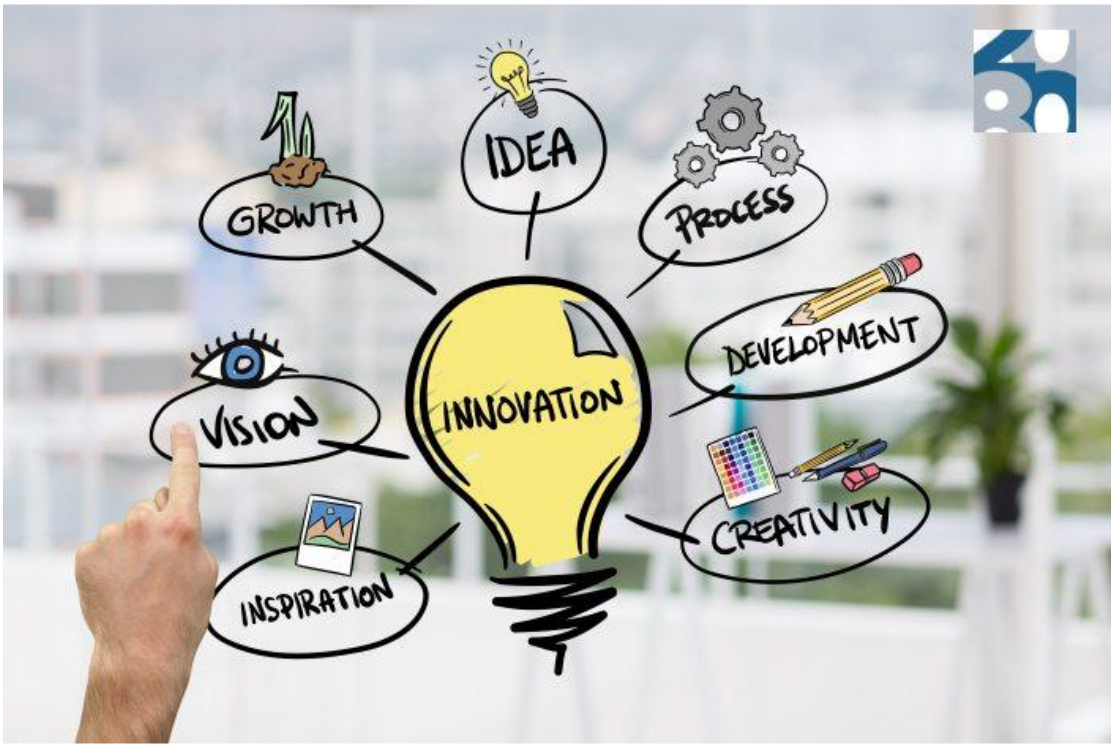


Figure 2: Innovation strategy pillars in industrial organizations (Strategy Ex UK, 2019)

Introduction

This second part of the thesis will present exhaustive definitions of innovation, condition monitoring and predictive maintenance and how these concepts have involved during the past decades into what they are defined today. To achieve so, it appears essential to outline the organizational structures within their internal and external contexts while describing their connections and how exactly they are interacting with the innovative concept to accomplish their operations. This will include detailing the leadership, planning, support, operation, performance management and improvement evaluation concepts within the institution to gain an overall mindset on the role of innovation in the company's framework.
This part will also exhibit the challenges that condition monitoring and predictive maintenance are encountering on a daily basis in any given business and how this affects negatively the quality of its outcomes and the value making of its assets.

The main objective of the sections on this part is to highlight the need for inventive measures in monitoring and maintenance tasks in order for them to optimize their operational

performance. Thus, it comes into sight that it vital to show the recent and current technological developments occurring in the industries and examine their actual feasibility and operability in today's market always within the monitoring and maintenance disciplines.
Based on relevant theory from viable sources, it would be possible eventually to observe how these novel tools can actually solve the issues generated by the old-fashioned systems used in both monitoring and maintenance structures.

This part will likewise establish the impact of creative processes on assets utilization by revealing innovation's influence on condition monitoring and predictive maintenance systems. Subsequently this study will lead us to review the benefits of inventive programs and how they can enhance the safety, quality, operability, maintainability and reliability of the relevant equipment and procedures.

Section 1: Definition of relevant concepts

2.1.1 Definition of innovation

The term of "innovation" can be quite a puzzling buzzword and looking for its definition isn't as easy as it might seem. The search results on Google are far numerous and the articles that transfer the views and ideas of industrial experts or researchers on the matter are even more confusing. And that's because when reviewing their responses, it is expected to find a certain convergence or similarity, while in fact there is a significant difference between their expressed opinions on the definition of "innovation".
Nevertheless, we are going to present some of these definitions in order to acquire a better assessment on the innovation concept.

According to the BusinessDictionary, innovation is "*the process of translating an idea or an invention into a good or a service that creates value or for which the customer will pay*". It implies that for an idea to be called an innovation, it must answer to a precise need and should be replicable at a financial cost. It is supposed to derive from a creative and inspirational context within the intention of applying information and using imagination for coming up with new concepts resulting into new and greater outputs. However, this involves some serious risk-taking mainly by the companies who are creating new markets. Conforming to the same source, there is two major categories of innovation; the evolutionary one that is brought by incremental progresses in technology or and processes. The second kind of innovation is named the revolutionary or discontinued innovation which is often completely new and disruptive. *(BusinessDictionary, 2019).*

Nick Skillicorn, one of the top innovation bloggers and consultants, has gathered fourteen definitions of innovation expressed by his fellow innovation experts. It has been considered convenient to cite five of these responses to illustrate how distinct they can be.
According to David Burkus, a best-selling and an associate professor of management at Oral Roberts University, innovation is "*The application of ideas that are novel and useful. Creativity, the ability to generate novel and useful ideas, is the seed of innovation but unless*

it's applied and scaled it's still just an idea." A second innovation investigator named Stephen Shapiro states that innovation is all about remaining relevant and that firms must adapt themselves to maintain the control over the constant changes of their elements.
On the other hand, another practitioner in the subject, Robert brands, states that defining innovation isn't simple and that it requires a strict strategically alignment by everyone involved in the company to complete optimal results. Drew Boyd, adds on his side a new element to the equation that is surprise, for him, innovation is what makes him hit his forehead and says: "Gee, why didn't I think of that?". Another concept enlightened by Jorge Barba that is the future. This expert believes that it is not innovation if it is not making a better future and a better existence for people. *(Nick Skillicorn, 2016).*
Indeed, each of these figures holds his own vision on the innovation concept according value to some constituents above others. However, it can be agreed on that innovation can't be applicable without the involvement of some key factors.

Therefore and throughout this in-depth analysis, we can affirm at last that innovation should be focusing mainly on bringing the added value to both the organization and the customer with the basic of developing relevant, novel and executable ideas that respond to a need in the market and that better people's lives.

2.1.2 History and development of the innovation concept in industrial contexts

Many of the simplest devices that we enjoy currently employing and that we consider practically impossible to live without have been the result of an idea that turned out into a worldwide used product. With today's breathless eagerness for innovation, it has become harder to recall the days where we heard about this term for the first time.
Benoît Godin, a Canadian historian, has carried out a very pervasive research on the history of innovation and how this concept has developed over the centuries. We will therefore work on naming some of the key stages in this long lasting journey in order to better facilitate the understanding of innovation in the upcoming sections. *(Emma Green, 2013).*

According to Godin, innovation is the last updated version of the old and previously used appellations such as imitation and invention. Innovation has indeed emerged for the first time during the thirteen century to make allusion to newness mainly in contracts renewed and not as a synonym to creation. During the seventeenth century, innovation gained a pejorative doctrinal connotation whereas it was considered as an accusation of heresy and innovators were regarded as sinners worthy of a sentenced life in prison. After several decades, innovation started to get linked to industrial contexts and scientific researches, specifically during the nineteenth century, parallel to the advancing march of the Industrial Revolution. Although during this period, the used jargon was all about invention and chiefly the technical invention instead of innovation. Various elements have contributed to grant invention a prominent position; including the ascent of consumer culture, the rise in patent numbers and the solid support and intensive sponsoring of the government for founding more research laboratories. Following that, the year of 1939 was a shifting period according to Godin where invention switched into innovation with the introduced definition elaborated by the Austrian economist; Joseph Schumpeter. The latter has described invention as the action of intellectual creativity initiated without any consideration accorded to its possible economic import, while innovation occurs when companies discover how to turn inventions into useful and constructive transitions in their business plans. *(Emma Green, 2013).*

Over time, innovation had a new element included in its definition that is the introduction of new technologies into the market. Godin explains this novel transformation in the innovation concept by the fact that governments started investing and financing more the foundation of laboratories and their research operations. At that time, mainly between the 50's and the 80's, innovation was thought of as a process beginning from research actions concluded in laboratories providing initial foundations that when correctly developed leaded to commercialized goods. *(Emma Green, 2013).* The aim of companies back then was to expand their existing business towards new corporate territories or corporate venturing. *(Rita Gunther McGrath, 2012).*

There has been a remarkable transformation for the 80's or 70's primarily when it comes to the primacy of market share. Enterprise leaders are no longer targeting modest shares in their launching plans. Today, they address more venturing, business development and innovation as a greater ambitious and aggressive notion. Industrial institutions do not delimitate themselves to explore new product categories but instead work harder to reach novel business models and to create completely new markets for their inventive products and services. *(Rita Gunther McGrath, 2012).*

The last decades have made these goals relatively possible but further challenging. The introduction of internet for instance has generated some significant impact on the development of the innovative structures of industrial corporations and their profitability. Indeed, it has scored important economic gains primarily from the applications using the internet in multiple fields such as heavy manufacturing, automobiles, textiles and steel. Another greater influence of this huge innovation of the twentieth century is the access to a bigger power to manipulate information and shift the innovation path easily towards more enthusiastic results. *(Emma Green, 2013). (Rita Gunther McGrath, 2012).*

Hence, innovation has come a long way to gain today such a far-reaching and a critical position in the decision making and value making inside industrial contexts. It is as well expected that the innovation concept will acquire even more attention in the upcoming decades as most industrial players have come to the conclusion that wining the competition race is directly associated to how far their inventive programs can go.

2.1.3 Context of the organization with respect to industrial innovation

In order to undertake a more conclusive scrutiny of the implementation of innovative systems into the organization, it resembles pressing to pinpoint the internal and external context of the organization and how they can possibly react and interact with such novel establishment.

The internal context of the institution consists mainly of its perspective, its vision on how the future of its business will be on the long and short terms, its principles, its core values, the objectives it has on various sections of its activities and its overall culture. These factors hold a crucial role when it comes to the decision making of investing in innovative project launchings and putting them in place. The company in question requires therefore availability and a relevant degree of acceptance for these new and relatively risky decisions. In other terms, if the corporation has established ahead a conversation among its stakeholders on the importance of innovation in the accomplishment of their targets and have arrived to a solid alignment on the matter with the organizational culture, it will be much easier to agree on the steps they must follow eventually to achieve so. The expectations and demands of stakeholders will constitute an elementary part of these discussions and a basis for the expected settings of changes. However, a contradiction between the concept of creativity and the applied principles inside the firm in question will only engender more confusion among different departments and disciplines leading to a slower insertion of inventive tools and in certain cases to their total failure causing the organization some serious financial damages. Consequently, it is imperative to be aware of the internal organizational and structural frameworks before adopting any new policies.

The external context, on the other hand, includes principally the business environment, the customer base and the company's owners. This implies that the terms availability and acceptance do not only apply to internal organizational segments but also the external ones. Innovation as defined above responds to a pressing need by offering a valuable solution. The latter definition suggests that to be capable of introducing innovative schemes or programs into the institution, the business environment has to be the one making the call for that. It should additionally be ready to procure a portion of the market for this novel asset or create a new market share for it if required. Indeed, it can only be concluded that innovation isn't a simple concept after all. Furthermore, the customers hold an important part of this discussion. Companies cannot invest or decide to develop any innovative product without elaborating an extensive study on the customer's reaction on such an introduction. It signifies that the customers are to some extent, the ones who decide what they want and what they need. Nevertheless, the owners have their own say when it comes to deciding what the market needs. When the company perceives an opportunity and a willingness of the business environment to take in the inventive system, it may sometimes resolve to finance this innovation launching without necessarily having the authorization of the customers. In fact, we have witnessed multiple technological advancements during the past years that we thought at first we wouldn't primarily need or even want to use in our daily life, but we are surprised today that we can't almost spend a day without.

There are other factors that must as well be taken into consideration when assessing the context of the organization and its interaction with innovation such as social and environmental structures, financial contexts and regulatory requirements. These aspects are not included in the internal or external contexts of the organization but they can be directly and indirectly linked to them as they affect greatly the success of innovation establishment in the organizational surroundings. The financial component is probably one of the first elements to be regarded in this equation. The organization should be able to find the necessary economic support for its expected operations whether it's an independent internal financing or an external one. Besides, the inventive process should fully respect the regulatory, social and environmental standards before adopting any actions.

2.1.4 The key components of the organizational processes in relation to innovation

For a better comprehension of industrial innovation and the factors included in its introduction and implementation, it would be extremely essential to nominate the key elements of the organizational processes in relation to innovation including leadership, planning, support and preparation, organization and operation, performance evaluation and improvement.

2.1.4.1 Leadership

Innovation is used to be considered like long skirts, one day into fashion and the next one out; it becomes popular when it scores high profits but rejected in the opposite case. However, globalization has succeeded to gradually eliminate the barriers that long retained firms from attaining their fullest potentials allowing them to perceive innovation as the new must do in their plans. Indeed, innovation has evolved into a principal driver for value making, growth and performance. And since leaders are the major responsible figures for developing the adequate measures that should be aligned with their internal and external contexts, they are the first ones to implement innovative vision into their organizational schemes. In fact most executives today strongly believe that the only way to accelerate the pace towards positive change goes through seeing beyond traditional and old-fashioned procedures. This implies establishing innovation in business models, value chains, distribution channels, operational processes, monitoring procedures, maintenance practices and even the functions of management. As simple as it might sound, it is actually difficult for a great percentage of leaders to explicitly lead and manage innovation as a part of the organizational culture. Everyone can see how innovation is imperative for progress but a few who succeed to fully integrate it. . *(Barsh Joanna, Davidson Jonathan, M.Capozzi Marla, 2008).*
The response to that is; it’s time to hold senior executives accountable for encouraging and modeling innovative behaviors. Top management must take the necessary steps to achieve a strong introduction of inventive models and attitudes in their respective institutions. To achieve so, leaders should promote creativity and innovation through a culture of trust and openness. They must involve employees into decision making and show them that they are totally allowed to express freely their ideas and to experiment them. This will enable to create a safe and friendly environment allowing workers to come up with novel concepts, to take risks and learn from failures and mistakes. Considerable efforts have to be made in order to obliterate any signs of bureaucratic or fearful working ambiance. It is also imperative to create strong communication means between employees and top management as a well as with customers, suppliers and service providers so as to exhibit the goals and benefits of the inventive programs implementation. Accordingly, executives should be able to adapt to the responses of the various stakeholders and use this feedback as basis a for improvement and adjustment actions. Nonetheless, innovation shouldn’t be only encouraged but entirely

integrated in the organization's strategic-managerial agenda of senior executives. In this way, it will be supervised, tracked and measured as a central component in the firm's aspirations.

It is further important to mention that while looking for external sources for innovation, top management has the responsibility to promote the existing ones within its corporation. In other terms, the success of bringing about new concepts doesn't necessarily imply radical transformations of the internal structures or procedures. It can simply be performed via restricted but carefully placed ameliorations. When discussing changes, it is quite obvious to mention the possible problems that can emerge. As a consequence and when facing these obstacles, top leaders must put in place thoughtful procedures to respond to the eventual conflicts that might occur between the innovative tools and the existing ones.

All the above cited favorable actions wouldn't be truly efficient without the financial metrics and the budget settings as leaders who spend more time elaborating their details have a greater chance to accomplish a successful establishment of innovative concepts. *(Barsh Joanna, Davidson Jonathan, M.Capozzi Marla, 2008).*

The following figure illustrates an innovation planning example which summarizes some of the initiatives that an industrial organization can undertake to implement its inventive strategies.

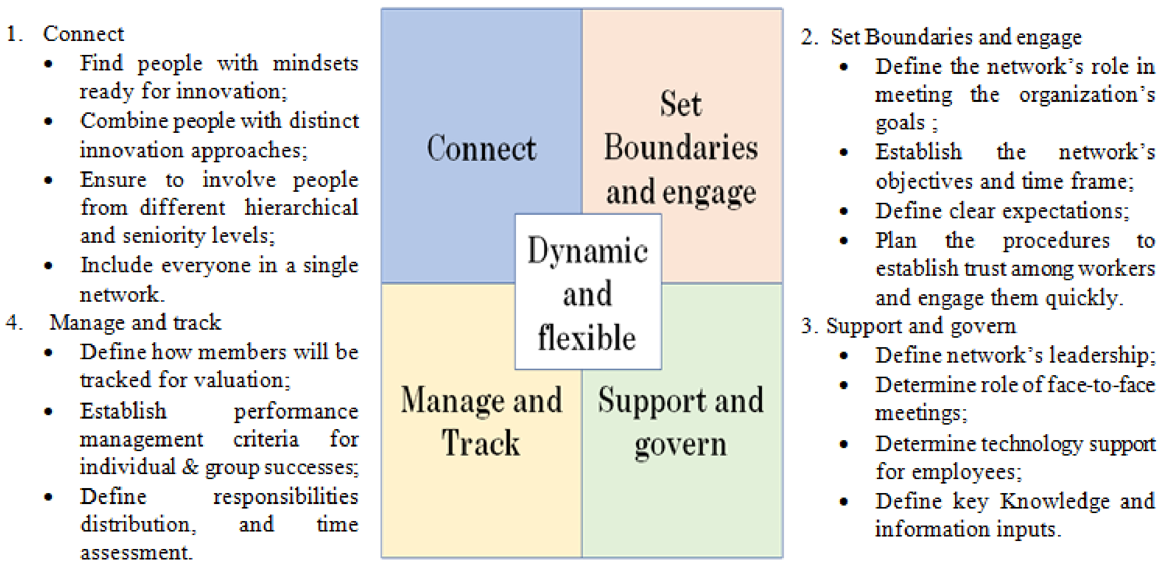


Figure 3: Example of the steps in designing an innovation network (Barsh Joanna, Davidson Jonathan, M.Capozzi Marla, 2008)

2.1.4.2 Planning

The whole point of innovation is the creation of a successful future, no matter how we define successful, and the making of this future an actual reality. Still, innovation's success doesn't crop up all of a sudden; it requires some serious and intensive work. Indeed, it takes a persistent execution of a long process starting from planning going through support and preparation till organization and operation.

When we discuss planning in relation to innovation, we have to mention the fact that this kind of planning is a much detailed and risk-based one. And that's mainly because when we start an innovative project, we have to keep in mind that the results are still unknown to a large extent. There's in fact a higher degree of uncertainty and risks in this case. Consequently, the planning process has to make sure that all expected and unexpected cases must be analyzed thoroughly. Companies who decide to invest, especially the ones who put in place large amounts of financial resources, have to undertake exhaustive quantitative studies on the matter before taking any actions. Usually, it is required to begin above all by setting the primary aims of the organization. These objectives constitute the foundation for the firm's planning activities mainly the innovative developing and launching programs in this case. The industrial institution has to maintain these goals in mind throughout the entire process and remember that any deviation can cause considerable losses in time and economic resources.

A determination of the recommended and existing resources and capabilities is indispensable for the formation of a solid planning of the innovative activities. Subsequently, the firm has to identify the financial and human resources so that if there's a lack in the internal resources, it should look for external financings and new competences or experts who will work on the novel projects. Another vital step on the planning course is to design how exactly inventive organisms are supposed to be inserted in the organizational structures. The resulting arrangements have to be documented as a foundation for the actions that will assigned to specific parties. These tasks will be prioritized according to their importance defined by the relevant stakeholders. The planning will additionally include behavioral and financial settings and metrics related to the projects in question. Accordingly, detailed and measurable studies on the expected impact of the introduction of inventive systems must be established. This will require conclusive examination on the market's state, the customer's thoughts and other variables related to the business environment. It appears to be pressing as well to organize timelines on the advancements of the explained above actions. Addition to these steps, the institution should track the progress of the entire planning tasks and establish quantitative measures and evaluation procedures on their development according to some of the major criteria including quality, reliability, efficiency, effectiveness, operability, maintainability and safety. Such measures will allow head employees to have an idea on the overall expected performance and gain a better understanding on the possible forthcoming investments to finance other innovative programs. Since the risks taken in the implementation of novel procedures are higher than the usual, planning should focus furthermore on creating solid and all-inclusive protocols for possible emerging issues and unexpected or unwanted events. Installing similar plans will aid the company on getting a better view on the market they wish to enter or create and have in place the adequate responding plans in case of an emergency.

Although with all these carefully planned steps and great efforts to score a high rate of success on the innovative plans, it is usually expected to adjust some parts or abandon some or add others. However, if these tasks are taken with consideration the amount of improvement and adjustment actions will be less and the possibility of having better outcomes will increase significantly.

2.1.4.3 Support & Preparation

The human and financial support from relevant parties is a central element in any given investment or project development and innovative launching programs are no exception. We can't therefore mention the implementation of inventive tools in an industrial context without explaining its possible interactions with the support systems and how they can impact its progression towards the achievement of the desired targets. Indeed, joint efforts from different workers from all included departments, divisions and disciplines inside the firm must be gathered and emplaced for tracking the formation and advancement as well as the continuous improvement of the inventive concepts. In order to hold an accurate vision on the needed support, data from various operations and their interactions has to be collected in real time and transmitted to the responsible parties on their analysis and diagnostic. As activities evolve, stakeholders must know if there's a lack in support assets or oppositely an excess in their availability. As we have mentioned on the previous subsections, financial support is a must when we talk about starting or inserting a novel business. The quantity of the required resources will escalate gradually as the size of the initiated project grows. In this case, executives have to consider thoroughly how these resources will be granted and consequently managed on the short and long terms. They will have to think as well about the necessary resources to correct procedures and decisions that need to be adjusted chiefly in cases of failures, misjudgments on the behalf of the responsible individuals or any other expected issues. Nevertheless, the financial resources aren't the only ones to take into account, human capabilities and competences constitute a vital segment in the support system. Thereupon, the company has to ensure that, before executing any operational steps, it possesses a concrete outlook on what kind of human resources will be required and how it would be possible to manage them in accordance with the imposed timelines and goals on the planning charts. It is essential to point at the fact that, besides human and economic support, commitment from all involved stakeholders has an influential part in the success of the support system to fulfill its objectives.

The supporting structures are imperative for the progression of the inventive processes and do continuously interact with all the industrial divisions inside the corporation in question. Moreover, they are regarded as the base for the preparation phase and the installation of its organisms. According to the Merriam-Webster Dictionary, preparation is "*the process of making something ready for use or service or of getting ready for some occasion, test, or duty". (Merriam-Webster Dictionary, 2019).* Companies that have chosen to invest their time and money into innovative projects, must assimilate that their preparation is more extensive than any usual program preparation. This implies that the gathered competent human resources have to go through some intensive coursework and all-inclusive training for a starter. In other terms, acquiring the necessary skills doesn't make these workers absolutely ready for any situation. They should be able to fulfill the fullest potential demanded by the firm and respond efficiently to possible undesirable or surprising events. Preparation is where all the actual hard work begins because it allows the company to have a real view on how its innovation concepts will take place in reality. This is why, the stakeholders have to include into their tasks brainstorming meetings for keeping up constantly with the progression of the novel installations and how to react when encountering new problems in relation to any given organizational structure whether internal or external ones.

Evaluation and tracking the progress is a constant figure throughout the entire process. This segment allows the firm to assess the overall interactions between the innovation systems and the existing organisms and eventually have a clearer vision on the presented opportunities. When preparing for such crucial changes, the organization has to keep in mind that it won't face issues only but it can also deal with new opportunities if well managed can be sources of improvement. By having the company's preparation teams work on gaining all these competencies and accordingly enhancing their strategic-management skills, the success rates for inventive implementation will rise significantly.

2.1.4.4 Organization and Operation

Even when all the financial and human resources are collected and well prepared, innovation process won't be efficient and effectively rewarding if it isn't well organized. Creativity and collaborative innovation require making space for the organization phase and the careful installation of its components. Organization in this sense doesn't refer to cleanness but to order and a detailed knowledge of the emplacement and function of each established procedure or system. It signifies that the company has to know exactly when, where and how to use the various materials, equipment, tools, data, research and competences during the inventive courses of action. The formed planning sheets and the preparation programs must as well be arranged according to the imposed schedules and timelines. Responsible employees on organization should maintain precise and strict policies on how to inform relevant stakeholders on changes throughout the procedures of innovation. Flexible communication channels should as well allow a clear transferring of the information between various involved parties. This point might seem simple to put in place for many but it is a fact that a great number of industrial organizations have encountered some serious issues due the wrong organization of the planning and preparation agenda. Therefore, availability and access to the requisite knowledge and mechanisms have to be provided for everyone concerned. As we have previously explained, companies will face several obstacles during the innovation process and losing time and other crucial resources in solving organizational issues shouldn't be one of them. However, as procedures differ from an industrial context to another and evolve greatly with every digital or technological breakthrough, there isn't a unique method in organizing the multiple tasks. Therefore, coming up with an adequate approach is the responsibility of the organizational teams and the executive seniors who will agree on it.

It is quite obvious that the next move to seize is elaborating the operation stage and its structural elements. Indeed, operation functions as the evident new phase resulting from the planning, support, preparation and organization activities within the industrial institution.

The operation process will involve the operational activities that are chiefly related to the setting up of the actual formulated plans and agreed on by the stakeholders while utilizing the financial and human support resources within the organizational frameworks and through respecting the preparing procedures explained all above. This course will contain furthermore the operational demands and standards of the innovative organisms including the functional policies, the technical requirements and the statutory specifications. And since unexpected transformations might occur leading by that to changes in the operational status of the inventive systems in question, the operation process must include as well management plans for any operational mutations. These plans aren't just theoretical ones but have to be implemented ahead of any issue. In addition to these components, it is recommended to develop a risk assessment enlightening the risks surrounding the industrial novel assets. The company should therefore be aware of the risks but also of the opportunities and new possibilities of development. Technological advancements are more likely today to bring about new solutions for the most complicated industrial dilemmas. Thusly, organizations have larger abilities to use these developments in their own benefits. It is essential also for the organization to be knowledgeable of the degree of complexity of the relevant operations and various responsibilities and how this can impact the overall operational performance of the related products or services. When mentioning operations, it is important to remind the types of operations that we are addressing; if these are internal or external ones. Indeed, the level of complexity is expected to rise when dealing outsourced activities. As a consequence, it appears fundamental to have a strong control over the entire groups of operations within the development and introduction of innovative processes.

2.1.4.5 Performance Evaluation

Performance evaluation is considered a central segment in the organizational processes in the industrial contexts. Still, it becomes more complex than the usual when associated to innovation. In fact, when the company enters the market with a novel concept or goes beyond that into creating a completely new market share, it starts to establish as well new properties to assess the overall performance of its processes. These criteria might be the right ones as they may need some intensive adjustments. In both cases, it is a learning process for both the company and the customer. Thus, the evaluation begins by the appraisal of individual performance going through group performance till the assessment of how the assets and their linked activities are managed. This evaluation depends to a large extent on the policies adopted by the company itself, as some firms decide to install strict practices on directing the inventive tools while others offer more freedom to employees to interact freely with these systems. It is true then that the approaches might differ according to the industrial context; nonetheless, the performance evaluation must remain constant throughout the whole implementation process. In addition to that, the continuous evaluation of the procedures and processes ought to be planned in advance and performed with respect to the demanded timelines and imposed standards in case of their existence especially when we deal with purely technical inventive installations. All the previously explained organizational phases and their segments including the planning, support, preparation, organization and operation must be involved in the performance evaluation. We have already clarified that during each stage, there's necessarily an evaluation of the process in question as it progresses, still, an overall assessment is required when all the phases are accomplished.

The ingredients for a good performance evaluation are: an exhaustive collection of pertinent data, a complete tracking on the history of variables, the transformation of data into valuable and comprehensive information and a detailed analysis of the output. If all these key factors are taken into account, the performance evaluation will be more accurate and thus provide more accurate results. When executing this evaluation, the responsible figures must agree on the criteria on which their study will be based as well as the weight of each characteristic. They should moreover be capable of identifying the aspects that could lead the innovative mechanisms reach their goals within the organization and which drivers will oppositely hold them for doing so. While taking all these elements into consideration, it is crucial to recall that point of this entire evaluation is to be able to assess the outcome and how it can be used in the decision making processes. If the company has for instance a wrong output, this will jeopardize the quality of decisions made by stakeholders. Therefore, a very careful evaluation of the output's performance ought to be executed to avoid any pejorative consequences. To achieve so, the company has to elaborate intensive revisions for the entire operational, organizational and preparation plans as well as their interconnections within the novel programs.

Performance evaluation will be more effective if a review of the objectives is performed and reexamine by that if they are truly aligned with the organizational culture and structure in order to ward off any possible conflicts or issues.

2.1.4.6 Improvement

The aforementioned performance evaluation results on possible opportunities and obstacles will constitute the foundation for eventual improvement and development processes. It is absolutely typical for the organization to require improvement procedures when significant changes have been made into its structures. No matter how the company invests in the excellence of its operational and organizational strategies, there will be a continuous need for adjustments and alterations on many segments of the innovation processes. Adding to that, the constant technological advancements that can be extremely helpful to the improvement mechanisms but also challenging in terms of keeping up with the increased level of creativity. Consequently, improvement must take part in every single division in the industrial context. This signifies that revision courses shall include all the assets, procedures, equipment, systems, and processes that are involved in the innovative implementation schemes. However, prior to any establishment, improvement will have to target the risk assessment and control activities in order to avoid any conflicts between the novel organisms and the existing ones and erase all ultimate nonconformities. To accomplish so, it would be preferable for the company to diversify its competencies and hire outsourced parties such as external audits and consultants to undertake management reviews on the related operations. Getting similar support will endorse the organizational capabilities on holding a better perspective on its actual status and the actual threats and opportunities presented.

When dealing with innovation and its relation to the improvement practices, the company should continuously make sure that the executed changes will be aligned with its objectives, its vision and it core values to bring more profitable aspects to the inventive processes.

Improvement actions form a long and continuous process that needs to add gradually some additional revisions and investigations as the complexity of the systems escalates. This can be observed closely in case of emergency situations where regular responses aren't sufficient most of the times to identify the real sources of occurred incidents. In this case, stakeholders ought to take into account the probability of having possible faulty inputs or inadequate procedures in their innovative plans to eventually the roots behind these unwanted circumstances.

2.1.5 Definition of Condition Monitoring and its benefits

When it comes to industrial contexts, knowledge is power, data is benefit and the ability to use this information carefully, in order to determine the machinery operational state and identify the existing problems and even predict the potential ones, is beyond crucial. Like any other discussion on condition monitoring, it is imperative to start above all by defining the significance of the term.

Condition monitoring (CM) is considered as one of the most innovative methods through which firms can save considerable economic resources. It can be defined as a group of techniques or an established process that determines the condition of certain parameters of equipment while in operation. It includes the application of particular hardware, software or the combination of both to collect and report data about the status and performance of the relevant machines. The technologies employed in condition monitoring concentrate on the areas in which multiple categories of failures are most likely to happen, conceiving a clearer vision on the equipment's state of health and productivity level. *(Proaxion Official Website, 2019)*. Condition Monitoring involves therefore all the automated and manual activities associated to gathering data about the technical state of equipment. Such operations can be inspections at precise intervals or continuous or semi-continuous monitoring and collection of data. It can as well comprise the application of remote analysis or special equipment. *(The international Organization for Standardization, 2003)*.

An amalgam of technical approaches can be executed so as to acquire the required knowledge on the physical situation of the equipment. It is indispensable subsequently to be capable of choosing the right tools and methods to monitor the exact characteristics that need to be supervised in order to maximize the output's accuracy. Moreover, the company must elect the adequate personnel for the gathering and assessment of data. The workers ought to hold the necessary expertise to interpret correctly the results and know what decisions need to be made when it comes to elaborate the mandatory maintenance plans upon any upcoming or existing failures. Hence, condition monitoring seems to be vital to the health, productivity and effectiveness of the machinery as well as to the overall organizational performance.

It can be easily agreed on that condition monitoring has multiple benefits urging organizations to implement its strategies. Indeed, a reliable gathering of data and its definite diagnostic do not only provide rigorous identification of problems with the equipment in question and their components but moreover helps to streamline activities and significantly reduce the costs. In fact, the major advantage of CM is cutting the costs especially the maintenance related ones. Operating machines and fixing them until they fail has appeared to be a very expensive approach mainly on the long run in terms of lost outcome and equipment destruction in addition to the threats on the personnel's safety. Consequently, leading maintenance tasks in given intervals seems to be the obvious solution to the engendered issues. Nonetheless, the only variable that requires intense attention is how we shall determine precisely these timelines. Here where interferes condition monitoring to present the collected data with their assessment in order to facilitate the maintenance activities and the establishment of their exact schedules. Furthermore, several equipment failures are due to hidden internal faults that are practically impossible to track without condition monitoring techniques. *(Sensor-Works Website, 2018).*

Deficient equipment and damaged components will have negative impact on the organization's productivity reducing by that the profit margins and creating severe effects on delivery schedules and agreements with customers. Thus, condition monitoring permits to solve these difficulties by allowing maximizing the production output, meeting the imposed deadlines and diminishing machinery downtimes. On the other hand, fine machinery and great quality parts are made to last longer than casual equipment, and CM can actually expand the lifespan of the machines and longevity of their components. This will engender again a remarkable boost in the overall performance and an elimination of additional costs. Besides, with the relevant data that is being collected and assessed, real time information on the industrial systems and the needed maintenance tasks will be continuously provided according to their priority. On that account, these updates can resume a lot of work that can be done in shorter schedules and with less human and financial resources conceding by these terms the organization to improve the value making of their decisions when it comes to purchasing new equipment or extending its contracts with the suppliers and the original manufacturers. We must though remember that condition monitoring is only the foundation for predicting and describing the possible and actual failures so managers must take action based on the resulting outputs to avoid downtime and enhance the availability and operability of the machinery. *(Sensor-Works Website, 2018).*

However, CM tools can't be valuable if they aren't updated constantly with the needs of the market and the current technological advancements. Innovation seems again the key to the imposed dilemma.

2.1.6 The history and development of CM

Condition Monitoring has been utilized for a long time chiefly by organizations with strong capitals and high risks in order to conserve their investments. This concept has known considerable transformations over the years due to developments in digital tools and computerizations offering broader capacities for sophisticated facilities. Therefore, condition monitoring is starting today to be used on a larger extent. However, this hasn't been always the case principally with industrial corporations operating with numerous pieces of machinery. According to maintenance resources, the history of condition monitoring development can be divided into three main generations going from the 30's to the 80's until the current times. During the first era of evolution, mostly during the 30's and 40's, the majority of the machinery of industrial factories was actually quite basic and there was little focus to none on downtimes. The related systems were also less complex so the reparation of their failures was relatively easy and performed in short notice in comparison with the case in today's institutions. Nevertheless, as the number of operations started to escalate, there was a need for more machines making their interactions with the surrounding environment more

complicated. This was the second generation throughout the 50's till the 70's. During this period, executives and managers began comprehending that condition monitoring should be one of the first priorities where the focus must be on as a direct way to decrease downtimes and enhance maintenance tasks. Then finally comes the last generation starting from the 80's until today. Condition monitoring during this period has attracted more attention principally in terms of machinery reliability and availability as organizations got larger and more complex with time. In fact, a simple deficiency today in a certain system, especially the mechanisms that are interacting the most with others, will have a strong impact on the overall functionality, operation and performance of the organisms. *(Scanimetrics Website, 2019).*
The importance of CM has been accentuated through the breathless enthusiasm of the technological community in creating new systems and practices elaborated for equipment condition measurement. From mechanical tools that can catch a simple, low frequency active waveform to highly developed digital instruments including vibration analysis, meticulous fluid chemistry and debris analysis, lubricant analysis, motor current and circuit testing, ultrasonic and acoustic digital tools; the alteration has been beyond astonishing. Accordingly, advancements in electronics and signal processing have concluded to exceptional improvements in machinery diagnostic technology. Indeed, with the current transportable data collectors, it is almost impossible to believe that they acquire a broader functionality and a better performance than a whole truck-load of laboratory instruments. As tools and procedures for data gathering and their assessment have greatly involved, companies have larger abilities to detect the majority of faults in their earliest stages and succeed consequently to limit their impact on production and avoid a great deal of failures and their respective maintenance activities. *(John S.Mitchel, 1999).*

Thereupon, the concept of condition monitoring has come a long way from the 30's and 40's. This can only incite us to consider the huge change that can be made if companies invest more in innovative procedures and creative minds and the greater future that awaits condition monitoring in the next upcoming years. *(John S.Mitchel, 1999).*

2.1.7 Condition Monitoring Methods and Techniques

2.1.7.1 Condition Monitoring Methods

During the late 70's, two major approaches used for condition monitoring were defined which are trend monitoring and condition checking. Trend monitoring is defined as the continuous or regular measurement, interpretation and analysis of data, gathered during machine operation, to determine alterations in the condition of the equipment and its constituents, in the interests of safe operational and economic performance. This includes the election of the most adequate and quantifiable indications on the status of the machinery and its components deterioration through the detection of the changes in the machinery and the defects in its elements (structural components, fixed joints, moving joints…), and the study of the trend in this calculation with running time to identify when degradation is surpassing a critical point. One of the principal advantages of using trend monitoring is indicating a lead time which is a certain amount of time given before deterioration leads to an exact degree where the equipment must shut down. This positive property is considered better than adopting other casual or traditional methods such as simple alarms or automatic shut down devices. *(M.J Neale, B.J Woodley, 1978).*

Condition checking, on the other side, is where a check measurement is performed while the equipment is operating using a suited indicator and this then chosen as measure for the machine status at that interval. For this kind of condition monitoring to be efficient, the measurement has to be precise and calculable with the determination of certain values that shouldn't be exceeded for a limited and permitted running hours. Identifying these values necessitates extended time a thorough collection of data a considerable amount of recorded history of the equipment in question. This will reduce the level of flexibility of condition checking in contrast to trend monitoring. However this type is regarded to be more favorable when it comes to carrying out a comparison between a given machine and others. In other terms, the company for example can implement comparative checking to analyze the differences and similarities between an operating machine that is being monitored and analogous machines that are considered to be in new or in a great condition.

These trends allow therefore the company to have better machine knowledge (condition checking) and acquire lead time values for the operating equipment (trend monitoring). The following table illustrates in detail an established comparison between condition checking and trend monitoring. *(M.J Neale, B.J Woodley, 1978).*

	Trend Monitoring	Condition Checking
Timing of Measurements	Readings performed at regular time intervals while the equipment is operating.	Readings performed at one time while the equipment is operating.
Qualitative Measurements	Skilled operators can perform subjective trend monitoring if they are close to the relevant equipment.	Regular activity when an engineer in checking on the running equipment.
Quantitative measurements	The collection of regular measurements and their recording and analysis allows the identification of the lead time on equipment problems.	The resulting values are the foundation for comparative studies with established standards or with other similar machines to offer knowledge of machine condition.

Table 1: A comparison between the methods of Condition Monitoring (Trend Monitoring and Condition checking). (M.J Neale, B.J Woodley, 1978).

2.1.7.2 Condition Monitoring Techniques

We aforementioned on the subsection 2.1.6 some of the examples of current condition monitoring techniques used nowadays in industrial contexts. These techniques will be explained more in detail in this part.

The majority of condition monitoring instruments is hardware in essence. These devices can be placed inside, under or nearby the machine or linked to one of its components depending on the kind and amount of data that needs to be collected. For many years, condition monitoring relied on the capacity of personnel, whether they are internal experts or outsourced consultants, to assess the collected information and report results on the condition of the monitored machinery. This analysis wasn't undertaken in real time, although the enhancement in plant performance for critical equipment could still advocate the time and expense for manual condition monitoring. However, recently, various condition monitoring devices have started to be supplied to industrial organizations with accompanying software constituents. The said components have usually the function to collect the relevant data that has been collected into one area and display it in a scheme that it much simpler to review and interpret. Condition monitoring software may as well be utilized to conceive averages and trends, additionally to present the measured ideal data in contrast to the actual observed one. This will permit eventually to predict in a much precise manner the future performance of the equipment and its possible failures, and to install the plans for the required maintenance tasks according to their priority with their respective schedules and time intervals. *(Proaxion Official Website, 2019).*

- *Vibration Monitoring*

Vibration is seemingly the most popular and widely used condition monitoring technique. This can be explained by the fact that this approach is extremely flexible as all machines encounter practically some level of vibration at a certain point making by that this kind a suitable choice for firms with larger numbers of equipment to monitor and maintain. Generally, a vibration monitoring instrument is joined in some manner to the covering or outer part of the equipment. As rotating or alternatively moving components within the machine execute their functions, the casing experiments common vibrations which are gathered, registered and catalogued by the monitoring hardware, normally via accelerometer technology. Numerous problems can actually engender deviations in the vibration pattern, other than lessening or shutting down the moving elements, such as bearings rubbing against each other in an odd way, misalignments and any other internal imbalances. Thusly, an alteration in vibration will happen before a complete breakdown of the part which permits to establish repair or maintenance activities ahead of a total shutdown of the equipment or the relevant process. In other terms, vibration monitoring devices allow companies to detect problems in most cases so as the deficient part or machine can be successfully put in repair without causing long downtime or any at all. Additionally, vibration monitoring tools are mostly utilized because they concede to save a lot of time by indicating faster and easily where exactly the problem is occurring and determining the origin of the failure and by that excluding any additional unneeded troubleshooting sessions performed by highly skilled but also expensive experts and operators. It is crucial to add that vibration monitoring is one of the top recommended techniques chiefly when dealing with rotating parts like pumps, motors engines, fans, and blowers. It appears to be as well the most suited approach for discovering misalignments of gearboxes and other kinds of bearings such as the pillow-box or rolling-element varieties. . *(Proaxion Official Website, 2019).*

- *Sonic and Ultrasonic Monitoring*

If unusual vibrations are number one evidence on a possible existence of a deficiency or a failure, then unusual sounds are definitely number two. Indeed, worn, damaged, misaligned, broken or any other abnormal operating machines or parts can induce some strange sounds. These sounds differ depending on the material, surrounding environment, the machine's status, its lifespan and other factors. They are typically described as screeching, cracking, creaking, grinding and other sounds. Before the invention of any mechanical tools that could gauge acoustic vibration, experienced operators in manufacturing chiefly used to fulfill this job by telling if a machine was probable to know failure only by the presence or lack of sound. Currently, the market presents sonic condition monitoring instruments that are capable of detecting and measuring these sounds and subsequently produce an alarm informing if the machine needs any inspection or maintenance. Since an unusual sound doesn't automatically identify which part or section of the machine is facing the problem, in multiple cases sonic monitoring is executed along with above explained vibration monitoring in order to accomplish more accurate outputs. Nonetheless, not every sound caused by a deficient part of the machine can be caught by the human ear. As a consequence, another type of condition monitoring has started to become more popular during the last years, which is ultrasonic monitoring. Ultrasonic devices share with the prior mentioned sonic tools the fact that they can detect odd sounds made by equipment and that might be a reference to a certain number of defects. Still unlike their sonic counterparts, these ultrasonic instruments focus principally on sounds that are too high-pitched or too high-frequency for operators or engineers to hear. The signals supervised by an ultrasonic instrument are designated as data using the unit decibels per microvolt (DBuV). Considering, ultrasonic condition monitoring devices concentrate on sonic and electrical signals coming from the machines, they are able of determining not only mechanical failures but electrical ones as well. It is therefore imperative to affirm that ultrasonic condition monitoring is a highly precise technique when it comes to indicating and detecting the exact location of potential deficiencies in a short period of time. Failures that could be detected by ultrasonic condition monitoring involve rubbing or excess generated by worn-down bearings, part speeds which can be too slow or too high and strange electrical diffused frequencies. (*Proaxion Official Website, 2019).*

- *Quality Monitoring and Lubricating Oil Analysis*

Most types of machinery use various kinds of lubricating oil in order to maintain their devices moving smoothly without any harsh rubbing between them or any sort of influence between relatively small or delicate parts. The used oils ought to be examined closely due to high risk

of defect; they are indeed an excellent indicator of the overall health status of the machinery in question. This is why, instruments have been developed to evaluate the constituents and the composition of lubrication oils and hand over detailed information mainly through software.
Recently, companies have been exploiting multiple oil analysis devices accessible for use as various approaches have been created that appear to be efficient in indicating the health of the oil. We can mention for instance the scanning electron microscope which can be utilized in order to take images of oil samples and therefore offer close-up views of hanging debris or particles. In addition to that, spectrographic oil analysis is regarded as one of the most used tools. It determines the chemical structure of the oil at distinct time intervals during the monitoring cycle and produces alarms when uncommonly high amounts of certain components or metal are present. Another device is the wear debris detection sensor which uses very much alike means but concentrates chiefly on the detection of metal particles and the related proportions of ferrous and non ferrous metals contained in the oil. (*Proaxion Official Website, 2019).*
Giving the above details, it can be concluded that all these instruments share the common focus on debris and particles. This can be explained by the fact that specific categories of unusual particles found in the lubricating oil can lead to the direct identification of potential failures and by that gain a conclusive idea on the machinery's health state. Hence, it would be beneficial to detail some of the most common found fragments:

- Dirt, dust or grit can imply that the equipment has become dirty and needs a meticulous cleaning and the replacement of the lubricating oil. These particles can be furthermore the indication of larger problems, such as a crack or a break in the machine covering leading to the access to harmful fragments from the enclosing environment. Significantly high amounts of dirt and dust can even be the sign of the failure of other equipment like for instance the cleaning or the used vacuums in the operating block in question.

- The existence of metals can indicate that some components of the machine are starting to wear down. We can mention some examples of these metals like aluminum, iron, chrome or others. As the relevant parts such as gears, cylinders and bearings, begin to rub against each other and gradually deteriorate, they will eventually diffuse these particles into the lubricant oil. By assessing which kinds of particles are present and what are their respective concentrations, quality monitoring tools can define precisely the failing constituents of the machinery and the type of deficiency that is occurring or expected to occur. (*Proaxion Official Website, 2019).*

It is recommended therefore to frequently clean or/and restitute the lubricant oil to make sure that it remains healthy and continues to carry out its intended function. Still, it would more beneficial for firms to consider installing quality and lubricant oil analysis devices that can actually provide the necessary and detailed data on the machinery's health and eventually predict the potential failures prior their occurrence. (*Proaxion Official Website, 2019).*

- *Thermographic (Temperature) Monitoring*

We cannot discuss condition monitoring techniques without mentioning one of the most popular existing approaches that is thermographic monitoring. In fact, machinery parts have usually the tendency to exhale unusual heat especially when they are deteriorating. Heat can also be an alarming indication that too much friction is happening which can be a manifestation of misalignments or components rubbing against each other while they aren't supposed to do so. Thermographic condition monitoring tools measure the changes in temperature across the surface of the equipment in order to identify locations in which uncommon proportions of heat can be transmitted. These instruments are generally highly hypersensitive and able of detecting any small variations or irregularities. Most of the said devices use thermal imaging, as a basic method for detection, which is the registration of a series of images of the machine's temperature landscape. Some other tools use infrared technology. Since temperature based tools can be extremely efficient at detecting defects especially related to rotating parts, they can actually be combined with vibration monitoring hardware primarily on large machines operating with several small and interconnected components. (*Proaxion Official Website, 2019).*

- *Current and Voltage Monitoring*

As most of the aforementioned tools are mainly employed to detect mechanical failures, additional hardware has been developed in order to identify the electrical deficiencies instead. These devices measure principally electrical currents running through the operating equipment and test for unconventional voltages. Current and voltage instruments may detect imbalances in the electrical supply, such as the cases where machinery is receiving extremely low or significantly high amounts of electricity to function properly, or if something has interrupted the flow of electricity or broken or disturbed any circuits. Such devices will permit the equipment to be fixed prior any power outrages or possibly critical defects, like sparking or fire engendered by an excess of electricity for instance. Some current monitoring tools are able as well to identify some categories of mechanical failures, such as unbalanced rotors or rotating elements moving too slowly or too quickly. Recently, a common trend among manufacturers of current monitoring instruments is the usage of model based voltage and current systems, which are thought to be efficient when it comes to determining all three of potential deficiency: mechanical, electrical and operational. The current and voltage monitoring devices compile therefore data so as to measure the perfect performance of a machine's electrical parts and/or power supply, and compare these totals to the actual respective performances to achieve a full detection of areas within the machinery that can start to degrade. (*Proaxion Official Website, 2019).*

- *Other Types of Condition Monitoring*

We have described all above multiple types of condition monitoring devices that are regarded as the most popular and broadly used ones among a vast variety of tools available for usage. Basically every parameter, characteristic or quality of a machine can be supervised, controlled and measured and will eventually lead to the establishment of a conclusion on its health state and actual performance. Thusly, it’s practically impossible to cite every single condition monitoring tool that is being currently developed, manufactured or used. Nevertheless, we can still name some other known monitoring methods. We can discuss for instance the speed sensors. This type of instruments calculate the speed of rotating parts or other moving elements of the related machine so that it would be possible to notice automatically when it begins to speed up or slow down in an unusual manner revealing by that an existing failure or upcoming one. Moreover, it would be essential to mention the pressure sensors that are considered as useful for equipment that mostly operate on combustion or flowing or pressurized fluids in their usual running cycles. An imbalance in pressure, mainly when it’s too high, can cause some disastrous failures such explosions. This is why it seems a priority to be capable of detecting such faults or problems prior their occurrence. It shouldn’t be neglected either the importance of motor monitoring or motor current signature analysis (MCSA) device. The latter focuses chiefly on the extended range of approaches in which motor s can fail, as the deficiency of a motor usually induces an overall failure of the entire machine. (*Proaxion Official Website, 2019).*

2.1.8 Problems and Challenges facing Condition Monitoring

In the previous subsections, we have demonstrated in detail how condition monitoring appears to be extremely crucial in the operating activities and maintenance tasks in any given industrial context. We have shown as well how monitoring techniques have involved during the past decades to be capable of providing today highly developed methods described in detail on 2.1.7. Therefore, in a large number of organizations, an intensive attention is placed on the utilization of technologies and the amount of economic savings affiliated to the development and implementation of approaches allowing the prevention of unexpected outage or even disastrous failures. However, the concept of condition monitoring still has a long way ahead to achieve high levels of performance and operational excellence. To accomplish so, companies must be capable of overcoming all the challenges facing the establishment of condition monitoring tools and techniques. These various obstacles can be linked to many factors whether technical or managerial. The focus on this subsection will be on general challenges and not associated to a specific technique per se.

2.1.8.1 Technical challenges

One principal technical obstacle in condition monitoring is the extreme difficulty to address the root causes when it comes to failures. In fact, in various cases, even the physical problem has been determined; the emerging actions do not focus directly on the source of the problem. In other terms, companies should become more proactive in order to identify the true essence of the fault and not just its manifestations and engage consequently the necessary and adequate solutions. Hence, condition monitoring techniques are only beneficial when they are used properly and taken to the next level in terms of searching the root causes and if there are similar cases to the studied failure in other plants. In addition to that, it appears to be complicated for endoscopes or condition monitoring tools, mainly the vibration based ones used in large machinery rotating at high speeds, to indicate at short notice any failures such as cracks in bearings or other and that result into catastrophic damages. Therefore, companies under these circumstances, choose the process of dismantling machines at given intervals and check their respective parts to establish any replacement when seen fundamental. They consider indeed this option as the only way to make sure that the machine in question is absolutely safe to operate. Nevertheless, stripping equipment during chief servicing can be time consuming, expensive impacting by that the productivity, the profitability, the imposed schedules and the safety of operators and engineers above all. Another challenge presented is the ability of monitoring tools to gather the relevant data. In fact, the utilized instruments allow the collection of huge amounts of data and long streams of historic information making the responsibility of pinpointing and processing only the needed information more complicated. Besides, the mentioned devices have to maintain high levels of security and availability of data. These tasks are far from being easy especially when we are dealing with huge industrial plants that tend to employ considerable supplies of sensors. Thusly, directing all the gathered data from various sensors into a central hub is another resulting hindrance that must be fitly managed. Typically, it is imperative to discuss the importance of sensors in any given monitoring systems. Consequently, sensors have to be carefully selected to take the necessary proxy measurement of the related mechanisms. Obviously, sensors cannot operate without adequately competent power sources. Accordingly, industrial organizations have the obligation to identify which are the most well suited power sources for their used sensors and what can be the best alternative to ensure that the sensor network is robust to the environment conditions. The most broadly exploited power sources for sensors are batteries. Still, they are commonly very expensive and unable to provide power on the long term chiefly in extreme environments and sometimes may even be thought of as dangerous. Therefore, low bandwidth wireless data transmitters are believed to maximize the life of autonomous sensors. Still, when we talk about lower bandwidth and lower power consumption, we have automatically slower operations and measurements update. This constitutes as follows another challenge for companies using such power resources and who adopt similar concepts in their condition monitoring policies. Moreover, the selection of suitable processing algorithms is an aspect to which firms should accord great attention giving the complexity of the undertaken tasks, the availability of power and the price point of the used sensors. It is completely useless to use highly complicated algorithms for more or less simple operations or for relatively low-priced machinery. Yet, managers and executives must keep in mind that establishing new technologies can be rewarding and problematic at once. Put it differently, novel technological organisms can be complex, overpriced and above all arduous to maintain. As systems get more complex, it becomes more difficult for operators and engineers to identify the key parts and their respective failures. This why, companies must think installing new advanced equipment through prior doing so. *(Mark Tuckwell, 2015).* A vital feature of the concept of condition monitoring is the analysis of data that should be properly addressed. It is quite common indeed to encounter further difficulties into finding the necessary human competencies for monitoring and assessing the collected information. Subsequently, industrial companies should be capable of choosing enough experienced equipment specialists and analysts to undertake the required functions as a great number of disastrous outcomes are caused by mistakes in the analysis phases.

Condition monitoring does not fix equipment and doesn’t solve problems or fix failures either. Condition monitoring only points at the problem before it becomes a failure. Generally, when the condition of a machine’s or one of its components is issued to be urgent, the job will have to go to the head of the work order pile and be anticipated for maintenance or repair as soon as possible. The imposed problem in here is that usually the maintenance schedules are already busy. Therefore, in order to perform this high priority task, maintenance teams will have to postpone other jobs on the agenda and their planning and preparation efforts will be wasted. This will imply as well the ordering and unplanned parts which might lead the company to pay an extra price for getting a fast last-minute delivery. In other words, condition monitoring in this case sets a trap for us that is executing pressing work to correct failures by suspending failure-preventing activities. In some cases, the company might not acquire the needed internal resources to undertake the said urgent job. It decides then to subcontract it out. This will lead to a significant increase in the costs relevant to the expected tasks as outsourcing an activity is more expensive than doing it in-house. Also, the work becomes more logistically complex due to all the additional preparation and authorization required to bring external experts and operators into site to take on the job .Furthermore, the application of condition monitoring techniques might breed another challenge for the related organization that is the determination of exact points in the timeline where the company should perform replacements of wearing parts. Typically, when there’s a large variability in the wear or deterioration rate and especially when inspection periods are quite long, then CM is expected to offer flawed predictions and a false sense of security in the given numbers. Additionally, the industrial corporation has to be extremely careful when setting alarms to indicate serious problems that require urgent responses. If this isn’t the case, the company might end up with thousands of alarming points per day which might engender unneeded inspection tasks and huge losses in time and cost. *(Francois Gagnon, 2013).*

2.1.8.2 Managerial challenges

It has been above mentioned various technical challenges that companies might experience when implementing condition monitoring approaches. Though, they might as well meet managerial issues when doing so. Indeed, management has an enormous responsibility for guarantying that an industrial plant is in line with particular operational, maintenance, performance, safety, financial and competitive goals. Unfortunately, management teams have been known to make multiple mistakes when it comes to installing condition monitoring devices and programs. One the most common errors is bad planning; what is not well planned can never be well implemented. Since planning is an essential phase of any process, the simplest indiscretion in one of the constituents including the funding requirements, the standards or the database implementation or others, can lead to severe drawbacks. One of the biggest problems in putting in place CM is not allocating enough time or resources for training such as increasing the skills, capabilities and knowledge of the workers. Training is a continuous process when executed properly can lead to astonishing advancements including improvement in the work quality, increase of the productivity, limitation of mistakes and the enhancement of the creativity and the mental health of employees. Still, training costs are the first to be eliminated when the company's budgets are narrowed. The real mistake in this situation that most companies make is the fact that they are absolutely willing to invest in the implementation and funding of a new technology or updating an existing one, but choose to no do the same thing when it comes to training workers about the technology's use and interpretation of the results. Lack of training is without a doubt of the primary causes of CM systems failures. For this reason, it appears fundamental to include training in the funding of any CM mechanism. There are two principal categories of training to take into consideration and that are equally crucial to the success of a CM program; technology training and analytical training. Technology training involves how to utilize the hardware and software that gathers the data to be assessed. Most firms make the error to assume that if personnel have been using a similar CM technology then there's no need for training them to exploit the new inserted one. This understanding should be absolutely corrected because different methodologies can be applied to the same CM technology, it is therefore imperative for workers to know exactly to use the CM tools and programs in order to get the best possible outcomes. The second type of training that is the analytical training means to learn how to interpret the resulting data that has been collected from CM instruments and sensors. Without this kind of training, little to no value will be drawn out of the used technology because no one would be capable of understanding it or making sense out of it. Managers seem in many cases to find a difficulty is picking the right technology or technologies to establish in CM activities. Most of them rely usually on a single kind of technology or choose to adopt low-tech or low-priced devices that are more likely to generate issues instead of benefits. A suited monitoring program should therefore be based on a variety of adequate technological tools to accurately detect, diagnose and report the machinery condition and failures. A great number of CM programs fail as well for the reason that management won't permit employees to work full time with the CM technologies. This is primarily due to a wrong thinking that managers hold over the workers which makes them believe that employees are only an extra maintenance resource that can be used to repair or maintain the equipment. To assimilate perfectly how to use the software and hardware of the CM technology is not a task that workers can succeed to learn during a part time job. They must fully engage themselves in this learning process. However, when management sees the opposite and since workers cannot undertake two jobs at the same time, they become obliged to concentrate on their daily duties instead of dealing with the CM programs. This way of reasoning contributes unfortunately to the reactive work that CM technology is supposed to avert.

Spreading awareness about CM systems and tools is a crucial point that various firms seem to overlook. This training isn't costly nor time consuming but it could be extremely beneficial on the long run mainly to the overall success of a plant's CM efforts. Indeed, CM experts and reliability engineers generally comprehend the practices and technologies they use on a daily basis. Repair and operations workers and supervisors on the other hand might not always understand these concepts. Furthermore, they might not even be used to observing their colleagues walking around the plant with odd instruments or spending long hours in front of their computers or screens reviewing odd looking information or graphs which can cause distractions. As a consequence, if not everyone involved in the facility is aware of the multiple capabilities and limitations of the employed CM programs, the company will some serious issues in communication among workers that won't be all aligned with the CM principles.

Another managerial issue is directly linked to the established standards. In reality, many organizations do not grasp how essential standards are to the overall condition monitoring organisms. Standards must be identified for the technology selection, including how it is put into use, how outputs are analyzed and reports are produced. Indeed, a lack of crystal clear standards will lead to aimless efforts from all parties involves and disappointing results in response to those efforts. So if an employee is free to act as he/ she wishes, the results might not be in the interest of the firm. The importance of creating standards in the related CM program can also be connected to the fact that similar technologies can be obtained from distinct vendors. Again an absence of the suitable standards to the system in question will introduce different training and implementation needs, integration problems, a shortage of specificity in the demanded abilities, inability to lead constant enhancement and other pejorative effects. As we have explained previously, continuous improvement is a principal objective of any CM program that cannot be achieved if the assessment of data and the reporting of outputs are random and not based on the overall principles and objectives of the company. Some enterprises make the good choice to install the required standards but fail to update them; this is again another managerial error. Standards would be useless if they become obsolete. The organization must establish a process that revises automatically the standards.

We have discussed earlier on the technical challenges of CM, the fact that data can be collected in huge amounts wasting a lot of time and resources. Another challenge is when data isn't collected enough. Hence, failure to gather enough information will cause to miss the detection of equipment failures that would be eventually unseen. In fact, the machinery defects can be the outcome of the action or inaction of the management in various cases. Put differently, the management will usually rely on misguided reasons to indicate the desired data gathering interval for CM systems. Oftentimes, this interval will be based on a random number or even will depend on the amount of time the management will decide to spare in order to collect the required data. It is obvious that information collection intervals shouldn't lean on any of these factors. They must be fixed by the failure rate of certain machinery deficiencies that the CM technology can detect. It is therefore important to recall that data collection intervals differ depending on the machine itself, its common failures and their timeframes. It also crucial to transmit the results to both operation and maintenance teams as soon as possible to take the necessary initiatives and corrective actions in order to remedy to the presented failures in the shortest notice.

Most companies believe that only by implementing CM technology and its instruments, their facilities will become instantly proactive and reliable. Although, CM is a key element of a proactive-management process, this is another common misunderstanding of the CM programs. If the organization's culture endorses repeated inquiries for monitoring of machinery to acquire every last minute of operation or the CM technology's outputs are just ignored then this signifies that the processes are simply becoming reactive. This is usually due to the fact that management isn't assuring that the results of CM devices are being followed accurately or the CM workers aren't accorded enough time to properly monitor the equipment, to analyze the results and report them accordingly. Consequently, employees are

expected to rush out to check why a certain machine is having a specific reaction (sound, vibration…) and would force by that unscheduled equipment downtime. In this case management has brought a reliable and proactive tool that is CM technologies and made it into a reactive instrument.
Failure to properly apply CM technologies in the industrial plant is another mistake made by management. Not every CM technology can be executed in every single machine. A lot of firms spend huge amounts of financial and human resources and time on implementing devices and programs that do not fit their equipment only because they had given good results for other machines in a different facility. This thinking needs to be changed for good and companies must start to assimilate that certain technologies are only favorable for a specific kind of machinery and the fault conditions they experience. To remedy to this situation, it is indispensable to comprehend how the equipment operates in relation to its surrounding environment and how it responds to certain failure conditions in order to choose the best CM technology that will suit the machinery in question and will allow its accurate monitoring and the identification of its potential deficiencies. *(EP Editorial Staff, 2013).*

During this section, we have succeeded to determine some of the most common technical challenges and management mistakes when it comes to the implementation of CM programs and devices. This study will allow us on the upcoming parts to underline the ways in which innovation can help companies to overcome these obstacles.

2.1.9 Definition of Predictive Maintenance and its benefits

Predictive Maintenance (PdM) is a method/ strategy in which the service life of important parts is predicted depending on inspection and diagnosis results in order to use the related components to the limit of their service life. *(Mak John, Mokhatab Saeid, Poe William, 2015).* It focuses then on determining the optimal time to execute maintenance, after a certain condition has started to deteriorate and performance to decline, but before failure occurs. It aims to establish a satisfying medium between preventative maintenance, which utilizes rigorous time-based scheduling and might take place too frequently, and reactive or run-to-failure maintenance, which does not repair equipment until after they have already failed. *(Proaxion Official Website, 2019).* In other terms, predictive maintenance would ideally allow the maintenance frequency to be as low as possible so as to inhibit unplanned reactive maintenance without incurring costs connected to performing excessive preventive maintenance tasks .The goal of predictive maintenance therefore is first to predict when machinery failure may happen and secondly to prevent the occurrence of the deficiency by performing maintenance. Monitoring for future failure permits maintenance to be planned before the failure occurs. *(Fiix Website, 2019).*

Predictive maintenance cannot exist without condition monitoring whether it is periodic, online or remote condition monitoring. Indeed, the central part of PdM is the detection and resolution of failures prior their occurrence through accurate observation of the actual conditions of the equipment. Machinery can fail in multiple manners, from the wear of a component, the environmental degradation, to insufficient electrical power supply. PdM concentrates consequently on observing and gathering information about the equipment performance via CM techniques. In fact, there are several approaches for accomplishing PdM such as infrared testing, acoustic and ultrasonic analysis, vibration analysis, oil analysis and sound level measurements. Predictive maintenance focuses subsequently on assimilating the trends in the data that imply failure might be forthcoming, and scheduling and executing maintenance actions only when it is indispensable yet suitable to do so; in other words, when the condition had deteriorated to a critical state or if certain warning signals had been set off. *(Proaxion Official Website, 2019).* Computerized maintenance management systems, sensors, condition monitoring programs, integrated tools and other data processing and data integration devices are all instruments that are considered crucial parts of the environment surrounding predictive maintenance concept and that are used to achieve its overall goals.

For several years, when we used to talk about maintenance, two main types came to our minds: corrective maintenance and preventative maintenance. The first kind was considered as a positive maintenance which ought to be given high priority while the second type was seen as a burden and should be applied only in case of an emergency. However, today companies are more discussing a third type that is predictive maintenance which used to be undervalued until lately where firms started to notice its advantages. It has become a reliable method because of its high effectiveness in detecting faults at early stages and therefore decreasing downtime and unneeded maintenance costs and other positive aspects that it brings to the industrial plants in question. We will try therefore on this subsection to elaborate in detail the benefits of predictive maintenance.

- **Reduction in Maintenance costs**

PdM is unlike corrective or routine maintenance where is many cases operations are repetitive and therefore more expensive. PdM is also different from preventive maintenance because it is based on the concept that maintenance shouldn't be performed unless the condition of the equipment indicates so. In other quarters, tasks are only performed when needed and in a more engaged manner leading to a significant decrease in the maintenance costs. The relevant maintenance costs include the maintenance labor whether it is an internal or an outsourced one as well as the inventory costs, the costs of the replacement parts, devices and other equipment required to maintain the machinery. The labor costs are indeed reduced because technicians and experts are called precisely for focused jobs and specific tasks. And since orders are only made for what is regarded essential for the maintenance activities, then it won't be necessary to keep any costly parts or materials in inventory. Additionally, only a specific number of critical parts are dealt with eliminating by that all the costs associated to unnecessary replacements.

- **Reduction in machine failures**

Regular monitoring of the machinery conditions and responding to them by the required maintenance tasks will decrease in a considerable way the number of unexpected and cataclysmic failures. A comparison between the rate of unexpected equipment failure before and after the establishment of predictive maintenance programs can show clearly a reduction in the machinery failures with a high percentage that can even exceed 50 percent in many cases. This can be explained by the fact that PdM is able to identify problems at early stages before they escalate and induce more damages to the relevant equipment.

- **Reduction in downtime**

Predictive maintenance allows reducing the actual time demanded to repair or recondition plant equipment. In reality, PdM creates what is called planned downtime which is generally shorter than unplanned or reactive repairs and can be consequently scheduled for specific time intervals that would be adequate for production agendas and less expensive. Also, unexpected failures would less frequent increasing by that the overall machinery performance and improving the entire effectiveness of the industrial facility.

- **Reduction of spare parts stocks**

The ability to pre-indicate deficient components demanding repair, instruments and required labor competencies will provide a remarkable decrease in both repair time and costs. Indeed, instead of purchasing huge quantities of spare parts and stocking them, PdM allows currently industrial companies to have enough time to get hold only of specific numbers of spare parts needed for replacement.

- **Increased service life of parts**

Predictive maintenance allows maximizing equipment lifespan. Predictive maintenance grants as well the possibility of preventing disastrous failures and allows early determination of machinery problems increasing by that the service life of the industrial facility’s machines and their parts. With PdM, dismantling machines occurs as well less frequently expanding again the remaining useful life of the relevant machine that eventually could last longer than expected. PdM reduces also the frequency of repairs and limits to large extent the severity of machine damage. Besides, it prevents the propagation of deficiencies enhancing the actual state of the machinery with or without repair. Another side benefit of implementing PdM is its capability to deduce the mean time between failures (MTBF). This statistic procures the means to indicate the most cost-effective time to replace equipment, rather than constantly absorbing the high maintenance costs. In fact, MTBF of plant equipment is reduced every single time an important repair or reconditioning takes place. Predictive maintenance will cardinally decrease the MTBF over the service life of the machinery. When the MTBF reaches a certain point where maintenance and operation costs surpass the replacement costs, the equipment must be substituted.

- **Increased production**

The establishment of predictive maintenance programs contributes greatly to the increase of the total availability of systems. Indeed, by reducing the loss of production time due to the unplanned downtimes and unexpected failures, the productivity is awaited to rise considerably in the entire industrial plant. A complete predictive organism which involves process parameter monitoring will enhance the operational effectiveness and by that the production of processing and manufacturing facilities.

- **Improved operator safety**

Since any possible problems are detected as soon as they occur before they are developed into severe failures, safety risks for workers are diminished. Predictive maintenance allows therefore the early warning of the most urgent potential deficiencies reducing the risk of having destructive failures. This will improve the overall safety of operators and on site workers and decrease the personal injury and death rates due to professional accidents.

- **Verification of repairs**

Predictive maintenance often uses vibration analysis, which is originally a very popular condition monitoring technique as we explained earlier on subsection 2.1.7.1.1, as a method to examine closely if the repairs executed to the failed machinery have entirely corrected the existing problems and have created additional abnormal conditions before the equipment starts up again. Consequently, there won't be a need for another shutdown that is usually essential for achieving uncompleted or inadequate repairs. Predictive maintenance makes therefore planning for shutdown a much easier and shorter task than it is in preventive maintenance or reactive maintenance and that's mainly because of the use of relevant data that provides the necessary information to schedule for certain repairs or inspection operations.

- **Other profits**

Predictive maintenance goes further as a strategy to search the root causes behind any defect so as to predict accurately future performance trends. Preventive maintenance presumes often that the equipment's performance will degrade and it will be more likely to fail as time goes by. It responds therefore by performing inspection and maintenance actions to prevent from these deficiencies ignoring where they come from. Oppositely, predictive maintenance checks every part of the machine and evaluates critical points where failures are more likely to take place. PdM takes interest not only in what could fail but mostly why and how. Such thorough analysis permits to hold an accurate prediction on the future performance of the related equipment, its efficiency and what are the best ways to plan the maintenance tasks. All the above explained benefits of PdM will allow enhancing the operation of processing and manufacturing plants and reducing the overall operating costs. PdM can as well lead to more and better products in terms of quantity and quality and substantially more satisfied workers and customers. Additionally, predictive maintenance is becoming today a more feasible option for industrial firms and that's essentially because sensors and condition monitoring devices are much more affordable and available than in decades ago. Typically, each company can experience some unique profits depending on their implementation procedures, their assets and their facilities (nature of business, size, plants characteristics…). *(Proaxion Official Website, 2019).(SeeboBlog Website, 2019)(Tobias Schroeder, 2017).*

2.1.10 The history and development of Predictive Maintenance

It is vital for companies to grasp how predictive maintenance has matured over the years so they can determine where their operations currently are and where they are headed.
Predictive maintenance has greatly evolved during the past few decades. Today, it is considered as one of the most reliable types of maintenance providing valuable and adequate solutions to machinery potential problems. Even if the first advancements of predictive maintenance were quite slow and primitive, they are still regarded as extremely crucial as they constitute the base that the pioneers of today have succeeded to build on. Indeed, the most rudimentary measuring of simple waveforms has diverged into a large variety of techniques ranging from the acoustic till the Thermographic.

The origins of predictive maintenance and condition based monitoring have been broadly credited to the British developmental biologist Conrad Hal Waddington who led a team in charge of organizing the maintenance of The Royal Air Force Coastal Command 502 Squadron. Although Waddington had no mechanical knowledge and no expertise in any kind of maintenance or on how to improve equipment availability, his initial observations allowed him to deduce the most surprising conclusion that the rate of deficiency or repair was much higher, in many cases, after an inspection or maintenance session. In fact, prior to the execution of the recommendations, aircraft were inspected based on planned schedules as indicated by the manufacturer. Some of the instructions required disassembling parts of the aircraft so they could be thoroughly verified. One of the most unpredictable findings was according to Waddington "*the rate of failure or repair is highest just after an inspection and thereafter falls, becoming constant after about 40-50 flying hours.*"Therefore, he concluded along with his team mates that the inspection tends to increase breakdowns which can be interpreted by the fact that it is disturbing a satisfactory and valid state of parts. The irony of circumstances was not lost on him, as the planned maintenance schedules which instead of avoiding sudden failures were creating more equipment failures in the process. This phenomenon was termed "the Waddington effect" which was the first step towards the development of the condition based maintenance concept. The presented solution was then to adjust the maintenance process to conform to the physical condition of the equipment and the frequency and the actual patterns of its usage. The economic and probabilistic information was accordingly compiled and assessed. This was the foundation of new reformed inspection cycles and strategies and more importantly it was the revolutionary start of a new era, a new concept; the beginning of predictive maintenance. And the outcomes were astonishing. It took a scientist, not an engineer utilizing observational data and a scientific method to successfully boost the equipment availability by transforming how maintenance was perceived and scheduled. Despite his no experience in the field, C.H. Waddington managed to make the squadron average surpass the previous maximum by 61% and exceed the best average of any other squadron over a similar period by 79%. *(Peter Darragh, 2015). (SensorWorks Website, 2018).*

With the arrival of small scale computing technology such as embedded sensors in valuable machinery, firms began to invest in condition based maintenance. Instead of maintaining machines based on their already planned schedules, this new kind of maintenance observes the condition of the equipment and therefore decides if a maintenance intervention is required. As technology developed further, condition based maintenance became more widely used by industrial plants chiefly in aeronautical engineering and heavy machinery facilities at first until it became employed in the simplest things such as supervising temperature and humidity variations in storage units. In the beginning, condition based maintenance was performed usually by veteran maintenance teams executing principally physical inspections or using old-time and simple technologies to evaluate the relevant condition such as carrying out a casual pressure meter reading. With the automation of the majority of the industrial fields and the broad expansion of computers and sensors which became more affordable and omnipresent, condition based maintenance turned into a machine-led maintenance. In reality, sensors connected to machinery are capable of indicating real-time information to centralized systems allowing maintenance employees taking the necessary maintenance actions before the occurrence of any failures. As a consequence, most companies have already adopted this kind of maintenance or are doing so in order to upgrade their operations performance and to accomplish their set goals. *(Matt Bellias, 2017). (SensorWorks Website, 2018).*

Nevertheless, during the last decades many companies have chosen to take condition based maintenance into the next step: predictive maintenance. With this renewed type of maintenance, gathered data is exploited as the basis for analytical studies undertaken to identify the asset reliability risks that could possibly influence the plant's activities. The use of highly precise and subtly calibrated technological devices has made it possible to predict the future patterns of the machines in questions and the potential breakdowns of their parts. The measuring and analyzing tasks has become today condensed to simple yet powerful and quite complex software and hardware instead of the massive of laboratory and calculating equipment that existed decades ago. Predictive maintenance which was a fictional thought for many industrial mangers is becoming today a reality thanks to the great advancements in terms of the sophisticated electronics and the improved analytic algorithms. Companies with developed processes and high value digital systems are speedily applying predictive maintenance solutions. They are gathering real time data and employing scientific and technical assessments to thoroughly comprehend their assets performance and predict accurately their future status. This is far from being the easy job as technology and industrial equipment are constantly changing and firms need to acquire considerable financial resources and highly trained experts and operators. *(Matt Bellias, 2017).*

Today, predictive maintenance is still changing and a lot of industrials believe that the future is called prescriptive maintenance. It utilizes advanced technologies to make predictions about maintenance but it varies from other kinds of maintenance by the fact that it doesn't only elaborate recommendations but acts on them. Prescriptive maintenance will need that all the asset management organisms and the operational and maintenance mechanisms are finely integrated. This maintenance is situated at the intersection of big data, analytics, machine learning and artificial intelligence. By evolving from time based, to condition based, to predictive and prescriptive maintenance, industrial firms are developing their maintenance systems from being simply effective to becoming completely strategic. *(Matt Bellias, 2017).*

We can consequently conclude that predictive maintenance had known great advancements from the seventies till today times. With the technological and digital progresses that we are constantly witnessing, we can without a single doubt affirm that it still has a long way ahead to improve furthermore its processes and tools. Still, achieving such high standards and objectives is a burdensome task that needs serious commitment from the industrial organization as a whole and a placement of all the required resources.

2.1.11 Predictive Maintenance Approaches

As we clarified on the previous section, predictive maintenance affords industrial organizations the possibility of using less expensive and more effective methods for reducing machinery downtime and enhancing its availability. In a predictive maintenance program, maintenance tasks are planned based on diagnostic models that identify when exactly to execute the needed services. The monitoring of machinery conditions allows data trending in order to predict accurately the future maintenance requirements. Over time, machinery can break down for multiples causes such as mechanical failure. This can take place as a consequence of overheating, load alterations or loose connections. Environmental limitations involving corrosive conditions, intensive dirty and dusty environments and high humidity levels can engender more frequent problems. Other recurrent reasons of unexpected downtime are principally associated to human errors and the incompatibility between human and machines interfaces leading to significant communication issues and by that to large gaps in the operational systems and maintenance activities. Consequently, so as to avert expensive disruptions, the majority of companies nowadays are shifting from preventive and reactive maintenance approaches to predictive maintenance models. The advancements in technological and digital tools and sensors are endorsing this critical transition in multiple industrial contexts. In order to accomplish so, firms are employing three distinct main predictive maintenance approaches that are defined in terms of their sources of data and that are the following: the existing sensor-based approach, the test-sensor-based approach and at last the test-signal-based approach. We will attempt to explain each of these methods on this subsection.

- **The existing sensor-based approach**

This first category regroups maintenance methods that utilize data from existing process sensors including pressure sensors, resistance temperature detectors (RTDs) and thermocouples that measure parameters such as temperature, pressure, level and flow. Put it differently, the outcome of a pressure sensor for instance in an operating facility can be employed not only to determine the pressure but also to control thermal hydraulic effects and diagnose turbulence, standing waves and flow-induced vibration responses. It can furthermore examine the calibration, response time and the dynamic performance of the sensor itself and single out any potential abnormalities in the process like blockages, leaks and voids that might hamper the accuracy of established measurements of process variables or retard the facility's operability, reliability, maintainability or safety.

- **The test-sensor-based approach**

This second category of predictive maintenance is regarded like the first type of predictive maintenance, also named online maintenance, a passive one. Nevertheless, instead of employing existing sensors for its data, it relies on data from test or diagnostic sensors such as accelerometers for measuring vibration and acoustic sensors for indentifying leaks. For instance, acoustic sensors implemented downstream of valves can actually indicate if the valve is functioning as demanded: if a valve is entirely open or entirely close there's typically no distinguishable acoustic signal above the background turbulence .This kind of maintenance is where wireless sensors are holding a vital position. Indeed, when existing sensors are unavailable to procure the needed data, wireless sensors can be used to fill their place. For instance, wireless sensors can actually combine acoustic, vibration and other kinds of information with the environmental parameters such as ambient temperature and humidity to achieve an accurate analysis of the plant's overalls condition and much specifically the equipment's health state. Wireless sensors can facilitate complex measurements in industrial plants where wiring is a fragile connection such as temperature and elevated furnace-temperature measurements. They can as well simplify the measurements elaborated in dangerous environments and in applications where space for wiring installations is restricted. They can therefore simply provide the answer to the danger imposed by dust, dirt, corrosion, steam water and rust in wires in industrial plants. Companies can by that employ wireless sensors to gather data from anywhere and link it to the internet where they can be easily accessed and assessed. The advantages of wireless sensors go beyond what has been mentioned to enhance the facilities productivity, lower energy usage, improve machinery availability and reduce the overall costs especially the material ones. Indeed, wiring costs in an industrial process can be as high as 2000 dollars per foot versus 20 dollars per foot if wireless equipment were exploited for the same applications. In order to endorse the development of wireless-based predictive maintenance, the Analysis and Measurement services (AMS) Corporation has come up with a software package named "Bridge" which is capable of reading information from wireless instruments from various manufacturers collecting by that all the facility's wireless data and placing it in one space and in a single format so it can be simply analyzed and compared.

- **The test-signal-based approach**

The first two categories of predictive maintenance are mostly passive as they do not comprise any disruptions of the machinery being tested and can be executed in most cases while the equipment is operating. The third kind on the other hand depends primarily on signals that are introduced into the relevant machinery to test it and measure its performance eventually. The test-signal-based method involves active measurements such as insulation resistance examination and inductance capacitance, and resistance measurements also known as LCR testing. These procedures are employed chiefly to identify potential faults including cracks, wear and corrosion in the used equipment, cables, sensors, motors and other tools. This category of predictive maintenance technology includes moreover another method which is called “loop current step response” (LCSR). This method was actually developed in the mid 70’s of the last century by professors, technicians and graduate student from the University of Tennessee in the United States. It is essentially used in nuclear power plants for the testing of resistance temperature detectors, thermocouples and other applications. In fact, the LCSR approach is capable remotely to evaluate the response time of temperature sensors as implemented in a facility while the plant is online by sending an electrical signal to the sensor in form of a step change. It can be as well applied to ensure that temperature sensors are finely installed in their thermowells in a process and they are answering to any possible alterations in a timely way. Typically, LCSR might be adopted to indicate if aging lead to deterioration in the dynamic performance of temperature sensors so sensor substitution planning can be subsequently performed. The LCSR can be furthermore utilized for other reasons such as determining the water levels in certain equipment like pipes and detecting the bonding of sensors like RTDs and strain gauges to solid surfaces. The test-signal based predictive maintenance includes as well the time-domain reflectrometry (TDR) test. It is employed to detect the exact location of problems along a cable, in a connector or at an end device by introducing a test signal through the conductors in the cable and evaluating its reflection. The TDR technique has also served the power and process industries in testing instrumentation circuits, motors, heater coils, and a variety of other components. During a TDR examination, a step signal is transmitted along the cable, and its reflection is represented versus time. The resulting plot will illustrate any possible variations in impedance through the cable, inclusive the end of the cable. Even if implementing TDR and *LCR* measurements as predictive maintenance approaches is not a complex task that has been adopted by numerous companies for several years, their applications in industrial plants are still considered novel. Companies and industrials are still performing ongoing research into the three main categories of predictive maintenance that have been discussed previously. The elaborated studies assure to produce technologies that can be exploited remotely, passively, and online in industrial facilities in order to upgrade the equipment performance, prevent potential failures prior to their occurrence, and achieve a better effectiveness of operations and a total safety for workers. Integrating the predictive maintenance approaches described above with the newest sensor technologies will allow industrial facilities to avert unneeded machinery replacement, cut down costs, and enhance equipment availability and process operability. *(Wendell C. Bean, H.M. Hashemian, 2011).*

2.1.12 Problems and Challenges facing Predictive Maintenance

The concept of predictive maintenance has significantly evolved during the past decades from a reactive service activity to a proactive notion that gets more attention nowadays. This term has become broadly used by industrials in multiple fields and by academic researchers. Various involved parties have proven that predictive maintenance applications have succeeded to score considerable improvements in the industrial facilities by enhancing the overall performance and productivity of their equipment and taking breaking through steps in the technological and digital advancements. Nonetheless, predictive maintenance as any other type of maintenance encounters diverse challenges and problems that need to be addressed thoroughly. Indeed, it is always interesting to observe what occurs to an organization that decides on introducing predictive maintenance along with its condition monitoring techniques in its related plants. Firms apply predictive maintenance because supposedly it will cut down the operating costs and will enable to increase the savings by reducing the unplanned breakdowns and performing less planned corrective work. This is not always the case.

- **Huge amount of financial and human resources**

One of the main challenges related to the establishment of predictive maintenance is the huge amount needed of financial and human resources, hardware to test the machinery, personnel to collect the information and software to store the gathered data and produce the necessary order for the maintenance activities. In fact, predictive maintenance requires more operators, engineers and analysts than any other type of maintenance because more regular checks are demanded. Unlike, reactive maintenance where companies usually just make the call for someone to execute a onetime repair, this approach requires for the employees to be continuously on site performing their daily inspection tasks. The application of predictive maintenance necessitates moreover highly specialized skills and extended expertise for workers to analyze and interpret the collected information and the condition monitoring results correctly and accurately and eventually put it into proper use. To achieve so, employees must go through a lengthy, time and resource exhaustive training to become capable at first to assimilate the data and acquire enough knowledge in both IT and machinery. This sounds quite simple to explain but in reality it is regarded as one of the biggest issues when it comes to installing predictive maintenance programs. *(Ho Nguyen, 2018) (Proaxion Official Website, 2019).*

- **High up-front cost**

Furthermore, PdM is considered as one the most expensive maintenance methods and the presents the highest up-front cost. In other terms, PdM needs a lot of money mainly at the beginning of its establishment and industrial managers believe that it costs them much more to regularly maintain their machines than to wait them to fail eventually. This typically induces them to turn to condition monitoring contractors to reduce the high upfront costs of their maintenance systems. *(Ho Nguyen, 2018) (Proaxion Official Website, 2019).*

- **Over maintenance**

Industrials and researchers call for another obstacle as they name it the over maintenance issue. Some predictive maintenance setups can actually involve a large amount of time to be able to operate at their highest effectiveness and efficiency levels. The installation is therefore slower than expected and the setup isn’t fast in getting completely to work. Under such circumstances, additional maintenance procedures must be put in place in conjunction until the testing system starts functioning as it should exploiting by that more time, money and other resources. *(Ho Nguyen, 2018) (Proaxion Official Website, 2019).*

- **Compatibility aspects**

We must also discuss the common mistake that many companies make when they decide to install predictive maintenance tools and mechanisms which is the fact that they rush into the implementation procedures without elaborating the necessary research and studies on their facilities and equipment and how will they adapt to the expected possible changes. Consequently, the first step to do before taking any initiative of installation is to examine the levels of compatibility between machinery and predictive maintenance organisms and assure that the selected PdM software technology is entirely able to store data and detect the existing and potential failure modes and more importantly make sure that employees are experienced and skilled enough to monitor and assesses the collected information. For instance, in-depth algorithms for PdM applications must be created carefully requiring reliability engineers, data analysts and other specialists to work all together. Such skills are usually hard to find and harder to develop and might demand the partnership with various external providers. In addition to that, we must mention the necessity that the company acquires a full willingness from its areas and its operators to fully embrace PdM strategies and models and apply them accordingly. *(Marc cousineau,2015).(Yuval Lavi, 2018).*

- **Security aspects**

Another challenge that PdM faces is linked to the security aspect. Since predictive maintenance depends on tying together diverse assets along with digital systems employing cloud technology which will oblige the relevant company to put some heavy investments in protecting these assets. This will include preserving the access to personal data and applying a proactive position toward cybersecurity. Securing data is a therefore a must. Information has to be gathered and shared with a certain level of security in order to conserve the intellectual property of the organization. If the security aspect is taken care of properly, this can be a real competitive advantage for the company. Moreover, the protection of information ought to involve as well the customer’s financial and personal data and make sure that it is well aligned with the imposed regulations especially the ones that impose high penalties when client’s information is employed with their explicit consent. Time, effort, money and human resources should all be available and aligned all together to ensure that predictive maintenance technology would be secure and safe. *(Marc cousineau,2015).(Yuval Lavi, 2018).*

- **Risks and uncertainty**

When replacing preventive maintenance with predictive maintenance, the company must be aware that in many cases it goes from a state of certainty to a state of uncertainty. An essential point to take into account while discussing the selection of a certain type of maintenance; is if maintenance providers would be capable of adjusting and coping with the elected program. It is true that preventive maintenance can more or less yield certainty, regularity and standardization for maintenance operations while predictive maintenance provokes more the idea of uncertainty and risk which can worry a lot of maintenance providers. Uncertainty causes more spares holding so as to bring contentment to people. It will probably lead to subcontract to more services since the majority of internal employees would be busy working on predicted failures or will find much difficulty to assess the condition monitoring results due to the high level of uncertainty. Also, when dealing with PdM systems, managers should accord some serious attention to the way the operators and other workers interact with the changes occurring to the equipment. They must be careful to not make the proactive character of PdM become a reactive one. Otherwise speaking, once a company begins monitoring for deficiency, it will as well take machinery off-line to focus on the severe possible failures. Since these deficiencies will be haphazardly timed, the firm will be taking equipment out of service randomly as well in response to the size of risk connected to the defect in question. Such situations will happen more frequently with aging machinery and will lead the maintenance to become more reactive. Besides, it will cause pressing procurement requests on stores. In the coming years parts will be reduced randomly without any given concern to the most cost effective maintenance. Predictive maintenance will therefore drive organizations into component/assembly concentrated maintenance instead of establishing the most economic type of maintenance. *(François Gagnon, 2013).*

- **Economic considerations**

Applying predictive maintenance techniques comes with another trap when it is not regarded along with economic considerations essentially when industrial plants start using alarm units to trigger corrective actions. Typically, by producing work orders depending on alarm units for machinery components chiefly to replace them, the company automatically praises an ad hoc maintenance. Machinery and equipment will constantly be taken out-of-service to get back to function rapidly. The industrial facility can possibly arrest a breakdown, but everybody is absolutely rushed. Various maintenance jobs are therefore executed independently without searching for opportunities to optimize the utilized resources. *(François Gagnon, 2013).*

- **Quality of collected data**

One of the biggest challenges that deserves to be addressed is the quality of collected data during the condition monitoring techniques. We have already talked earlier about the amount of data and how it can hamper the accuracy of predictive maintenance process if it is extremely large and not well controlled and used properly. Companies have come to the obvious conclusion that huge amounts of data are insufficient to accomplish meaningful objectives and it is quite complex to obtain high quality information from industrial equipment to start with. It appears to be even more challenging to apply the gathered data to provide engineers, experts and technicians with relevant and actionable condition based maintenance insights. It is to some extent simple to collect large amount of raw and unlabeled data but working on developing and building accurate and adequate learning digital algorithms for predictive maintenance platforms is a complicated task and if not performed properly can lead to more operational and economic issues. Indeed, constructing databases of high quality and labeling information, that is attaching to each piece of information a certain label or a tag to make it insightful and useful, is truly technologically burdensome and time consuming venture. For instance, technicians and engineers have employed vibration monitoring techniques in their testing and analysis tasks through the predictive maintenance programs for many years. Vibration sensors, meters and relevant technologies have greatly developed and have become today more advanced and affordable instruments. Nevertheless, an ongoing obstacle with gathering considerable amounts of vibration data is that the information alone isn't sufficient to offer the required insights. *(Amnon Shenfeld, 2019).*

- **Implementation of sensors**

Also, when we discuss the implementation of technological sensors depending on the chosen condition monitoring technique, we often disregard the challenges imposed during the installation process thinking that is another feasible and uncomplicated task, while it is completely the opposite. Companies are susceptible to face some serious trouble while inserting sensors and condition based maintenance tools due to the fact that the relevant installed devices and systems do not always adapt properly with the industrial environment and its machines. Since industrial maintenance software platforms, sensors and operations are presently fragmented, it's a challenge to combine sensor information with actual events or maintenance operations that personnel perform on machinery. Various existing predictive maintenance solutions such as vibration condition monitoring techniques via handled devices necessitate regular sampling and diagnostics organized by technicians working from machine to machine. The issue here is that these methods can fall victim to delivering biased and partial outputs based on the location of the sensor and the level of expertise of the operator or technician and consequently are always monitoring and transmitting warnings in real time. Moreover, the non-handled sensors with smart monitoring and controlling procedures usually demand complicated integrations, training and recycling of long-established industrial assets. Technological and digital advancements are actually procuring aids to overcome these obstacles but so far restricted to the hype phase. A great part of the elaborated PdM solutions has been chiefly about software to assess the gathered data from sensors fabricated and designed by third parties. In most cases, users and implementers of similar software resolutions do not fully command the sensors or the information sources. Consequently, they are very exposed to garbage in, garbage out plots where false-positive alarms take over and subsequently maintenance teams overlook valuable alerts because they are prepared to doubt the results of such mechanisms. Industrial equipment data will be only as reliable and as good as its most unfavorable sensor and it's quite impossible to determine which sensors are good and which of them are not if they are not accurately monitored, implemented or manufactured in relation to the software that has been handling the data inputs. Furthermore, reliability monitoring software must be absolutely steady and reliable. The challenge is to fill the gap between maintenance engineers, sensors and the company's resource scheduling and monitoring software principally when operating under rough industrial and environmental conditions like steel plants for instance or oil rigs or with equipment spread across remote locations including energy producing turbines. *(Amnon Shenfeld, 2019).*

- **Communication channels**

We can therefore deduce that in order to end up with a completely predictive maintenance system, there are multiple factors that ought to must be taken into consideration. As we have mentioned before compatibility is a must in this equation. To accomplish so, machinery, sensors, instruments and employees have to connect and communicate with each other in a consistent manner. Obviously, great communication doesn't involve only the internal components but has to include moreover the external environment. Indeed, there has to be a virtual replica of the physical world so as to make sense of all the relevant information in order to conceptualize the data. Sophisticated solution technologies are used for that purpose and as a way to support decision making and problem solving. Companies can come up against various technical issues if there's the communication channels aren't robust enough or if there's overdependence between industrial systems. In other quarters, good interaction and communication do not necessarily mean excessive interdependence; this requires the cyber systems in the industrial plants to be as autonomous as possible. It is true that predictive maintenance is capable to offer better outcomes when it utilizes more advanced technological tools. Still, this mean can be disadvantageous as much as it can be beneficial if the company doesn't accord the appropriate attention to the implementation process. Such proceeding has to begin with the state-of-the-art sensors whose technologies might be associated to extensive amounts of data in almost real time. We can easily observe that it always comes up to the use of sensors and how accurate they are; this can be explained by the fact that they constitute the origin of data collection which rely on the rest of the PdM steps.

- **Sensors' lifetime**

The selected sensors must be capable to monitor parameters and conditions with high levels of reliability and precision in real time to procure useful data. The problem with sensors technology is they can become rapidly obsolete and therefore would need to be updated. Even after collecting data, there's still a huge risk in organizing and choosing the meaningful information improperly. For that, the company must adequately select robust systems to handle, integrate and aggregate unstructured data from separate solutions of various product manufacturers in order to unlock the data value and create some insights. Still, the process and its related challenges do not end up here. The industrial organization has to establish careful procedures when it comes to storing the data, processing it and analyzing it thoroughly. For predictive maintenance solutions implementers, this is usually not an easy thing to do; so many variables must be studied in terms on how they could potentially react to such installations. Even if the implementation succeeds, managers and workers must keep up with the process development and learn how to manage any possible issues on the short and long terms.

- **IT systems integration**

Furthermore, IT systems integration ought to be included in the company's priorities as to ensure better interconnections inside the industrial plants and more solid interfaces between these mechanisms and the rest of the organizational structures. For instance, hand-coding integration might restrict the IT department's capabilities to answer any eventual business alterations. This is prone to generating the danger that IT can be considered as slowing down a company's growth by becoming a barrier, utilizing important resources for integration projects. Integration platforms seem to be another option to establish instead of hand-coding integration as can procure a more flexible environment that can manage diverse integrations with multiple systems that regularly require updating. Still, administering various vendors' technology stacks and optimizing between these stacks can be highly complicated and might lead to more integration issues if the IT teams are unable to build strong structures and supervise data in a standard manner through building in fault-tolerance, resilience and elasticity as well as monitoring and performance management abilities.

- **Access to data**

In addition to that, the access to data has to be secured in a way that it won't be too restricted. When we discuss the communication issues, we usually do not reveal its connection to the limitations of data access. Information has to be shared among the workers and employees so they can be aware of current state of machinery and the potential failures and to gain as well the required insights in order to accomplish higher levels of quality and productivity. As for manufacturing organizations, the integration level of manufacturing execution systems and resource management organisms can control how predictive maintenance is well established. In fact, if we are dealing with a full integration of the related systems and an appropriate management of its interfaces and their interconnections then this will allow taking immediate actions for preventing downtime, though if we are facing the opposite case then more integration problems will come to the surface. Moreover, managers have to work harder on making the maintenance management programs more integrated into the production activities. In fact, maintenance management is much more efficient when brought to the operations level because it can be introduced to the production processes closer to where things actually occur. Only under such circumstances, we can indeed refer to "real time" gathered information. This leads us to consider the concept of "real time" and how different interpretations of the term and unsynchronized operations can cause inaccuracy in data collection and further issues in the assessment and prediction phases of potential deficiencies. Consequently, industrial executives must sync maintenance tasks, orders and inventory data with the organization's operations in order to meet the actual production requirements and coordinate material usage for more effective scheduling. If this is established properly then managers can envision, control and document the overall industrial processes and have a better vision on the machinery conditions so they can finally be capable of detecting variations and put the operational and maintenance functions in motion to remedy to the given situations like ordering novel parts and planning the upcoming services or tasks. *(Yuval Lavi, 2018).*

- **Connections between industrial structures**

Stakeholders should as well stop making another common mistake that is regarding the different industrial structures as distinct parts with specific limits surrounding them. Indeed, when systems function in harmony and not just in parallel, industrials can respond more efficiently and quickly to rapid varying operating circumstances. In other words, logistic systems, IT systems, management systems, transportation systems as well as production and maintenance systems do not have to coexist all together, they must be all integrated at once under a whole entity so as to automate an end-to-end business process for equipment maintenance and schedule maintenance operations with the required experts/technicians and with the necessary tools and expertise. Though, investing in multisystem integration can have significant financial profits on the long term but demands a lot of money mainly at the beginning of its implementation and requires furthermore considerable efforts from all stakeholders and employees to adjust to the possible changes; it is never an easy task to adopt a new thinking then an old one that has been used for decades. *(Yuval Lavi, 2018).*

Despite the various challenges and problems that we have scrutinized all above, predictive maintenance remains an essential element of maintenance management of the future. It still holds some valuable benefits for any given industrial organization but there are multiple elements to be considered before a predictive maintenance installation can be truly called a successful one. Jumping into predictive maintenance is usually unfavorable to firms that aren’t completely ready for the enormous investment in money, training and time that is needed. Consequently, before taking any step ahead, companies must consider their priorities and their capabilities and what would be the best way to implement predictive maintenance while taking into account all the challenges and mistakes that could be made in order to avoid them with the least damages possible. Although predictive maintenance necessitates an elevated upfront cost, in the long term, it turns out to be the most cost-effective choice for the industrial organization.

We have attempted on this section to explain as much as possible the concepts of innovation, condition monitoring and predictive maintenance as well as their respective benefits, history and techniques so as to facilitate the mission of revealing their possible interactions and comprehending the eventual impact of novel technologies on CM and PdM on the upcoming parts. Based on the above details, it can be easily observed that CM and PdM establishment require some intensive efforts to achieve the organizational desired objectives.

Section 2: Technological innovations in relation to CM and PdM

2.2.1 Technological developments in CM

Just as multiple fields such as telecom, data analytics, infrastructure and smart instruments have been enhanced by innovative technological tools, the exact same thing has been said about condition monitoring. Constraints of human inspection including diminished effectiveness, fatigue, high level of human mistakes occurrence, inconsistency and individual disparity have been essential drivers to boost the development of CM techniques and devices. Typically, the drive has been accelerated by the technological progresses such as cost-effective, rapid and rigorous inspection mechanisms and examination means provided by machine conditioning monitoring technology. The advancements of sensors, internet of things (IoT), analytics, electronics, software and machine to machine (M2M) communication have been other factors to lead the improvement of condition monitoring systems. Such developments have brought up some meaningful advantages of scalability, remote operability, real time data and automation resulting in upgraded performance, efficiency, maintainability, accuracy, safety and decreased human intervention and by that reduced potential failures. It seems therefore vital to discuss the current technological developments in relation to condition monitoring in today's industries.

One of the currently broadly utilized technological ameliorations in CM is the advanced **software**. As sensors are placed to register the multiple parameters of the operating machinery and their conditions, it appears more crucial to use the suitable application to gather the information and report the needed actions. For this reason, the establishment of condition monitoring software has been expanding speedily within multiple industrial environments as manufacturers and managers search for easier and more effective methods for data interpretation and analysis after its eventual collection by CM systems to take the necessary actions upon it. Such software doesn't only concentrate the condition monitoring data but can as well support the scheduling and delivery of an entire condition monitoring structure from scratch. Where should the sensors be implanted? What should they be measuring? How should they be calibrated? What kind of warnings and alerts should they be sending and to where? All of these requests can be answered by condition monitoring software allowing industrials by that to assess the facility's operations progress and the equipment state of health. Usually CM software is constantly linked to another technological innovation that is related to **remote control devices**. Once CM remote has been put in place, the software persists to behave as its hub focusing and collecting all the data inputs being reported by the used sensors into a single focal repository permitting to undertake deep data analysis and determine the required corrective actions.

When discussing the novel advancements in CM techniques and methods, it is essential to mention **industry 4.0** as a central part of the CM improvements. Indeed, condition monitoring experiences significant transformations regarding the way its devices are fabricated and designed due to digitization of manufacturing. This progression is so compelling that is being named industry 4.0 to illustrate the fourth evolution that has occurred to manufacturing. From the first industrial revolution that was about the mechanization through water and steam power to the second one consisting in mass production and assembly lines through electricity, the fourth industrial revolution has takes what has been initiated during the third revolution with the application of computers and automation and worked on ameliorating it with smart and autonomous mechanisms fueled by data and machine learning. When computers were introduced in industry 3.0, it was a breaking through innovation that brought up multiple opportunities to stakeholders in diverse domains. Today and in the future as the fourth revolution extends, computers are affiliated and communicate with each other so as to make decisions without human involvement. An amalgam of cyber-physical systems (CPS), the Internet of Things, Artificial Intelligence, Cloud computing and the Internet of Systems make industry 4.0 possible and more efficient. With the implementation of such concepts in industrial facilities, the access to information will be much easier and its analysis will be more accurate. Smart machines make our firms better, more productive and less wasteful. Thusly, the real power of industry 4.0 relies on the high reliable network of machines that are interconnected and do share data. As an obvious outcome, companies have started noticing the importance of introducing industry 4.0 in their CM systems and devices. Industry 4.0 gives indeed the relevant company the opportunity to enhance the quality of their daily CM operations rapidly and effectively by letting employees and managers discover what actually requires their attention. *(Bernard Marr, 2018).* Moreover, it allows machines, sensors, devices and people to communicate and exchange properly information. Another advantage of industry 4.0 introduction in CM systems is the ability to have information transparency where systems are capable of aggregating data collected from the physical world into a virtual duplicate. Additionally, it provides vital technical assistance to workers in order to help them in solving issues and taking the right decisions. While talking about decisions, it is primary to mention that with the application of industry 4.0 tools we talk more about decentralized decisions giving by that the related systems the ability to take their own decisions through mainly employing artificial intelligence to execute tasks with a minimal human interference. *(Yash Mehta,2018).*

When we consider any given industrial facility that employs CM techniques as a central part of the fourth industrial revolution with all its segments, we usually contemplate the use of reliable wireless sensors with pre-engineering monitoring solutions that can spontaneously collect, analyze and report maintenance technicians and operators at the start of a developing condition. This is industry 4.0 condition monitoring at its best. Following the trend of industry 4.0, automation in multiple manufacturing schemes has generated the usage of intelligent condition monitoring systems, which have proven themselves essential for upgrading productivity, operability and availability of the relevant production mechanisms. In order to develop similar intelligent systems, semantic technologies are of a preeminent importance. The manufacturing industry of CM systems is benefiting from a trend of automation in data exchange processes. A central part of technological advancements in condition monitoring is Cyber Physical Systems (CPS) which make industrial facilities more productive and more capable of operating with autonomy and intelligence. The automatic interchange and assessment of information offer crucial opportunities for industrials mainly manufacturers to optimize the production processes. Gathering data from diverse parts in a production line and assessing them in an expandable Cloud infrastructure can automatically enhance the performance, productivity, maintainability, reliability and availability of the production systems in heterogeneous environments. The appliance of CPS in industry 4.0 has led to the rise of the so named “Smart Factories”. With the adoption of Cyber Physical Systems, information within Smart Factories is closely controlled and regularly synchronized between the manufacturing organizations and the cyber computational space. Hence, in order to ameliorate the quality, availability and productivity levels of productions mechanisms, CPSs are supplied with advance technologies to acquire the needed abilities to self-awareness and self-maintenance. These capacities are able to provide significant resilience, automation, productivity to the CPSs and facilitate the establishment of intelligent condition monitoring systems (ICMs) which can offer optimal solutions to manage the large amounts of data efficiently, to perform prognostics in an intelligent manner and procure predictive decisions about equipment deficiencies and machines degradation trends. Figure 4 illustrates a schematic view of a condition monitoring task based on an intelligent condition monitoring system performed by a three-layer cooperation between cyber space and the physical environment. *(Bertrand de Beuvron, Cao, Giustozzi, Reich and Zanni Merk, 2019).*

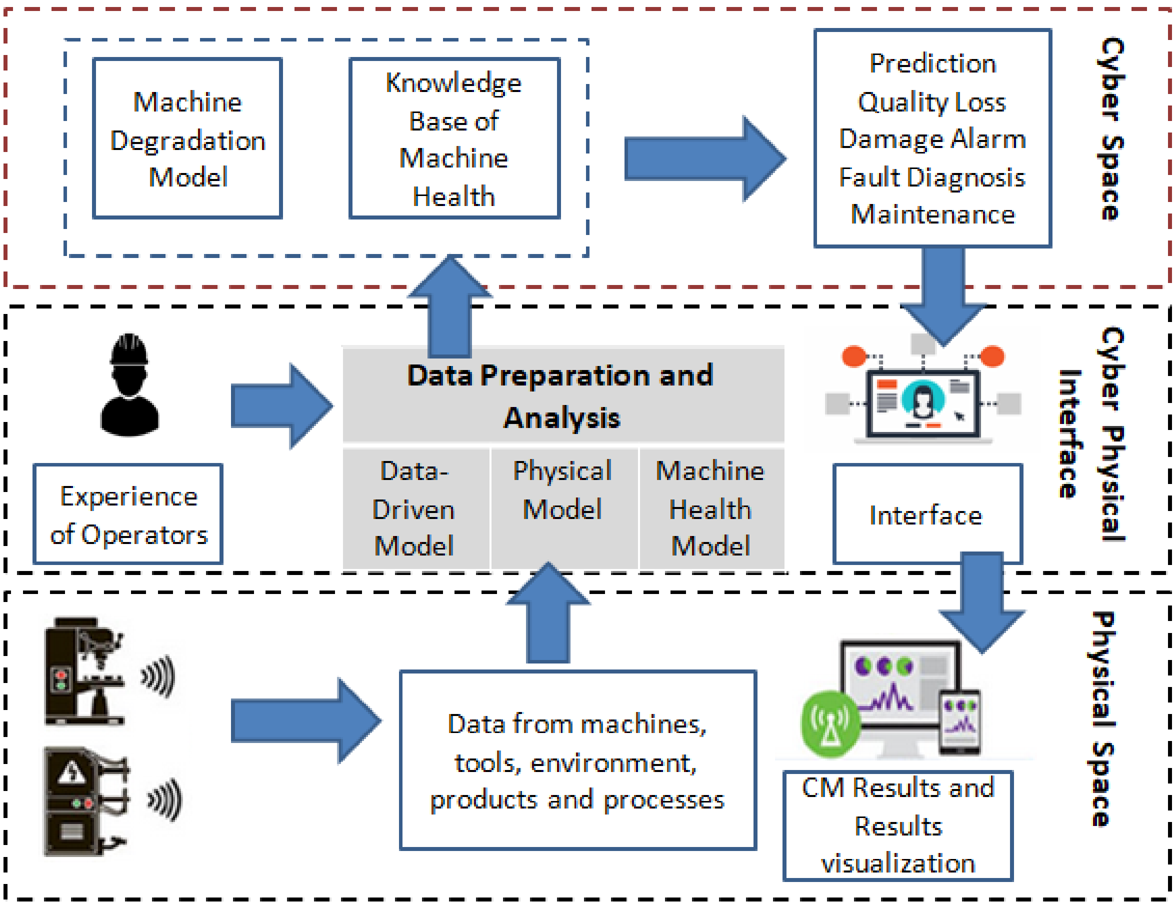


Figure 4: A condition monitoring task performed by an ICMS, based on a cyber-physical approach. (Bertrand de Beuvron, Cao, Giustozzi, Reich and Zanni Merk, 2019).

As we can notice on the figure above there are three main layers:

- At the bottom there is the physical space layer, where information is collected from sensors implemented on the machines and tools. Additional information might be gathered as well from the industrial environment, the equipment itself and the operators' experience. Following that, all the information is visualized on the relevant screens and devices.
- The gathered sensor data are therefore stored and processed at the middle layer which is called the Cyber Physical Interface. At this layer, statistical methods such as large data algorithms utilize the stored data in order to comprehend in a better way the industrial and manufacturing processes and to learn from the operators' expertise.
- Concerning the cyber space, it procures decision-making about equipment defects prognostics and maintenance. Machinery deterioration models that are derived from the mining of sensor data are acquired in the cyber space. Thus, ontologies are employed to generate the knowledge base of equipment health, and ontological reasoning approaches are used to predict machinery degradation, damage, and quality loss or maintenance requirements in the future. These predictive outcomes are transmitted downwards to the physical space so as manufacturing organizations would make the suitable responses in a timely, efficient and accurate manner. *(Bertrand de Beuvron, Cao, Giustozzi, Reich and Zanni Merk, 2019).*

In order to develop such an intelligent condition monitoring system, the first thing to do is to establish and define domain knowledge. Indeed, information that can come from distinct sources can hold various meanings according to the relevant domains and contexts making by that the task of working on harmonizing the data an extremely difficult job. To overcome this challenge, multiple companies have come today to the conclusion that technology have to work harder on constructing semantic doctrines in order to deal with the collected data by ICMSs. They are building for these reasons shared and rigid and equipment understandable vocabularies with solid structures. Typically, semantic technologies, mainly ontologies, seem to be the most appropriate solutions to solve the semantic interoperability issue. In fact, the usage of ontologies can provide a better comprehension and coherence of semantics among the diverse participants within a domain. *(Bertrand de Beuvron, Cao, Giustozzi, Reich and Zanni Merk, 2019).*

Another key element of the technological improvements is the usage of the Internet of Things in offering much more reliable and advanced solutions in CM techniques and devices. The IoT which is an essential component of industry 4.0 is chiefly characterized by connected instruments. The adoption of IoT doesn't only support the internal operation, but through the usage of cloud environment where information is stored, machinery and activities are improved by putting in leverage the insights of other parties employing the same machinery or allowing smaller organizations get the access they need to the technological tools that they couldn't have access to on their own. *(Marr, 2018).*

The use of IoT brings so many benefits to the industrial facilities in question; principally more efficient cloud storage for large amounts of data. In fact, every company has a specific data center and owns multiple dedicated servers to bring in data and process it. Hence, IoT leverages computing cloud and keeps considerable amounts of data in the cloud. As different kinds of machinery are connected through IoT, a huge amount of data is produced. By leveraging industrial IoT, industrial firms can store larger volumes of data and still optimize and enhance the storage capacities. IoT has had also a valuable impact on condition monitoring systems that is increasing the ability of the company's machine learning. We are aware that machine learning necessitates huge content of information. Let's consider the example of a predictive instrument which recognizes the vibration in a drilling machine and analyzes the results to determine the existing cracks. A proper machine learning will require data from more than 100 crackings. So, if a company derives the data from one machine, it will take several years for the process to be achieved. While with the use of IoT, the process will last less than a year as IoT can simultaneously collect data not just from one machine but from many. Additionally, taking data from distinct equipment will lead to a diversification of information sources and by that to more accurate results improving eventually the reliability, functionality and precision of the predictive model. Besides, IoT predictive maintenance tactics are much more performing. Indeed, the IoT predictive maintenance tactics observe carefully and closely the machinery health state and subsequently detect in real times and exact figures the variations in the equipment condition parameters that could be pinpointing to a developing problem. IoT ensures therefore a rapid and efficient predictive maintenance in condition monitoring. Another advantage of Iot is the remote condition that has been significantly improved lately and still is. With IoT advanced solutions, companies are today able to monitor accurately thousands of machines from a specific location. It does no longer require the physical access to the equipment which can be extremely costly and time-consuming affecting negatively the productivity level and downtime. For instance, multiple firms in the oil and gas industry mainly as well in the electric sector exploit IoT remote controlling advanced devices and systems for better condition monitoring of their machines as they facilitate the monitoring of remote installations especially equipment such as pipelines and drilling rigs. The collection of data itself is performed rapidly and accurately then transferred to the cloud for better processing. One of the industrial sectors that had greatly benefited from the condition monitoring IoT is the automotive sector. Based on the statement of the Automotive Fleet per driver automobile, downtime deduces in an average loss of $79.32 per hour. The damage doesn't involve the costs of repairing. Condition monitoring IoT allows thus to decrease the downtime and to enhance the usage of maintenance resources. Condition monitoring IoT permits as well to monitor the related vehicle based on the study of parameters such as vehicle vibration, engine temperature and fuel consumption. It measures typically the potential failures prior to their occurrence. The condition monitoring IoT technological sensors determines exactly when the vehicle condition goes beyond its standard functioning point. Other examples can be obviously point out when it comes to the adoption of CM IoT programs or devices. *(Singh, 2018).* Thanks to all the profits CM IoT has proven, companies are now convinced more than ever that the Internet of Things can considerably reduce equipment downtime, collect exhaustive amounts of relevant data, detect in more accurate and timely manner the possible deficiencies before they take place and manage more efficient controlling tasks.

2.2.2 Technological developments in PdM

We are witnessing today considerable transitions in the predictive maintenance programs and tools thanks to the highly advanced technologies that are brought into the industrial contexts. The world of manufacturing is significantly developing. We can name it the fourth industrial revolution, industry 4.0 or the Industrial Internet of things (IIoT), it’s all about performing operations in a timely, effective, safe, flexible and more environmentally friendly manner. Indeed, the introduction of novel technologies and services connected to the Internet of Things is enhancing constantly the use of multiple industrial applications. Such initiatives implemented in industrial companies, regarding automation and predictive maintenance, are able to create some opportunities for new entrants and the old industrial players to develop innovative models that can reform entirely the existing business structures and approaches. Organizations are working therefore harder than ever to assure a high level of performance in their industrial environments and for their equipment to be more efficient, intelligent, more connected and robust with a total respect of the quality and safety standards. To accomplish so, it seems crucial for these firms to do enough research on the subject and acquire the needed human and financial resources to invest in the implementation of technological projects.

As mentioned before on the 2.2.1 section, industry 4.0 which is the latest industrial revolution utilizes artificial intelligence (AI) that changes completely how the data is stored and assessed. Industrial procedures and activities especially the manufacturing related ones in this novel phase of machine learning requite little to no human intervention and a smooth progression from an input and output approach to a flexible conversation between human and robots. AI can bring machines to become more able of making decisions and providing technical assistance leading by that to more effective and transparent communication channels. Equipment is additionally capable today of calculating and determining risk factors ameliorating greatly the work environment and increasing exponentially the overall safety of the operators and machinery. IIoT is an essential facilitator for predictive maintenance. It plays an important role through the usage of IoT sensors to translate actions into signals. These signals are transferred digitally where they can actually indicate and provide information such the functionality of production machinery. By implementing this type of IoT sensors, smart factories are spreading out gradually with the use of connected machines that can exchange information with each other and with operators so as to take the necessary actions eventually. The IoT technology can more efficiently and rapidly detect variations in the equipment parameters and locate accurately the possible or expected deficiencies that are probably unobserved by humans. This will endorse the predictive maintenance programs and will allow the company subsequently to make decisions or take actions in order to solve the potential problems prior to their occurrence. Hence, IoT optimizes the PdM tasks, maximizes the machinery lifespan and avert expensive technical disruptions. The technical advancement of IoT makes PdM enhance two of its important criteria that are the needed technical assistance and the decentralized decision making ability. With IoT, PdM requires a larger technical support by detecting faults that humans usually can't see reducing by that downtime and improving the job safety. Also, based on solid and precise collected data, centralized decisions will be entirely eliminated of the industrial systems. Following that, the coherent combination of machine to machine (M2M) communication and artificial intelligence will make it much easier for companies to make data-based decisions with reduced human intervention. Decisions are now driven by data eliminating by that the sources of human errors. As more companies use IoT technologies, the relevant devices and tools required by the smart factories become more affordable and therefore less restricted to limited key industrial players. Storage, network and bandwidth fees that were more or less expensive, are currently coming down and bringing IoT and industry 4.0 closer to the original manufacturers and to the smart factories. *(Roubaud,2017).* This will be a great motivation for the technological inventors to work harder on innovating and bringing to the market better and more advanced systems for greater outcomes.

According to Frost and Sullivan studies, the predictive maintenance systems have been characterized by implementing novel technologies in a deferred fashion, quite similar to Bluetooth and Wifi appliance in instruments. For that reason, it is quite simple to forecast the possible new applications in predictive maintenance including chiefly cloud platforms or cloud computing. As the technology developments go forward, companies own the responsibility of ameliorating the mindset of the workers to enhance further the value of their professional industrial activities. Nonetheless, it has become much harder lately to create more value to the predictive maintenance programs in interaction with the technological advancements as huge improvements have already made in the matter. Still, technological tools manufacturers that are heavily investing in developing advanced systems believe that there's always a room for improvement and innovation. This is why their prime goal is the introduction of digitalization in PdM mechanisms as an essential approach of dealing with the industrial challenges related to maintenance and operation tasks. From a technical point of view, to digitize is to integrate artificial intelligence in the usage of machinery data and processes in the making of production and maintenance decisions. This involves mainly online systems, utilization of platforms, industrial communications, algorithms and personal training. This has been a real breaking through point for industrials in the last years allowing them to manage more efficiently their stored information and have access to more details so as to take the right decisions at the right time. However, the technological advancements must be assessed not only from a technical perspective but also from an organizational one. Indeed, according to the Fraunhofer-Institute, the digitization would as well include new organizational and business models. As maintenance is constantly interacting with the other industrial divisions, it appears important to study and comprehend the extent of digitization impact on the organizational structures. Typically, technological improvements provide methods where the data is standardized, industrial organizations are revolutionized, novel business models come to the surface and industrial communication norms are reinforced. This will permit maintenance decisions to be made by machine learning algorithms. Therefore, when working on digitizing the predictive maintenance programs, the first step to be taking is to digitize the maintenance reports by employing cloud platforms. Though, digitizing the predictive maintenance reports goes beyond implementing industry 4.0 concepts. It mostly signifies developing value when it comes to enhancing the communication channels with the maintenance departments by transmitting the appropriate diagnostics in a clear manageable manner. *(Torres, 2018).*

We do not only talk nowadays about smart factories but also about smart predictive maintenance (SPdM). Smart Predictive maintenance is actually the new modern concept of PdM that puts in place various technologies integrated in the maintenance tasks. It is the continuous monitoring and assessment of a group of connected assets that allows the prediction and determination of potential disruptions with the usage of highly advanced technological tools. Moreover, SPdM procures information on maintenance scheduling and spare parts planning, as well as the automation of maintenance operations. In fact, SPdM surpasses PdM in major three ways:

- **The monitoring of assets through the extensive use of IoT**: the Internet of Things isn't just about sensors or actuators. The true importance of IoT is mostly about the digital connections it constructs. Digital data was not of a great significance before the invention of the Internet mainly because it was all kept locally on individual computers and couldn't be shared remotely. The IoT joins data similar to the Internet only that is information from operational technologies (OT). When the company is networking its assets, it can eventually observe their integrity in a single controlled dashboard. Additionally, a network produces much more information points than individual equipment. By bringing together OT network information, maintenance experts are able actually to discover patterns between equipment deficiencies and develop machine learning platforms that can advance prediction algorithms over time.

- **Advanced automation of maintenance activities:** Predictive maintenance is capable of predicting possible equipment faults and failures. On the other hand, SPdM goes a step further by automating maintenance activities through the usage of cognitive information processing technological methods. For instance, if a fault in a certain machine appears, Smart Predictive Maintenance sets off a maintenance order, charges a technician to do it and arranges a ticket in a Computerized Maintenance Managed System (CMMS). Following that, SPdM would examine the spare parts inventory required to restore the defective part in an Enterprise Resource Planning (ERP) system and involve it in the work order. In case the component in question does not exist, SPdM would produce a purchase application in the ERP system that would require to be authorized by the procurement expert.

- **Integration in other maintenance management systems:** In order to automate certain operations, the predictive maintenance platform must be integrated into one of the following; the CMMS, ERP, or Manufacturing Execution System (MES). The traditional predictive maintenance might fail if it is not incorporated into the company's daily maintenance courses of action. By merging smart predictive maintenance with other maintenance systems, the relevant firm can actually develop both a sustainable platform for procedures and the potentiality to automate maintenance processes over time. *(Durmus, 2019).*

It is extremely crucial though to acknowledge the fact that companies can't introduce directly SPdM programs into their structures and adopted organizational models. Therefore, for a better and smoother implementation, Smart Predictive Maintenance has to go through five major steps:

- **Asset Monitoring and Health:** display of real time data.
- **Condition-based maintenance:** definition of variables and machinery parameters and display of intelligent alarms.
- **Performance-based maintenance:** Optimization of the relevant parameters and definition of tolerance ranges.
- **Prediction-based maintenance:** Predictive maintenance to detection of future failures in time.
- **Smart Predictive maintenance:** Automation of maintenance plans and optimization of executions by digital technologies. *(Durmus, 2019).*

Once the information is accurately stored, and a certain machine has generated enough error data, the mistake thresholds could be corrected. Following that, a data specialist with a high expertise in statistical assessment can start developing predictive schemes. Smart predictive maintenance can in many cases boost the equipment availability and uptime by 20 until 30 percent. In fact, it is believed that as errors happen more frequently, the machinery learning platform would monitor deficiency data in a better way and could update algorithms more efficiently. This will strengthen the capability of industrials to estimate each breakdown so as to decrease the percentage of unplanned downtime. Installing and creating a similar platform is far from being easy and can be time-consuming, therefore it is imperative to begin at an early stage and concentrate on the most important resources above all. Multiple companies in several industrial fields have been adopting PdM systems and procedures for years and a great number of them today are starting to get interested by SPdM concept and decide consequently to integrate it in their operations. As we have already explained, such a maintenance strategy would be the ultimate solution to enhancing the overall performance of the related organization, its operations effectiveness and productivity, its maintenance programs efficiency and before anything the safety of the personnel. Furthermore, maintenance and spare parts inventory costs are more likely to be diminished. *(Durmus, 2019).*

Until now we have tried to explicate how the predictive maintenance concept has evolved in the past few years. Still, to be able to assimilate the possible and current technological developments, it appears to be essential to look at the current state of predictive maintenance. In fact, IIoT predictive maintenance is still in its beginnings. Despite the promise of the introduction of industry 4.0 concept into the predictive maintenance programs, there is a long way ahead of the current PdM systems to advance its methodology and strategies. The traditional Predictive Maintenance, including vibration monitoring analysis, thermal imaging and oil residue analysis is still monopolizing the industrial maintenance programs, and manual statistical modeling programs like Microsoft Excel for instance has not been replaced by more advanced cutting-edge technologies or machine learning systems in many companies. *(Jalan, 2018).* This is why it is imperative to understand how industrial organizations can achieve a better development of a comprehensive predictive maintenance through the concept of industry 4.0. Based on the modern trends adopted in the industrial companies and the evolution of industry 4.0 concept, the improvement of the machine tool sector is that it will rely into the implementation of Cyber Physical Systems (CPS) incorporated into the global production context. Although, to accomplish so, some requirements are much needed including the incorporation of embedded organisms, the advancement and integration of the relevant cognitive models, the expansion of the companies capabilities in the decision making process through the usage of sensors without forgetting one elementary part into the equation that is the solid interconnectivity between the machinery and the overall production system of the firm in question. The first meaningful driver for the improvement of industrial internet solutions remains in the opportunity of better coordinating and organizing horizontal and vertical value chains. The digitization and interconnection of assets constitutes a second primary diver. Another driver to be named is the current emerging digital business models that often provide critical additional value to customers through tailor-made resolutions. These novel business models generate usually a significant rise of horizontal cooperation across the value chains and are defined by the integrated usage and assessment of related information. Thusly, they can more efficiently respond to the company's clients' demands. The multiple opportunities, the extended extent of transformation and the increased necessity for investments make the industrial internet an extremely crucial subject for organizational management. Nevertheless, the diverse obstacles and challenges that the change involves are not to be underrated. The fourth industrial revolution has been providing appealing opportunities for industrial firms to enhance their predictive maintenance programs. Hence, the Industrial Internet isn't an end in itself. It is absolutely linked to obvious economic goals and has the potential for more understandable distinction in global competition. Nowadays, novel business models are being created by production organizations in relation to their maintenance tasks in order to answer the customer's requirements, to assure successful patterns for their related operations and to cut down the production costs. Predictive maintenance is considered to be the most cost-effective maintenance strategy. Still, it can be further enhanced throughout the utilization of smart sensing technologies so as to procure the Original Equipment Manufacturer (OEM) with new advanced capacities and added value services. We must though confirm that the current algorithms still require some serious improvement. Indeed, currently they are more or less based on the divergence from the reference baseline and it appears to be imperative to monitor the actual existing machines to acquire updated and additional information. As a new data concerning the deficiencies of the equipment becomes available, the verge of these circumstances of fault will be analyzed. And as long as this value will be noticeably distinct from the healthy data, it will be surely employed by the algorithm in question into the engineering procedures in order to upgrade its generalization, its accuracy and its robustness. Nonetheless, so that to assess the levels of deterioration of the related machinery, the personnel must know exactly the usage of the equipment and adapt their practices to the suitable maintenance culture that ought to be adopted, and this is far from being a simple task. This signifies that the company will possibly have restricted amount of information about the situation of degradation of the machinery at the very beginning. And even if the used algorithm will generate some warnings or alarms, the part in question will be functioning until its failure. In this way, the OEM or the maintenance service provider will be capable of procuring some degrees of degradation (healthy/anomalous/failure). At last, taking into consideration, machine learning classifiers can be implemented to get knowledge and enhance the utilized algorithms. Furthermore, more complicated data driven studies and technologies can be put in practice in case of getting more information about the machinery. Such approach will allow to the significant improvement of the algorithm that can applied as a local algorithm into the machine. *(Fernandez, Ferreiro, Konde and Prado, 2016).*

Section 3: The importance of innovation and its impact on CM and PdM systems

2.3.1 Importance of innovative technological advancements in CM

In the subsection 2.1.8, we have explained in detail the multiple challenges and problems facing the condition monitoring systems and procedures. As a response to these obstacles, the industrial companies have worked for decades on developing methodologies and techniques that would ultimately solve the presented issues. Subsequently, innovative concepts and creativity in establishing more advanced CM technological programs appeared to be for a great number of organizations the key to this dilemma. Indeed, the major significance and importance of innovative advancements relies mainly on the fact that they are able to aid the industrial organizations overcoming various technical and managerial hindrances related to the implementation of CM systems. The considerable improvements in sensors and their related software have proven themselves capable of providing real time value data empowered with an accurate analysis and permitting therefore to acquire a deeper and a better insight in the inner workings of the existing processes and equipment, their potential failures and their actual effectiveness. In other quarters, the historic data gathered could be a crucial resource for enhancing the deficiencies' detection operations and optimizing the processes' performance. Such technological enhancements will allow the company to address the root causes of the possible faults and concentrate primarily on the true sources of the imposed problems endorsing by that the proactive aspect of the new monitoring implemented devices. The internet of Things offers the engineers and the monitoring operators the possibility to never stay in the dark when it comes to machinery performance. Managers can consequently remodel a reactive approach that constitutes in replacing components based on set schedules utilizing historical information, into a proactive approach in which accuracy is increased, visibility is lifted, waste of time and ambiguity are practically removed. This would result into faster and better informed decision making procedures producing higher quality findings and decisions. IoT provides more powerful and accurate data at the precise moment of relevance making the personnel in charge of CM tasks capable of comprehending the real causes of deficiencies and faults and engage following so the required actions to remedy to the situation. In addition to that, the usage of wireless remote control devices helps the firm avoid the expensive and risky equipment dismantling and stripping. It actually eliminates the necessity for operators and engineers to be in direct contact with the running machinery. This means that the personnel would be operating in a safer and more freely manner away from the machines' debris, noise, dust and vibration that could potential harm them allowing them by that to acquire a better perspective on the functioning and health state of the equipment and their possible failures. For instance, industrials are using today in a much frequent way robots sending them to some dangerous locations so as to bear the risks while they are based in safer locations doing all the controlling tasks. Consequently, the operations would be mostly executed in a faster and safer way increasing the productivity, profitability of the company and the security of its workers. On the other side, machine learning advanced algorithms allow not only to collect huge amounts of data but more importantly to select the most relevant information and determine their degree of importance according to the criteria established by the machine learning engineers. In this direction, multiple data scientists are working harder to develop new techniques to get the AI programs into handling more efficiently the large amounts of gathered data and providing a better assessment. The progressive improvements in CM systems will permit therefore maintaining considerable levels of security and availability of information. Accordingly, novel intelligent systems are being introduced to the market so as to combine the outcomes of multiple sensors and allow the effective gathering of their data into a unified central hub. As we have already explained several times, sensors play a central role in the condition monitoring operations; this is why their selection has to be carefully performed. Typically, today's technological innovations has enhanced greatly the performance, quality and accuracy of these devices which signifies that companies aren't bound anymore to limited types of sensors with precise and restricted parameters but can actually make the choice to single out the ones that are more suitable for their machines and activities. As for the power supply challenge facing the CM sensors, industrial firms are trying to manage power more effectively for their remote instruments and adopt advanced methodologies to minimize their energy usage. For example, IoT praises one of its important concepts that is energy harvesting. Essentially, any given system that represents a certain change in its state can convert its form of energy into an electrical energy. Various instruments might employ this as their sole form of energy, while others are hybrid systems that utilize harvesting to elevate or expand the life of the used battery. In proper sequence, the energy that has been harvested can be stored and easily employed to power low-energy instruments like the IoT sensors for instance. There are other procedures that are being developed involving approximate computing and probabilistic design. Both of these techniques rely on the fact that infinite precision isn't that primary at all times when dealing with IoT sensors operating at the edge, mainly in use cases including wireless communication and signal processing. These schemes can therefore decrease the number of gates and power to an approximately exponential reduction over common hardware designs.*(Gall, 2018).* These are only some examples applied to optimize the usage of power sources. We have mentioned above the use of algorithms in handling the data collected and processed in CM structures. These algorithms must be suitable for the tasks undertaken and the types of machines involved. Thanks to the great developments in the fourth revolution of the industry, companies have more choices of advanced software and intelligent systems so as to select the most suitable programs for their equipment and activities. This wide diversity has played a vital part into making the software, the sensors and all the other intelligent or smart devices more affordable, less complex and easier to use and to maintain. In contrast to what a large of industrial believe affirming that technology is usually a source of complexity and waste of time of money, the innovative technological tools can be the solution for the CM problems if used properly. However, we often place a heavy load of responsibilities on the technicians and analysts in monitoring and assessing the gathered data and blame them for many failures occurring during the CM process. The truth is that we can make their tasks much easier and leading to better outcomes by implementing the right devices and the most accurately possible programs. It is true that even with these tools, the personnel has to make significant efforts in presenting a convenient analysis to the collected streams of information but their job would be less complicated and the mistakes percentage would be definitely lower. The importance of technological innovations in CM systems doesn't rely only on the improvement of the overall effectiveness but also on the time and resources optimization. Typically, by choosing to adopt AI, CPS and IoT adequate programs, the company will be capable of performing its operating in a faster way and the maintenance schedules will be less busy. Consequently, the failures pointed by the CM systems would be taken care of in a less amount of time and more importantly without influencing the order pile of the rest of the maintenance operations. In other terms, the company would find less difficulty in respecting its production and maintenance schedules and won't be facing less minute wearing parts delivery or replacement activities. It won't need to subcontract out the needed tasks because it will have enough resources and time to prepare for them internally. Thanks to CM advanced intelligent systems, the company would have relatively shorter inspection periods and a larger stability when it comes to the wear and degradation rates making the prediction of potential flaws more accurate. Hence, this will allow pinpointing exactly where the company should perform replacement of wearing parts and undertake the necessary preventive or corrective maintenance actions. The increase in the accuracy level of the utilized sensors is as we have noticed one of the biggest advantages of the innovative CM systems; for this reason the installed alarms that are usually set on when there is an indication on a significant deviation of the standardized parameters would produce a limited number of warning points that would actually signify the existence of an urgent situation. Thereupon, the unneeded inspection or maintenance interventions would be practically cut short with no more losses in time or cost.

As we have explained all above, the innovative improvements in CM programs and tools would ultimately endorse the organization's capabilities of surpassing multiple technical challenges that could potentially impact negatively its productivity and profitability. Moreover, they can also help the company overcome the managerial issues resulting mostly from the mistakes made the management teams in relation to the CM activities. Indeed, industrial IoT strategies and innovative machine learning tools make sense in the available information, quantify it, analyze it carefully and provide the adequate insights on how to proceed with the involved processes and procedures based on the given data. Overtime, these mechanisms can be employed to enhance the planning schedules for the monitoring activities and manage more effectively the funding requirements, the standards, the database implementation and other demanded specifications. It appears vital to acknowledge that today's technological devices and systems aim to simplify the industrial operations as much as possible; this is why the implemented tools themselves are nowadays easier to use then what they used to be decades ago. This will encourage companies on installing technological and analytical training sessions for their operators and engineers as these courses will be less time consuming and less complicated and above all less costly. Training in this case wouldn't be ignored anymore by managers but put instead in the high priorities of the company's projects' establishment. Nevertheless, various executives find it difficult to choose the right technology or the suited intelligent systems for their types of equipment. Some of them used to adopt elementary technologies or single kinds of systems because applying more sophisticated ones or a large number of these tools used to be high-priced while others had the tendency of combining distinct types of programs due to their need of performing various functions simultaneously. With today's novel programs, the company can easily purchase the system that can be more affordable, less complicated and more manageable by its personnel. Technological systems' providers and startups which are developing constantly new schemes are offering a wider selection of innovative condition monitoring mechanisms for the industrial organizations so as to choose the ones that would be more adequate for their structures, their machines' technical requirements and their financial capabilities. Such initiatives will boost the managers and executives on including the workers in the choice of the appropriate technologies and letting them therefore interact fully with the selected CM programs. The involvement of the workers in similar decisions might seem without importance for some but the truth that it will have a great impact on reducing many of the monitoring mistakes made primarily due to the insufficient engagement in the learning process and the inadequate analysis for the collected data. As a consequence of these improvements, the condition monitoring systems would be as proactive as desired and will concede the achievement of higher levels of performance and maintainability. Additionally, the personnel would be more aware of the critically and significance of the CM tasks, and not just the operators or engineers who are concerned with these activities but also the ones who operate in other departments. Likewise, organizations are paying extra attention to the development of semantic doctrines, as we have already mentioned on the section 2.2.1, as a way of enhancing the communication channels and making sure that everyone will have the needed knowledge and expertise in handling the novel systems or any possible changes in their interactions whether they are expected or not. Also, the communication aspect is further reinforced with the high-tech networks of sensors and devices granting the people to exchange information and communicate more easily and by that take the adequate decisions. Another crucial point to indicate is the fact that the great majority of the innovative systems today come with their own standards. This means that the company isn't any longer obliged to create new standards that can end up being unsuitable creating by that integration issues and incompatibility problems. In other words, the related organization can simply put in place the novel technology in question along with its standards and update it whenever needed.

Talking once again about the data feature, the relevance and significance levels aren't the only aspects to be considered when collecting information and assessing the observed variables. The company must as well accord enough importance to the amount of data gathered. It is not required necessarily to collect huge quantities of information in order to assure an accurate analysis of the machinery health state and a better prediction of the potential faults; still it is vital to acquire enough data. As matter of a fact, the size of the dataset has been always a center of attention for the industrials and IIoT specialists are we collecting too little or too much data; a question that has been repeating itself during the last years. The answer isn't always that obvious, but various current machine learning algorithms and heuristic statistical programs have shown themselves capable of determining the exact size required for the data according to the complexity of the problem and other parameters established in advance by the machine learning engineers as well as indicating the convenient data collection intervals so as to optimize the maintenance and operation performance and remedy eventually to the presented failures in time.

Even if the company adopts extremely advanced condition monitoring systems or procedures, it can still encounter some hindrances in relation to their appliance. Put differently, if the organization doesn't know how to use properly the innovative programs then there's absolutely no point in applying them. Therefore, so as to ensure a higher profitability of the established systems, the management has to make sure that the outputs of the condition monitoring devices are being properly followed and the CM employees are accorded the needed time to accurately monitor, assess and report the results. Such recommendations are much easier to establish when the innovative tools are easy to utilize and allow achieving the required monitoring for the equipment in question, which is actually the case for a large number of the programs introduced to the market nowadays. Nonetheless, not every single technology can be implemented in any given industrial context; there are certain intelligent systems that do not match with certain types of machines or tasks. This is where managers in accordance with the condition and maintenance operators and engineers must interfere to choose the convenient kinds of adopted tools that could be implemented successfully without engendering any incompatibility issues. This task has been hardly performed in the past but today is more easily done thanks to the diversity of the existing and emerging innovative concepts and also due to the fact that the manufacturing companies providing these technologies are offering detailed recommendations for the industrial organizations so as to overcome these kinds of obstacles.

We have tried during this subsection to explain the level of importance of the innovative technological CM tools including the usage of wireless sensors, the Internet of Things, the software, the advanced analytics, the machine to machine communication, the cyber-physical systems, the artificial intelligence, the cloud computing and other concepts. The great significance of these features relies mainly on the fact that they aid the company to surpass its problems when it comes to controlling adequately its equipment and managing properly its CM operations.

2.3.2 Importance of innovative technological advancements in PdM

We have exhaustively analyzed in the subsection 2.1.12 the various obstacles and problems challenging the PdM systems. The innovative technological improvements introduced to the predictive maintenance concept whether they are linked to the technical or organizational aspect are considered to be crucial as they play an essential role in fixing these issues and upgrading the performance, the productivity, the maintainability and the availability of the equipment as well as the safety of the personnel and the quality of the outcomes so that the customer base can be fully satisfied and bring eventually a maximum degree of profitability to the company. The current innovative tools contribute greatly to the resolution of one of the biggest challenges facing the PdM mechanisms that is the huge amount of financial, technical (hardware and software) and human resources needed to check up on the health state of the related equipment and generate the necessary orders for the maintenance activities. Indeed, today's technological PdM systems' suppliers and manufacturing providers offer a large variety of innovative devices and systems that can be affordable and simple to implement and use for the industrials in comparison with the traditional or old-fashioned PdM entities. The point of installing such programs isn't improving the maintenance or monitoring tasks for the operators and analysts by making them more convoluted but to assimilate facilely the gathered data and gain a thorough understanding in both the IT and machinery concepts. This signifies that the workers won't need any lengthy or expensive training courses to be capable of acquiring the necessary knowledge about these novel mechanisms. Also, the solid combination between machine to machine communication and artificial intelligence transforms human –based decisions into data-based ones with significantly reduced human intervention eliminating by that the possibility of having human mistakes. And as more organizations adopt IIoT approaches and techniques, the high up-front cost would be considerably diminished and the company in question wouldn't be obliged any longer to spend huge economic resources at the beginning of the novel PdM systems implementation nor feel the need to turn to condition monitoring contractors to reduce these costs. Furthermore, the establishment of intelligent PdM systems increases the production levels leading to more consistent outcomes. Under these conditions, the maintenance tasks wouldn't be time consuming and the managers won't ask to put in place some additional maintenance procedures so as to answer to the equipment repair requirements which would require again more time, money and workers. It is important to indicate as well that the remote technology hold a primary part when comes to solving the over maintenance issue that might hamper the productivity and profitability of companies which decide to adopt predictive maintenance approaches as a central maintenance policy. Another critical point to consider when discussing the importance of technological enhancements in PdM systems is the fact that they allow a smoother integration of their tools into the industrial environments assuring by that a better adjustment of the novel devices or programs within the existing ones. This is mainly due to the fact that the great majority of these programs come along with their own architecture design and their operational requirements making it much easier for the engineers to establish the needed operational and technical feasibility. Following so, these systems can be actually ready for usage; so they are tested and verified and this is where test engineers could interfere to examine if there is any eventual installation bug so it can be fixed immediately. The relevant system is ultimately put in use after making sure that no problem has been left without resolution. The advantage about today's advanced mechanisms is the fact that this process can be easily put in place and more importantly the follow up procedures to ensure that the systems in question are functioning flawlessly are even easier to establish. In this case, the company would find it more effortless to spread awareness about the appropriate utilization of the new business models, software technology and the innovative strategies that have been introduced among its employees whether they belong to the predictive maintenance teams or not.

However, this new era of connectivity presents a serious issue linked to the security of data. As the data becomes the most valuable resource for companies, it becomes the first target for criminals increasing by that the threats of cyber attacks and the security risks. This has made several industrial organizations believe that IoT development is more a curse than a benefit for them. Nonetheless, with these advanced systems comes the solution for the security challenges. In the past few years, security specialists have been developing methodologies to avert hackers from accessing the company's data. It is true that there be always security flaws for intruders to exploit but this will be much harder even impossible as the systems become more sophisticated and acquire more advanced options. For instance, the newer authentication instruments allow a better protection for data and the ID sensors are of great help in this sense. Other effective IoT tools prevent as well the unauthorized entry to the organization database such as the modern video technology and the motion detection algorithms and smart locks. Thusly, companies have started to grasp that connecting the security devices with their mobile devices would certainly ameliorate security. *(Ijaz, 2018).* Additionally, there's a broader use of additional security procedures like encryption, efficient and solid password policies for employees, network secure devices authentication and the design of structures and material with the objective of optimizing security and privacy. Nonetheless, it is crucial to keep in mind that spreading security should be an adopted culture before turning into applied technical procedures. Employees must insert in their usual activities the concept of security through the smallest actions such as changing their login information on the used devices on a casual basis without being asked to do so. Consequently, the company ought to take the necessary steps to avoid any security problems prior to their occurrence. In a Forbes piece, *How To Make 2017 The Year Of IoT Security*, contributor William H. Saito states that engineers must reassess the approach. "*IoT systems have to design security from the beginning on the principle that they will be attacked and compromised*." *(Imaginovation, 2017).*

On the other side, the technological developments are believed to aid the industrial contexts on overcoming the problem related to the elevated uncertainty and risks of predictive maintenance practices that seem to disturb many of the maintenance providers. Typically, the combination of large and accurate database, flexible cloud computing and elastic cloud platforms, AI and IIoT is becoming a central driver for digital transformation in this new era leading the most significant improvements of information processing in any given industry. Such innovative tools will enable achieving a proactive and targeted determination of potential opportunities and precise identification of the possible failures of machinery and services improving by that the maintenance tasks and increasing the standardization, regularity and above all the regularity levels. In other terms, they will cut decrease the duration and frequency of the unplanned maintenance interventions, permit to schedule the PdM tasks more effectively and make a more productive use of the human and material resources internally without having the need to outsource them frequently. Furthermore, the extensive usage of the Internet of Things through its sensors and actuators allow a better discovery of the unusual operational patterns that are deviating from the standard ones. Consequently, even if the company applies alarm units to trigger the required corrective actions, these warning signals wouldn't be numerous reducing ultimately the excessive number in maintenance actions and the needed spare parts. Moreover, maintenance decisions wouldn't be based on these alarms but on the prediction algorithms generated mainly by the machine learning platforms. Put differently, instead of choosing the apply maintenance jobs and taking the machinery constantly out of service so it could back again to its normal functioning, the company will look for valuable opportunities in order to optimize its resources.

Another critical point to be regarded in this discussion is the quality of data with the focus of its main aspects; its accuracy, its consistency, its integrity, its completeness and its timeliness. The amount of IoT information is escalating rapidly in multiple industrial environments. Although there is a significant amelioration in the comprehension of the quality of data at the network and the device levels, multiple obstacles are still hindering the full generation of high quality information across the organizational and industrial structures. Data quality is therefore of an essential importance especially in the era of AI, automated decisions and continuous process optimization. For this reason, technology providers are developing software solutions that can solve the potential bugs or improper handling of cases or any issues in the related machinery such as the system-level inconveniences and the changes in the data formats. The novel systems are designed with the assumption that at some point there could be problematic information feed or unexpected quality issue. Such modern data-intensive platforms would typically include accurate and consistent data streams, post-processing logic and an inclusive range of analytical or cognitive components. These advanced and well elaborated scenarios deliver eventually high performance data processing pipelines feeding and maintaining several data stores. This will allow the definition of a reliable data environment which would empower the existing analytical models, implement solid real-time decision making and improve the knowledge extraction and the AI applications' quality. *(Krasadakis, 2017).*

For many years, the implementation of sensors used to present various issues for the industrial companies due to the fact that these devices are sometimes incompatible with the existing machinery and procedures or do not adapt properly with the industrial environment. This can be explained by the limited options in sensors that used to be presented to the companies. Hopefully, this isn't quite the case anymore as nowadays vendors offer more choices in the smart sensors that can actually enhance the predictive maintenance strategies. The advanced industry 4.0 enabled sensors allow currently more solid and open communication standards and protocols within the smart devices and the industrial systems or subsystems ensuring a full interoperability across the employed technologies. Though, applying the latest sensor intelligence isn't just about ensuring accuracy in speed, location or data collection but goes further into maintaining reliability and steadiness in the inputs of the connected monitoring software. Hence, the early sensor identification of problems enables the operators and maintenance engineers to search, analyze, plan and schedule the necessary corrective maintenance that should be performed at the right time with the right tools. Still, it is stated that several industrial corporations have another concern that is the rapid obsolescence of the chosen sensors. Oppositely, the majority of the technology providers or manufacturers consider that this challenge is the base for their own profitability and a motivation driver so they could continue creating and developing better and more effective technological PdM systems and tools. They even offer low-cost instruments and systems so that the companies wouldn't' be losing huge financial resources. In today's growing IoT market, appears a new definition of the term "future proofing" which used to refer to keeping the technology as long as possible as a methodology of the company to reduce its costs and maximize its return on investment. Typically, this old-fashioned description of the term doesn't apply any longer. In this new era of technological advancements, future-proofing isn't about outguessing the future and selecting one single adequate technology so as to never be obliged to replace it ever again nor it is about avoiding the unavoidable change. Future-proofing is simply a continuous lifecycle and a management process that has the goal of expanding solution flexibility while taking calculated choices and managing the imposed risks. *(Chan, 2017).* It is likewise important to mention that compatibility insurance doesn't only involve the adequate choice of sensor intelligence or the right software but resides mainly in the consistence in communication channels between the workers, the devices and the executive managers. Indeed, a strong communication will endorse the decision making and the problem solving procedures. However, a solid communication doesn't signify an over interdependence of the relevant structures per se. Indeed, the main advantage of today's cyber systems and technological tools is how they are capable of securing autonomous features while being connected with each other, exchanging information and interacting without any physical or analytical obstacles. This will permit furthermore to grant better interconnections within the industrial platforms and stronger interfaces between the IT systems and the rest of the organizational and operational mechanisms of the company leading to a sophisticated integration of the related structures. Still, communication is constantly associated to the security aspects as industrials believe that if sharing an open exchange of data among workers can seriously put in danger the security level of the company's datasets. While, the truth is that if the novel IoT , CPS and AI systems are properly used with respect to the safety and security standards, then the data sharing among the involved parties wouldn't be threatening at any cost. The great significance of the innovative PdM systems and tools relies principally in creating the opportunity to gather technical, material, human and economic resources all working together in harmony so as to build a fully integrated predictive maintenance multisystem that can respond effectively to the organizational and operational objectives of the company.

Through this part, we have observed how important are the technological improvements brought to the PdM systems in the industrial contexts and how they are actually able of helping the relevant organizations in overcoming some of the major disruptions they might face in their implementation procedures and processes.

2.3.3 Technical and operational feasibility of technological advancements in CM with respect to industrial conditions

It is crucial to assess the technical and operational feasibility of the technological measures that we have explained in detail in the subsection 2.2.1 in order to illustrate if they can be actually implemented in the current industrial contexts and if so conclude further how they will actually solve the challenges facing the CM systems. Indeed, if the advanced condition monitoring tools and systems, chosen by the relevant company, appear to be convenient in terms of their adaptation to the industrial environment, then they can be highly efficient and of a crucial help to the machinery users in relation to the early detection of degradation or the upcoming issues. But if the applied programs are not adequate or even not feasible or installed in an unsystematic and chaotic manner, the outputs could be disappointing when it comes to the overall operational costs and levels of accuracy and safety. In this case, the efforts of installation would be a waste of time and financial resources. When studying the feasibility of the novel CM systems, it is essential to assimilate that even though the related programs might be technically and operationally feasible, they could be not be feasible from an organizational or structural perspective and therefore ought not to be applied. For this reason, the kind of industrial environment, the status of machinery, the type of assets and the company's culture and policies are real factors to be taken into account on this matter. It is obvious that these variables differ from an organization to another. This is why; we will mostly concentrate on an overall assessment of the feasibility of advanced CM techniques.

In order to implement the new invented CM mechanisms as an effective approach for identifying the maintenance requirements of the machinery in question and upgrade the quality of industrial procedures, some conditions must be met. Factors such as the easy physical access to the installation of the condition monitoring system, the manageable levels of complexity of the data acquisition and data processing must be obviously considered. Moreover, the cost related to the installation, operation and data processing or any other costs of the means utilized to perform the condition monitoring tasks should be examined closely before any implementation. In addition to that, the adopted CM approaches or techniques should be known and acknowledged by every single level of the firm, starting by the top leaders and executive managers till the engineers and operators that shall perform the related operations. The company has to make sure that everyone involved must acquire the necessary training, competences and expertise to handle the potential changes to the existing CM systems in an effective and safe manner. The needed amounts of resources to perform the established monitoring and maintenance activities should be subsequently determined and assigned.

We are witnessing today some significant improvements related to the utilized software in CM systems. Therefore, to insure an operational and technical effectiveness of the chosen software and the success of its operations, the company must make sure that it allows above all answering some basic demands. In other quarters, it should permit a better integration of all information associated to the machine health status in one unified program. The latter must have an open and an easy access to all involved parties and be ready to be modified when needed. The chosen software must acquire a solid and coherent sharing of data across the functional lines. For that, the adjustment to the machinery parameters, the environmental and the timing variables has to be on point; otherwise the program won't be capable of delivering the results. Multiple companies can use extremely advanced software and still face a total failure when it comes to its establishment and that because it hasn't prepared competently for its installation and usage or hasn't checked its technical feasibility. The selected software should be able to reduce lengthy learning curves and eliminate any possible software platform compatibility problems. In case it doesn't succeed to accomplish so, the company must replace it by another program or ask the original manufacturer to modify its parameters if this is doable. We have previously clarified that the developed software is mostly utilized in correlation with the advanced remote control instruments. These devices are becoming more important with time as environmental laws become more biding and decreasing funding considerably diminishes the available workforce. The economic feasibility of these tools depends on their manufacturing characteristics and the company itself. Concerning the technical and operational ones, they are more linked to the specific technical characteristic of the site or the facility, the staffing levels and expertise, the size and complexity of the machinery, the geographic location, the regulatory requirements and standards and the nature and frequency of operations where monitoring and control would be helpful. Furthermore, the company must make sure that the selected remote devices should be compatible with the adopted techniques (thermal imaging, vibration, ultrasonic...). More importantly, the feasibility of the software and the used remote tools is directly connected to the ability of the company on establishing clear and unified semantic regulations and principles so as the analysis of data would be simpler and more accurate. If all these conditions are applied, the industrial organization would find it quite easy to install the advanced CM programs and follow the development of their related processes.

On the other side, a great number of industrial corporations utilize wireless sensors. The scope of developing low-power microelectronics; the miniaturization, the manufacturing of sensor material, the design and the creation of complex and precise shapes have guided the industrials to the comprehension of intelligent mechanisms and programs for health and environmental monitoring reasons. With the development of materials science and technological advancements joined with the great opportunities starting from wireless networking and the usage of the Internet, the scope of sensor appliance has expanded significantly. Nevertheless, resourceful initiatives such as wireless monitoring mechanisms will build up a competitive advantage if the systems in question can function economically with resistant technical capabilities. The wireless condition monitoring technology usually employs interface modules in order to gather vibration or temperature information mostly from machinery in the industrial facility and then transmit the collected data to the software system responsible of diagnostic. Wireless sensors are consequently considered as feasible alternatives to handheld or hardwired condition monitoring systems, especially compelling for primary equipment which do not demand real-time machinery protection but necessitate a more regular monitoring percentage than the portable regime to determine possible deficiency modes. Wireless sensors are proven to be quite useful for applications that are logistically complicated or dangerous to monitor or control by handheld information collectors, or could probably call for more recurrent sampling than the walk-around route can financially sponsor.

When talking about the technological enhancements in the CM systems, we ultimately think about the introduction of the industry 4.0 in the industrial structures. The IoT is a first factor to be considered when analyzing the matter. Usually, a condition monitoring solution that is performed by an IoT industrial maneuver is carried out by equipping first of all the industrial machinery with sensors that will gather information on a large range of variables indicating its health and performance such as temperature, pressure, vibration frequency. Once collected, the data is transferred to the cloud. Following that, the cloud software accumulates the data from the used sensors and applies analytics devices to transform time-series data into descriptive insights concerning the machinery health state and the relevant operational variables. A condition monitoring solution apprehends the findings and passes them over to the users in an all-inclusive manner like in the form of diagrams or charts, etc. If the situation diverges from the norm, the condition monitoring resolution might as well send an alert to the maintenance managers, informing them about the degradation of the machines' condition. Typically, the information provided by the condition monitoring system offers an important insight about the actual state of the machinery and could be executed to indirectly control the quality of goods in production, through monitoring the condition of the equipment's parts. For instance, in paper manufacturing, condition monitoring solutions aid to monitor the quality of paper being fabricated through monitoring the state of roll presses. Still, the usefulness of condition monitoring isn't limited to quality control. Its findings could be employed to predict future machinery performance, forecast which equipment components are more likely to fail and determine on the scope of maintenance tasks based on the anticipated levels of deterioration. *(Shiklo, 2018).* The IoT techniques operational feasibility depends to a large extent on the capability of the company to choose the right sensors and software to undertake the specific monitoring activities. To ensure a complete integration of the IoT tools, it must establish an accurate execution of the IIoT steps and a thorough follow up of the applied procedures in order to achieve a better outcome. Companies have obviously become more interested in the computer based systems for health monitoring utilizing procedures and methodologies developed in the Artificial Intelligence field. They rely more often therefore on what they call "expert systems. An "expert system" is an intelligent computer code that employs knowledge inference methodologies or approaches to resolve issues that are seen as complicated enough to necessitate considerable human expertise for their resolution. The knowledge base of an expert system resides in facts and heuristics. The facts constitute a body of data which is largely and commonly agreed upon by specialists in the related domain. While heuristics are defined as rules of judgment and rules of good guessing or prediction that symbolize expert-level decision making in the industrial field. *(Meher-Homji, 1985).* At this point in time, it has been proven that a great variety of expert system software providing prognostics and diagnostics of the relevant machinery are today absolutely feasible technically and operationally. Still some industrials still believe that "expert systems" are regarded as an aid to the maintenance engineers or the monitoring specialists and aren't made to out think the experts or replace them in anyway while others maintain an opposite view. Consequently, it has been established that condition and cloud based prognostics and diagnostics provide the needed opportunities to decrease loss engendered by equipment deficiency and deferment in planning for maintenance tasks and spare parts. Still, the time complexity of the predictive algorithms employed for forecasting forthcoming component faults or the remaining useful life of critical machinery elements holds a crucial part in indicating the accuracy and also the feasibility of prognostics mechanisms. Moreover, the architecture and internal characteristics of the cloud computing programs adopted by the firm in question plays a significant role in determining how these advanced systems would be feasible.

As we have seen there are multiple factors deciding to what extent the explained technological programs and tools are feasible in a technical and an operational contexts. Again, this would depend on the economic capabilities of the company to install these improvements and establish the adequate follow up tasks to maintain their lasting performance.

2.3.4 Technical and operational feasibility of technological advancements in PdM with respect to industrial conditions

While assessing the technological advancements in predictive maintenance, it appears vital to study their technical and operational feasibility. The IIoT applications have become widely employed lately due to their significant advantages to the quality of operations and performance of related machinery. In fact, a large number of companies utilize different IIoT approaches for predictive maintenance as a way to decrease the maintenance costs and limit the frequency of maintenance tasks. The IoT platforms constitute a very good aid for predictive maintenance systems as they can integrate data from various machines or manufacturing equipment. However, an essential negative point in integrating industrial systems with IIoT platforms that must be indicated is the communication framework giving that the major communication protocols are usually incompatible and inconsistent with the modern communication protocols implemented in IIoT systems. This signifies that in order for the company to ensure a total technical feasibility of the IIoT platforms, it has to work harder on making the novel adopted communication tools and procedures match in a broader perspective with the existing ones. In other terms, the related organization ought to assure more solid and effective connections between the standard industrial devices and the web platforms. Therefore, the feasibility level depends to a large extent on the capabilities of the company to construct useful approaches and tools to translate the industrial machinery language in question to IIoT ready instruments and programs. In addition to that, the company must grant a special attention to the interoperability aspect which is mostly dependent on the standardization conditions and the communication protocols and represents the ability of the distinct IT systems and software to communicate, exchange and utilize information. *(Lacob and Parpala, 2017).*

It is quite obvious today and for most companies that combining predictive maintenance with artificial intelligence solutions can actually offer businesses the needed edge when it comes to maintaining their existing infrastructure or hardware. The major advantage of this blending is the warning that the company gets that a certain deficiency is about to be developed. If we also add to this, its ability to predict optimal operational patterns of the machinery, then we could easily conclude that the novel PdM solutions are much more efficient that the PdM traditional approaches. Still, a proper application of the relevant intelligent systems necessitates a convenient organizational work to garner entirely the expected rewards. In other words, the involved personnel, mainly the engineering maintenance teams, should be aware of the required advanced analytics competencies to build smart predictive maintenance systems. For instance, arduous-to-measure enhancement systems or programs such as Six Sigma or Lean require to be controlled with the company's new analytics abilities. Furthermore, maintenance workers must learn to employ the complete analytical capabilities of the presented intelligent solution. It wouldn't obviously make any sense to apply a total monitoring process on multiple machines when only a simple adjustment on a precise component is demanded.

The introduction of industry 4.0 mechanisms and approaches has to be carefully elaborated so as to ensure an effective operational feasibility of the related programs. So, in order to construct an advanced technological predictive maintenance solution, the organization must describe its use case in detail by defining what it wants exactly to predict, its business benefits, the data available to it, and the hypotheses it acquires. The signals and the failure examples that the company has gathered must be compatible with its use case. Nonetheless, the most elementary requirement to establish properly a predictive maintenance solution is to obtain the right dataset. It would be definitely ideal for the company to hold a dataset that illustrates identifiable machinery deterioration. In fact, for the company to be capable of starting the smart predictive maintenance journey, it has to define clearly the use case then make sure that it has or can produce at least an adequate dataset to match the use case in question. Following so, in order to validate that its dataset acquires the compatible pattern to construct the required model, the organization must utilize simple data exploration procedures to indicate whether the data involves any signs of deterioration or deficiency patterns. Once the company holds evidence of clear pattern, it can be qualified to set up the needed machine learning models. *(Dhingra, 2018).* As for building the adequate learning algorithms in relation to the PdM systems, it is crucial to prepare carefully the required data allowing by that to reveal certain patterns. Once the data has been gathered, it is more vital for the engineers to use the right algorithms for the machine learning models construction. The best way to accomplish a higher degree of accuracy is to choose the metrics that align with the teams' objectives and the equipment state of degradation.

Reducing the production costs and ameliorating the efficiency requirements have been primary goals for the manufacturing organizations. The most suitable approach to achieve these objectives is to enhance maintenance effectiveness and efficiency by integrating PdM devices and systems into cyber-physical production programs. Nevertheless, this integration is far from being an easy task for the relevant companies. This is why the firms must generate suitable and effective integrated production and maintenance planning systems in the complex cyber-physical production organisms employing mutli-criteria decision making platforms. Such applications will allow the cyber physical systems to install resilience and inject interoperability into the predictive production systems so that the overall manufacturing productivity could be optimized. Additionally, it will be expected from these applications to endorse the feasibility of the CPS into the predictive maintenance programs.

While discussing the technological improvements in relation to PdM programs, it seems quite important to underline the applications of machine to machine communication and their usage in industrial contexts. Indeed, the emergence of entirely embeddable instruments has elevated the bar on machine to machine technical abilities. Even if this technology isn't that recent, but its appliance has been relatively restricted until nowadays. M2M technologies engender considerable amounts of information that are mostly orders of magnitude larger than what operators have worked with before. Real-time big data computation capabilities have allowed the flood gates for developing novel predictive analytics into an otherwise uncomplicated data log programs providing real time monitoring and control to take the necessary preventive action in case of any deviations. Condition-based maintenance, smart metering ,usage-based maintenance and load generation are some of the predictive analytics use cases for machine 2 machine. It would be therefore accurate probably to say that the possibilities are various and the industrial firms are working hard in order to collect the benefits through cost-savings and innovative service offerings.*(Palem, 2013).* Nevertheless, the technical feasibility of M2M tools isn't simple either and requires some strict managerial and operational preparation to construct the needed base and structures for such innovative changes into the PdM organisms.

Still, it remains essential to keep in mind that each company has its own procedures to follow in order to assure the technical and operational feasibility of its advanced predictive maintenance solutions. It might as well expected for these approaches to evolve or change as their novel systems change or as the market develops innovative maintenance and monitoring tools and programs.

2.3.5 Business advantages of technological advancements in relation to CM systems

In the past few years, industrial organizations have come to the conclusion that the innovative improvements introduced to their condition monitoring systems haven't only helped surpassing the technical, managerial, organizational and operational challenges they have encountered but furthermore they have brought significant benefits to their relevant structures. Enterprises, mainly the manufacturing ones, tend to acquire large volumes of industrial machinery that require a lot of monitoring and maintaining. Consequently, the implementation of industrial IoT allows considerable enhancements in the decision making processes due to the higher availability of more accurate information. It could eventually ameliorate as well the production quality and uptime, as the data collected from sensors and devices on the network permits real-time and predictive maintenance across the industrial facility. The major point of establishing IoT bases CM systems is to be capable of making machinery smarter and more efficient at making decisions than humans. This depends on accurately, persistently spotting and transmitting the gathered data. For this reason, technology providers within the market are offering leading edge sensors that can provide highly reliable and precise measurements. This data would be coupled with real time and advanced analytics that could procure better inner insights on how the equipment is operating. Moreover, utilizing machine learning, the systems would be qualified to capture potential patterns which could possibly pinpoint at future failures and if the outputs are concerning they should be investigated immediately. Such information used to take a lot of time to be discovered when adopting traditional CM tools as the company would rely primarily on the availability of skilled professionals on every site. Oppositely, the technological improvements today would enable the usage of real time data which can aid those with the right skills control or monitor multiple machines in various locations taking by that better decisions faster and increasing the efficiency of the CM operations. *(Ismail, 2018).*

IoT based condition monitoring brings a strong foundation for process and business optimization. It provides multiple advantages to the CM systems. Typically, IoT enables cloud storage for large amounts of data. Indeed, it leverages cloud computing which permits the depository of huge quantities of collected information from connected machines in the cloud scaling by that the storage capacities. For instance one wind turbine would generate 2000 readings per minute which make approximately one terabyte per week. In case condition monitoring is applied for the objective of predictive maintenance, an IoT based CM solution puts in execution machine learning algorithms in order to draw a conclusion about machinery's state of health and to enhance diagnostic correctness as well. Nevertheless, machine learning is a CPU (Central Processing Unit) exhaustive course of action that necessitates sufficient computing power and parallel processing with multiple machines functioning in cluster. A cloud based condition monitoring solution procures indeed enough computational resources to make machine learning algorithms operate properly and efficiently. Another benefit of using IoT in CM systems is the ability to use a diversity of data from multiple sources or machines. Machine learning algorithms demand an important amount of information. For example, to prepare a predictive model that indicates vibration values inducing cracking of welding equipment's spindles, the data of a large number of cracking cases is required. If we rely on the data taking from one machine, the collection operation will take several years. While, the gathering from multiple welding machines synchronously will last about a year. In addition to that, the variety of data accumulated from different physical locations is expected to elevate the accuracy level and to enhance the functionality of predictive setups. Moreover, industrial IoT enables less intervention to shop floor processes. IIoT presents an opportunity to cleverly control hundreds of industrial machines from a single site without physical access to them. It is mainly useful for some industries such as electric power and oil and gas since it facilitates the monitoring tasks for remote installations counting the pipelines and the offshore drilling rigs. Thereupon, the data concerning the health and the performance of the machinery is gathered, assembled and communicated to the cloud for processing. Subsequently, the cloud assesses the collected data and features the outputs to the reliability specialists anywhere in the organization. (*Shiklo, 2018).*

The Internet of Things has brought the development of sensors to the next level. Smart sensors including infrared, light, motion, air quality, humidity, ultrasound, pressure sensors are usually employed to catch real time information that can be assessed and made available in order to upgrade decision making, traceability, process control and quality assurance. Continuous monitoring holds an essential part in protecting valuables assets from unfavorable environments through enhancing the operations' conditions, quality and supervisory conformity and enabling furthermore a better establishment of predictive maintenance mechanisms. Condition sensor networks have various applications like for instance industrial automation, energy management, environmental monitoring and disaster management. They are freely joined and integrated for retrofit or mobile/moving elements. *(Streich, 2018).* For manufacturers, IIoT represents itself an opportunity to score massive revenue potential in a variety of ways. Connected sensors can indeed collect and communicate real-time data about the quality and the performance of the product or the individual elements or parts of the machinery and materials. From aircrafts to automotive engines and sensitive medical equipment, for example, installing sensors on components as they go through their design and buildup progression conveys significant information associated to quality, durability, maintainability, performance, reliability, safety and other aspects. Though, the monitoring and gathering of information doesn't end once the related products are out of the manufacturer's site. Embedded sensors and control equipment can actually contribute in capturing potential problems in design, components and materials and eventually enable manufacturers the capability to better comprehend how customers are using their products. If we consider the example of manufacturers of refrigeration cases, we can conclude that they might not acquire any precise idea on how their machinery performs in the field until a support call occurs or until a request of repair comes under the warranty period. Therefore, the usage of condition monitoring sensors will allow the manufacturer to visualize and analyze closely the performance of the equipment or product prior to the occurrence of any failure. Based on the information they have received and assessed, manufacturers could help their customer bases and clients avert the possible disruptions and the performance issues. These enterprises could then as well employ the collected and analyzed data so that they could revise later on the design-in characteristics and the pre-engineering procedures and processes in order to complete better and more reliable and durable performing products and outputs. Also, there won't the need any longer to travel to visit production facilities so as to register their findings manually. In fact, the accumulated data from IIoT could ultimately generate immediate attention, followed by corrective intervention like repair, replacement or maintenance action for instance. Furthermore, data on how resources are put into use within the industrial facility can aid to reform the production schedules and permit organizations to better capitalize on opportunities for reserves and savings or plant enhancements. Utilizing sensors to gather information can as well facilitate for the firms to benchmark their machinery one it leaves their sites. They can log and compare information from machinery in various physical locations or where the equipment is settled in multiple operating environments and observe exactly how they function comparatively. This process could bring to light hidden operational inabilities that could probably go undetected until a terminal deficiency takes place. Additionally, manufacturers could employ and assess the data they receive to present more adequate predictive maintenance solutions and warranty programs. Instead of picking up calls when things go wrong, sensor data can actually allow the manufacturers to get warnings and alerts for service when something urgent occurs, depending on the performance of the machinery deriving from the recommended parameters and standards for optimal performance. The ability to access product or equipment status information in real time is extremely important for support services, mainly because it makes for much more effective root cause analysis and solution development. For enterprises making end consumer products, the introduction of IIoT procures an efficient way to upgrade customer service and induce as well higher sales revenue. This involves definitely a better all-around customer experience leading to an improved reliability and performance of the equipment in question and a higher profitability of the value added and IoT based services for the company. *(Vanderpool, 2017).*

On the other hand, the machine to machine (M2M) communication allows reducing considerably the operational and maintenance costs. Indeed, it decreases the need for physical intervention or visits to control or handle assets and machinery, enables to carry out calculations for logistical profits and optimizes the industrial processes for a better and faster and less costly functioning. M2M offers continuous communication channels within the organization. It never sleeps, so the data is constantly available in real time, ready to monitor and to measure 24/7, 365 days per year and since the information is kept on a cloud-based connectivity management platform, its access can be from any location and from any device. Besides, M2M enhances the quality of operations due to high level of control it has over the monitoring tasks. It also makes the company engage smarter work methodologies as it could direct the tasking staff towards more productive goals since the majority of daily tasks would be performed automatically without human intervention. *(Challenger Website, 2017).*

As for the usage of remote wireless sensors, it can also bring several benefits to the existing condition monitoring systems in any given industrial context. Firstly, the use of such sensors eliminates the necessity for operators or engineers to be in direct contact with the running machines. In other terms, the worker can operate safely by placing him/herself away from the moving parts, harmful noise, dust and vibration or falling debris that might happen. Employing wireless remote control enables also the operator to move more freely and get by that a better viewpoint of the job being executed. This is more possible in the case of robots usage in industrial facilities as the operator can send the robot to do his/her job especially in hazardous environments staying by that in a safer position and making the machine take all the risk. An obvious advantage of utilizing a remote is that it leads to less fatigue than the traditional manual equipment operating. Remote technology might captivate the interest for younger audience who is more knowledgeable of the physical damage caused by manual labor. Since employing remote control devices does not fatigue the technicians or operators in the same way that operating manually the related machinery, workers are capable to evade any possible injury and remain by that in the workforce for a longer period of time. Decreasing the physical obligation of strong endurance enlarges as well the labor pool available to contractors who are aiming to discover and keep skilled and experienced personnel. This will eventually scale down downtime for technicians and reduce the risk of physical injury on the work. While operating with much less fatigue raises the production level, putting in use remote control instruments contributes in more consistent outcomes. For instance, let's contemplate a simple example of a remote-controlled surface preparation machine. We can observe that with manual equipment, the technician is pushing the machine long in a straight line, but what exactly occurs when the operator decides to speed up or to slow down a bit? The floor will simply look different in these spots in comparison with the rest of the working facility. While if a remote-controlled machine is actually used on the floor, then the worker can set the adequate speed and pressure to end up with a unified form. In another example, some remote-controlled wall saws and core drills could accordingly anticipate when they hit steel reinforcement and decrease the feed speed while elevating power to the cutting instrument. An experienced technician might be capable of doing this by feel in manual mode, though as the fatigue sets in the day wears on, no operator would be able on keeping the same consistency and the same speed as an automatic remote controlled machine or device would do all day long. We can therefore conclude that the wireless remote controls allow upgrading greatly the entire workload and operational processes while maintaining a safer environment for the operators and enhancing the total efficiency of the operations in question. Vibration and noise are also diminished even stopped by using remote controlled machinery. In addition to that, the advanced remote control tools can further make it possible for the technicians to manage various tasks at the same time saving by that time and resources and increasing the overall productivity of the site. *(Micheals, 2016).*

It appears important as well to exhibit the positive impact of artificial intelligence (AI) on the condition monitoring systems. The AI did what no human could do. Thanks to its smart solutions and its advanced machine learning algorithms, it enables the monitoring of highly complex assets, potentially saving thousands of hours in downtime and entirely optimizing the condition monitoring routines. *(Messer, 2018).* Artificial intelligence decreases the percentage of errors and increases the precision and accuracy of the related industrial tasks. Moreover, AI and the science of robotics make it possible to explore more difficult and hostile environments with greater safety insurance. These technologies can be executed therefore to help the operators overcome more easily their limitations and be put in use for instance in mining and other fuel exploration processes or to explore the ocean floors. Due to the innovated programming of robots, they can apply more complicated and harder jobs with bigger responsibilities without having to wear rapidly nor facilely. These intelligent systems unlike human do not necessitate regular refreshments or breaks. They could function for several hours non-stop and be programmed to adapt to certain variables and respect specific parameters' values. This means that the condition monitoring operations would be performed on point respecting the operational and maintenance imposed schedules and the productivity objectives.

The cloud technology is composed of layers, mainly the front end and the back end. Concerning the front-end layers, they are the ones that specialists and engineers usually interact with. While, the end-back layers reside in the hardware and software architecture that usually support the interface that the personnel look at. Since all the used computers and intelligent systems are connected to each other and operate in correspondence, the associated applications take advantage of all that processing power and function as if all these CM mechanisms were operating on the same computer. Cloud computing or cloud platforms offer by that various advantages to the condition monitoring systems including reducing the costs, facilitating the CM operations and potential maintenance ones, improving the flexibility of machinery control, increasing the data storage capabilities, upgrading the communication within the IT interfaces, securing in a better way the networking among systems and operators and leading to greater profits. Typically, the cloud which is applied to the condition monitoring solutions, allows the access to the data from any location in the world by anyone who has an approved access counting third party specialists and analysts without having to add additional costly infrastructure. This will make it as well much easier to control the remote installations such as pipelines, offshore drilling rigs and furthermore small industrial sites with restricted resources through existing Internet connections, 3G cellular technology, or satellite communication. *(Berberian, 2019).*

The integration of cloud and wireless sensor networks is a crucial part of the Cyber-Physical Systems (CPS) used in CM activities. Indeed, CPS provides solid network integration features such as media access control procedures along with their impact on system dynamics, middleware and software that procure regulation and coordination over the existing networks, control over timing of network transactions and proceedings and fault tolerances. Such advanced tools would enhance the interactions between humans and the actual systems. Naturally, they will allow the measuring and the modeling of situational human perception of the equipment and its awareness of the potential changes occurring on the systems and the industrial environment which will lead to a better determination of the key parameters of the monitoring processes and contribute therefore to a much thorough decision making procedures. Moreover, CPS enable to deal better with uncertainty. As difficult as it might be, CPS can actually be capable of evolving and operating with completely novel and unreliable environments. CPS are as well able of delivering better system performance in relation to feedback and automatic re-design with close cooperation and communication of sensors and cyber infrastructure. As part of cloud computing, CPS are also apt to provide the needed resources to the equipment depending on their requirements improving by that their scalability. The cyber physical systems would also grant the industrial facilities a higher flexibility than Wireless Sensor Network (WSN) or cloud computing applied alone. Another advantage of CPS appliance is the increase of the fast response time and the enhancement of deficiency detection and resources usage within the industrial sites. *(Bhrugubanda, 2015).*

2.3.6 Business advantages of technological advancements in relation to PdM systems

Industrial organizations that have introduced industry 4.0 and its related innovative technologies into their operations and structures, have witnessed tremendous changes and considerable advantages mainly when it comes to the appliance of the predictive maintenance techniques. From improved productivity and enhanced worker security to streamline inventory control and quality management, the benefits are increasing by time. Next generation manufacturing equipment utilizes built-in sophisticated sensors and advanced programming tools in order to ameliorate the performed predictive analytics and anticipate possible failures before they occur. This won't just reduce downtime, but further data-based predictive assessment will eliminate the guesswork from any existing preventative maintenance strategy giving by that engineers enough time to schedule, plan and initiate the needed repairs when the machinery if dormant or offline. Introducing IoT into the predictive maintenance practices allows predictive analytics to concentrate on equipment or devices that need continuous attention leading operators and engineers to make the required adjustments on their stocks of tools and spare parts as seems convenient. This will eventually make significant savings in money, space and above all in time on the industrial facility. Besides, some machines will be capable of executing self-maintenance. Consequently, their effectiveness would be enhanced by eliminating the need for additional technicians. Smart predictive maintenance strengthens as well the safety of the workforce. It enables the establishment of an accurate follow up of the related machinery so it could be maintained properly if needed avoiding by that any sudden malfunction that could pose a serious risk to the security and health of the operators and engineers. According to recent studies, the smart factory is expected to exceed $200 billion by 2022. Its huge expansion is stimulated mainly by PdM innovations such as the IoT, big data and advanced predictive analytics which are awaited to raise productivity and profitability levels to brand new heights. *(Matthews, 2018).* This breakthrough of innovations would bring benefits to all parties involved from manufacturers to consumers.

With the development of industrial artificial intelligence (AI) and IoT, all industrial businesses are being reformed with software; huge amounts of data aren't only managed to analyze the past or monitor the present but to predict the future. As connectivity and data accessibility become nowadays cheaper and more outspread in multiple industries, organizations are more looking into predictive maintenance or condition based maintenance empowered by machine learning and AI. Indeed, companies have greater capabilities with AI and machine learning algorithms to accurately process massive quantities of sensor information better and faster than ever before. Predictive maintenance employs data from multiple sources such as historical maintenance records, sensor information from machinery and weather data so as to indicate when a machine will require to be serviced. Utilizing real time asset data in accordance with historical data will allow operators making more informed decisions on when exactly a certain machine would necessitate an intervention or a repair. Smart predictive maintenance takes significant amounts of data and by employing artificial intelligence and PdM software, transforms that data into useful insights and data points helping the company overcome the data overload issues. Typically, sensor data and machine learning programs make it feasible for the firm to rapidly to bring added value into huge volumes of unorganized data. Therefore, the smart PdM tools enhance the existing maintenance policies and strategies by introducing AI to make sure that the workers have the right knowledge and gain the sufficient expertise to maintain the mission-critical assets operating at their maximum productivity and performance. *(Uptake Website, 2018).*

Mobility Work is accessible from any location and any smart instrument. Any operator can simple log in to use or modify data or scan radio frequency identification (RFID) code on a piece of equipment so as to acquire all the needed information. By combining integration of the IoT with a constantly growing list of aspects, Mobility work will grant the operators and engineers a full access of all relevant data gathered by real time sensors so as to take the necessary actions and react automatically and immediately. Furthermore, CMMS and IoT allow upgrading the spare parts management. In other quarters, CMMS and IoT procure all company's divisions with a dataflow on when and how physical assets are utilized. This permits furthermore the included departments to follow closely the usage of spare parts and determine the purchase of novel ones. The sensors installed on physical assets seize and process data to the CMMS where in the information is stocked and assessed in the context of asset's records. Such an approach develops game-changing opportunities. For a start, operators can actually plan their interferences depending on predictive maintenance analytics and practically perform the required repair of the component or the machine before it breaks down and even the break down actually takes place, the maintenance team will be informed immediately through the implemented CMMS. This signifies a significant improvement of the production cycle thanks to use of advanced predictive analytics and innovative proactive maintenance. As we have explained above, the gathered data is used primarily to forecast when the machinery is wearing down or needs repair. As an obvious consequence, the unplanned downtime can be easily reduced and automatically the maintenance costs would be cut down as well. *(Peycheva, 2017).*

From a general point of view, O&M have a positive perspective on IoT predictive maintenance. In terms of change, the majority of industrials and PdM specialists don't assume that employment levels will be modified due to the introduction of industry 4.0 in PdM practices, however, they do foresee a transition in the job roles. Enhancements in Operational Equipment Efficiency (OEE) are greatly awaited. In fact, as we have mentioned previously, multiple companies believe that using, processing and assessing the data in real-time will lead to better decision making procedures. It is also believed that the appliance of innovative PdM systems will allow improving the financial results of the industrial facilities as the upfront costs of implementation will be justified by the benefits of these advanced programs and tools on the medium and long terms in terms of reduction of workforce and limitation of downtime and spare parts as well as the costly maintenance interventions. Furthermore as the capture, storage and use of real time operational data will become a high priority for the related company, the assets useful lives would be meaningfully extended. Smart PdM will widely upgrade the operational safety and health. It will contribute to the change of the roles and responsibilities of maintenance and reliability specialist and professionals and will eventually cause the convergence of operational technology and information technology. *(Jalan, 2018).*

The establishment of predictive maintenance has been greatly enhanced thanks to the introduction of M2M communication which enables a more accurate storage and gathering of data in real time so as to extract the necessary information and allow the operators monitoring and maintaining the equipment adequately. M2M sensors mounted on a machine or a device allow the continuous monitoring of its parameters and make sure it is functioning within the recommended tolerances. Once, they record a deviation of these tolerances' values, the technicians are informed to take immediate action. The huge advantage in the making of this process by M2M channels is the accuracy and rapidity in delivering the needed outputs. Indeed, data is transmitted through solid and suitable channels. The information being collected by the M2M sensors is being communicated by adequate networks that could vary depending on the devices. Though the choice of the channel would depend on some factors such as the device mobility, security protocols etc. After analyzing the data, trends for successful operation and maintenance are determined so as to develop a set of rules and procedures to follow in order to ameliorate the overall performance of the industrial facility. The stored information will furthermore permit to create effective maintenance schedules reducing by that the machinery downtime, the failures occurrence and the costs related to it. The combination of M2M connectivity and predictive maintenance is essential for procuring a business with the necessary Intel concerning the health and performance of its equipment and averting the potential deficiencies that could lead to serious human, material and financial damages. *(Fuchs, 2017).*

The innovative PdM concepts present a variety of benefits to the industrial companies. The cloud platforms allow the systems to be closely connected and exchange and communicate across the Internet facilitating their integration. Hardware costs and investment in information technology infrastructure are significantly diminished which signifies that firms wouldn't be forced to invest in their own data centers. Moreover, with a cloud based PdM solution, there's practically no time for expensive or lengthy adjustments and updates. The cloud provider would be capable of updating and maintaining the server as well as the application software. Cutting down the upfront costs would also encourage small businesses and start ups on implementing these advanced tools. Cloud-based computerized maintenance management systems (CMMS) could be evaluated by a web browser or an app. This signifies that maintenance staff could recapture data wherever they are placed. Maintenance can be monitored, planned, scheduled and automated from a web browser. Operators, engineers and managers can be sure enough that procedures and processes are traceable by examining casually up-to-date manuals or logging in real time. While cloud applications are able of cutting don the costs, increasing speed and enhancing the management of information and analysis, the key advantage is elevated equipment uptime. Data from shop floor can actually be transformed into meaningful information by the cloud application and utilized to progress from reactive to proactive maintenance. *(Wilkins, 2019).* Such improvements offer an accurate prediction of the future behavior of the machinery as well its Remaining Useful Life (RUL). The RUL itself is employed in order to schedule properly the PdM operations so as to avoid the potential deficiencies, the breakdowns and the stop time and to optimize the operational and maintenance interventions costs.

We can conclude therefore that the technological trends including the Internet of Things, big data analytics and edge computing are practically transforming the current industrial facilities into smart factories. Industrial Internet of Things sensors gather a vast collection of data from manufacturing machinery or items in production and communicate it to devices that can stock it and analyze it. As for big data analytics software, it shifts through the industrial IoT Intel, giving managers the necessary insights into the rights approaches to enhance the quality, streamline the production and reduce the costs. On the other hand, edge computing enables much of that analysis to be executed right on the facility floor which will eventually remove the burden on networks and the need to put in place IT infrastructure and reduce by that the overall costs. As an obvious outcome of these advanced technologies, it is expected that managers will have a larger visibility into their production processes gaining by that a huge competitive advantage in their related markets. For this reason, a large number of companies have started heavily invested in these technologies. Analysts at McKinsey & Company predict that by 2025, the economic influence of IoT factories will reach up to 3.7 trillion dollars per year. Consequently, edge computing is considered today as a technique for making predictive maintenance more efficient and more reliable. Indeed, in edge computing, devices assess the sensor data and analyze it on the factory floor. The outputs of this analysis are subsequently transmitted to the cloud or data center in order to produce the required insights. Such approach will permit firms to make more effective use of their network resources. A typical IIoT sensor could gather information about machinery pressure or temperature every couple of seconds or several times per second and the IIoT network could involve dozens or hundreds of these sensors. If the solution had to send all of the individual pieces of information to a single data center or a cloud computing site, it would probably consume all of the existing bandwidth on the firm network. Oppositely, with edge computing, factory instruments perform the majority of the analytics cutting down by that the data amount that has to travel across the industrial network. Moreover, edge computing saves organizations considerable financial resources on their cloud computing costs. Usually, most of the IIoT data is meaningful for a specific amount of time and then it could be eliminated. Therefore, if a company wants to keep this data for an extra period of time, it must pay additional expenses that could be highly expensive. Although, with edge computing, the quantity of stocked data is kept to a certain limited level and by that the related costs can be cut down. Another advantage of edge computing is the insurance of high availability. In some cases of IIoT implementation, the internet connectivity isn't always available due to the remote location of the relevant equipment or the unreliability of the mobile connection. With edge computing, the equipment and solutions in question don't require per se an Internet connectivity to perform the needed analytics tasks. *(DELL, 2017).*

We have tried to explain on this subsection the advantages of innovative technological tools so as to assess their impact on the PdM systems. It is easier therefore to sum up that industrial firms can get ahead of the competition by heavily investing in industrial IoT infrastructure nowadays. The key into making a full smart market today is by moving forward from the traditional and old-fashioned perspectives of the predictive maintenance concept and introducing fully innovation into its practices.

PART 3: Interactions between innovation, CM and PdM and the role of innovation as a business concept

Introduction

The third part of this thesis will be composed essentially of three brief sections. The point of this part would be to facilitate the comprehension of the overall framework that we are setting during this project by highlighting some crucial details on the innovation, predictive maintenance and condition monitoring discussion. During the second part of the thesis, we have started by defining innovation and its history, still, it remains vital to analyze the evolvement of innovation and its progression through the numerous industrial revolutions and generation models in order to discern the main revolution(s) that we are treating and interested in throughout this project.

As for the fifth section, it will illustrate the various connections and interactions existing between innovation, CM and PdM and how these concepts are operating all together in industrial environments so as to understand the position and role of these entities to each other and into the overall organizational structures. The interpretation of innovation evolution and its interactions with CM and PdM will be the basis of the construction of innovation's image not only as a source of novelty and creativity but furthermore as a business concept for industries all over the world. This idea will be discussed during the sixth section of this part and will constitute the foundation for the establishment of study cases on the fourth part.

Section 4: Evolvement of innovation through various industrial revolutions and generation models

3.4.1 The industrial revolutions

A large number of innovation researchers and analysts accord a great importance to a historical approach of innovation for various reasons. Indeed, innovation can be time and resource consuming, based on assumptions and speculations about the future and can be also considered uncertain to a certain extent. Therefore, the establishment of accurate innovation analysis requires not only a thorough comprehension of its history but mostly the understanding of its progression mainly through the multiple industrial revolutions.

- *First industrial revolution- 1765*

This first revolution extends from the end of the 18th century to the beginning of the 19th century. During this period, mechanization emerged as a process that replaced agriculture with industry as the new basis of the economic structure of society. The most critical innovation throughout this phase was definitely the mass extraction of coal along with the creation of the steam engine invented a new kind of energy power that pushed ahead hard all the processes and procedures thanks to the construction of railroads and the rapid development of material, economic and human transactions. Innovation was therefore visualized during this first revolution as an economy-wide process including organizational, technological and institutional transformation and involving numerous fields and products. *(Sentryo, 2017).*

- *Second industrial revolution- 1870*

A century later, at the end of the 19th century, new technological developments initiated the emergence of new sources of energy; electricity, oil and gas. Consequently, the development of the combustion engine set out to use these novel resources to their fullest potential. Additionally, the steel industry started to flourish and expand alongside the growing requirements and demands for steel. Also, chemical synthesis also matured to bring to the market synthetic fabric, dyes and fertilizer. Furthermore, communication tools had known a significant advancement through the emergence of the telephone and the telegraph, so was the case of transportation methods with the invention of automobiles and planes at the start of the 20th century. These innovations were made possible thanks to the focus of research and capital structures on industrial and economic model based on new large factories and the organizational applications of production as conceived by Taylor and Ford. *(Sentryo, 2017).* This second industrial revolution was known mainly by important organizational innovations that smoothed the way for connections between industry and formal science to become more solid especially through the 20th century. These strong links changed the innovation concept in so many aspects. Indeed, the training for the would-be innovators started gaining a bigger role and the importance of artisanal ingenuity decreased. Therefore, external institutions that had the job to perform such formal training and research began being extremely important as well. *(Bruland and Mowery, 2004).*

- *Third industrial revolution- 1969*

In the second half of the 20th century, a third industrial revolution emerged with the appearance of a new kind of energy with a greater potential in comparison with the other sources that is the nuclear energy. This period was characterized by the invention of electronics, with the transistor and microprocessor but also the rise of telecommunications and computers. This novel innovation has driven the production of miniaturized material which would ease the path to space research and biotechnology. This revolution was also considered as essential driver to the era of high level automation in production due to major inventions that are majorly automatons and robots. *(Sentryo, 2017).*

➢ *Fourth industrial revolution- 1969*

As we have seen the first revolution used water and steam to mechanize production, the second utilized electricity to develop mass production and the third revolution employed electronics and information technology so as to automate production. As for the fourth revolution which is based on the third revolution and the digital revolution that has been taking place since the middle of the last century, has taken its origin with the emergence of the Internet. The fourth revolution is regarded as the first revolution to emerge from a new technological phenomenon that is digitalization instead of emerging from a new kind of energy. Digitalization has allowed companies all over the world to build a new virtual world where they could control the physical world. The ultimate goal of various industries today and tomorrow is to be capable of connecting all production means to enable their interactions and connections in real time. Factories 4.0 have now the possibility of achieving high levels of connections among various players and objects in a production line through the use of multiple innovations such as Cloud, Big data and Industrial IoT. Innovation through the fourth revolution has greatly evolved and went a long road deviating from the energy greed trend to a more technological aspect of things. Consequently, the rapid developments of innovative technological tools has led to a wide diversity of applications that can be deployed in the industrial sectors such smart predictive maintenance, enhanced decision-making in real time, forecasting inventory based on production and upgraded coordination among tasks, etc. It is expected therefore that all of these improvements would gradually optimize the production tools and open the doors for endless possibilities for the future of industry 4.0. *(Sentryo, 2017).*

The following figure summarizes therefore these four industrial revolutions explained all above.

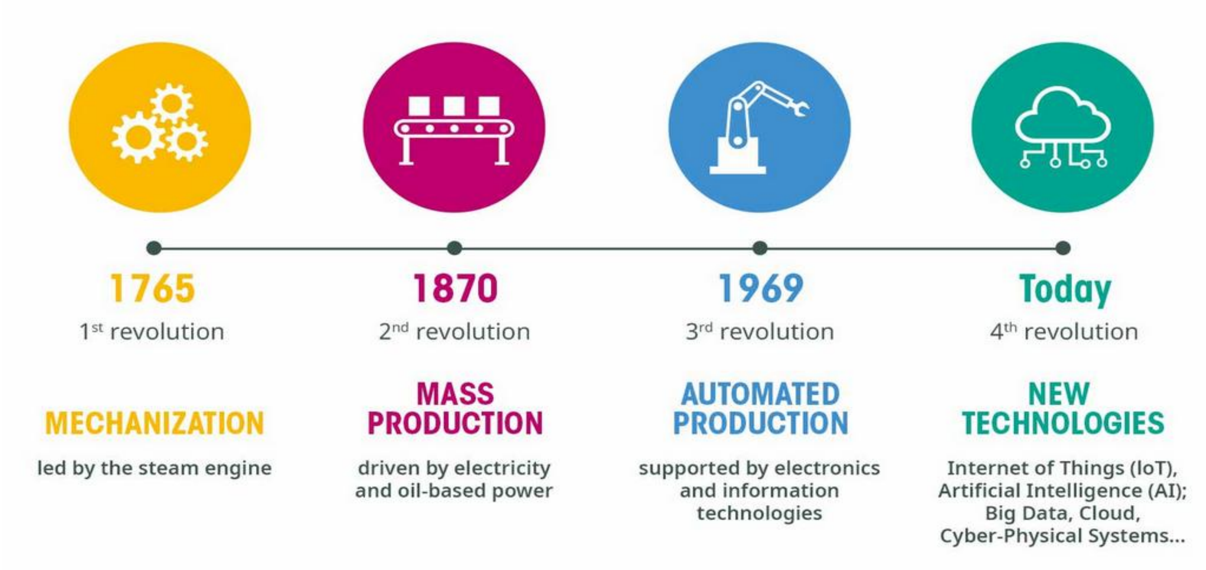


Figure 5: The four industrial revolutions (Visiativ-industry, 2019)

3.4.2 The innovation generations

Innovation can be defined as a process that comprises various phases and activities requiring resources, skills and knowledge. Therefore, prior any potential implementation, an accurate and rigorous comprehension of this process appears to be necessary. Typically, the understanding of the innovation process has known a significant development throughout the last decades from simple linear and sequential models to greatly complicated models containing a large diversity of inter and intra stakeholders and processes. The British sociologist Roy Rothwell was considered as one of the leaders and inventors in industrial innovation with his considerable contributions to the recognition of innovation management. He has therefore documented five generations of innovation showing by that that the complexity and the integration of the relevant models rises with each following generation as novel procedures and practices appear in order to adapt to changing contexts and respond adequately to the limitations and challenges of previous generations. Rothwell's five generations of innovation procure a historic perspective of industrial innovation management. He has discovered that each new generation was actually a response to a compelling change in the market like economic growth for instance, industrial expansion, strong competition, inflation, unemployment, resource constraints and others. The five generations of innovation management is therefore a descriptive model on how companies arrange their innovation processes over time. Rothwell's research has concentrated majorly on technological innovation at multinationals and high tech start ups. The model can be employed when designing a corporate innovation management strategy. *(Ipacso, n.d). (Buyse, 2012).*

- *First generation: Technology push*

From 1950 to the mid 1960's, rapid economic expansion enabled for a powerful technology push and industrial growth especially in the Western world and Japan. Companies brought therefore all their attention into scientific innovation adopting the approach of "more R&D in, more products out". *(Buyse, 2012).* This first generation represented then a simple linear structure viewing by that innovation as a sequential process executed through specific and distinct phases. Technology push is established on the hypothesis that novel technological developments based on R&D and scientific invention anticipated and pushed technological innovation through applied research, engineering, manufacturing and marketing towards successful products or inventions as outcomes. *(Ipacso, n.d*). In other terms, this generation was looking for solutions first prior addressing the market without truly taking the needs of the market into account. *(Hasan, 2013).* The following figure illustrates the major aspects of this first innovation generation model.

Figure 6: The first innovation generation model (Ipacso, n.d)

➢ *Second generation: Market pull*

The mid 1960's to early 1970 were known by a market shares battle with a growing competition leading firms to switch their development focus into a need pull. The main goal of companies was therefore responding to the market needs. Cost-benefit assessments and analyses were performed at the individual research projects level involving systematic allocation and management of resources. More solid interactions and connections were established between R&D and operating units by including product engineers in scientist run research teams so as to diminish time to market. *(Buyse, 2012).* Market pull perceives innovation also as a simple, linear and sequential process but this time the prioritization is all on the market need and demand. In this case, it's the market which is the origin of ideas directing R&D activities that only play a reactive role. Therefore, what actually distinguishes this model from the previous one is that instead of product development rising from scientific developments, new concepts and ideas emerge in the marketplace as research and development becomes as we've mentioned reactive to these requirements. *(Ipacso, n.d*). The following figure demonstrates the second innovation generation model.

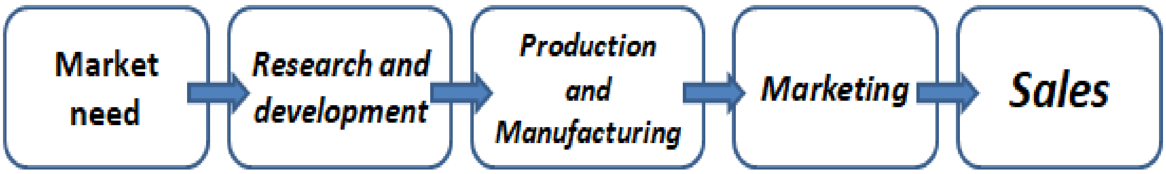


Figure 7: The second innovation generation model (Ipacso, n.d)

➢ *Third generation: Coupling*

From the mid 1970's to the mid 1980's, the strategic focus was mainly on corporate consolidation and resulted in product portfolios. Organizations have therefore departed from the ultimate focus on individual R&D projects. Marketing and R&D became more closely connected and coupled with the new integrated innovation processes. Operational expenses decrease was a main reason for the establishment of this coupling model. Technological innovation takes its origin from the combination and coupling of market needs and technological opportunities. It is not accurate to say that innovation results only of pure technology push or market pull forces, but it would more correct to express that innovation is the outcome of the merging and matching of both. Consequently, the model of the third innovation generation is still sequential but with feedback loops this time. R&D and marketing play a balanced role and the focus is on the interface existing between the two. According to Berkhout, third innovation generation models can be considered as open R&D models, highlighting the technical aspect via product and process innovation, omitting the non technical side residing in organizational and market innovations. *(Berkhout, 2006).* This signifies that third generation models tend to concentrate on the firm's novel technological abilities instead of involving applications for institutional boundaries and societal requirements. *(Buyse, 2012).* Figure 8 shows the third innovation generation model.

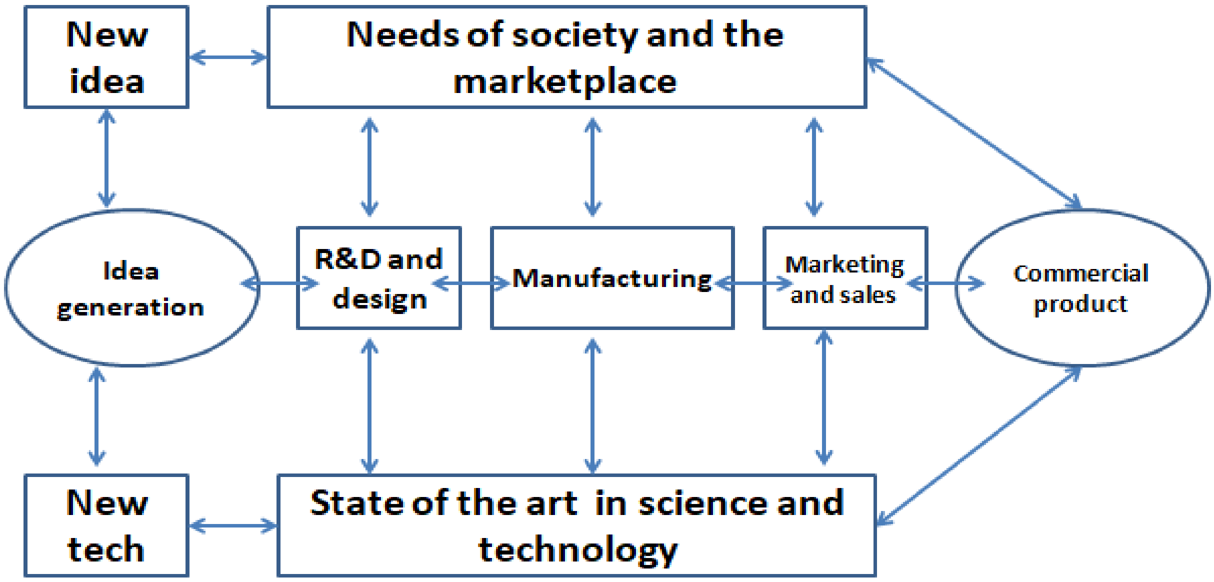


Figure 8: The third innovation generation model (Ipacso, n.d)

- *Fourth generation: Integrated business processes and cross functional teams*

When the Western economy recovered from the early 1980's to the mid 1990's, the core subject became a time driven battle as product life cycles diminished. The ultimate focus was on integrated procedures and products in order to create total concepts. The innovation process went from sequential deviation from function to function, to innovation as a parallel process of development, together with integration within the organization, upstream with leading suppliers and downstream with key customers. Unlike the earlier generations, this fourth generation isn't sequential, but cross functional by nature and often multi-actor. In this case R&D is just one of the functions included in the innovation process. The fourth innovation generation incorporated model underlines the concurrent and synchronized learning with customers and suppliers with the clear intention of reducing product development and product lifecycle. *(Buyse, 2012).* Thereupon, this fourth generation brought together cross functional teams that would operate on same projects so as to deliver innovations more rapidly and efficiently. *(Hasan, 2013).* The following figure illustrates the fourth generation model.

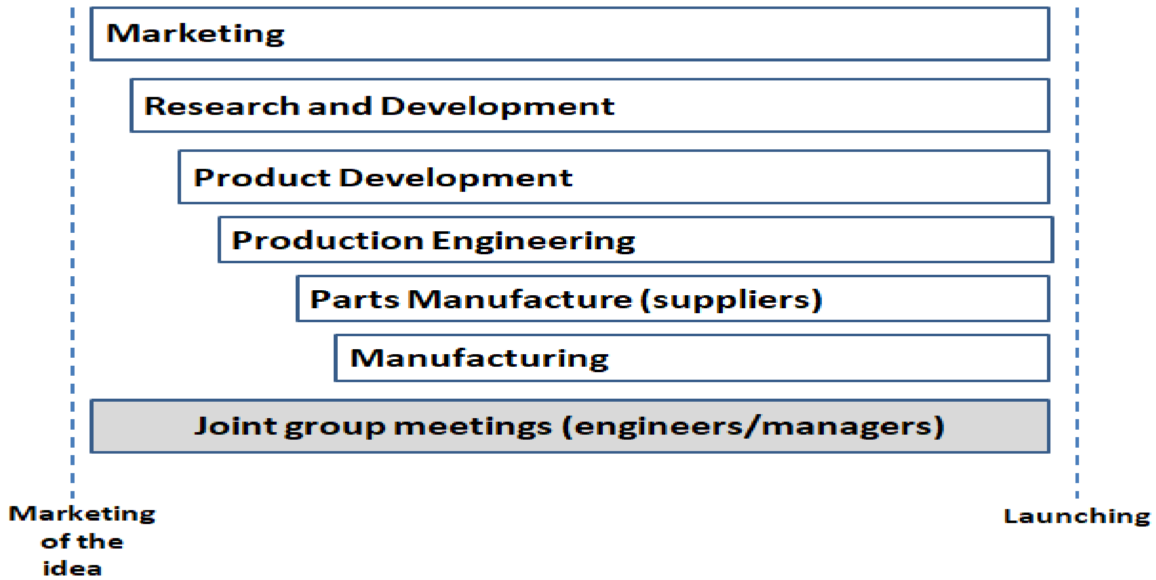


Figure 9: The fourth innovation generation model (Hasan, 2013)

- *Fifth generation: System integration and networking*

Starting from the 1990's onwards, resource constraints became elementary. Consequently, the main focus was on systems integration and networking so as to ensure flexibility and speed of development. Business approaches and processes were automated via enterprise resource planning and manufacturing information mechanisms. Expanding from the earlier generation of innovation models, fifth generation systems integration and networking models underscore the fact that innovation is a distributed networking process necessitating continuous transformation within and between companies, known by a variety of external characteristics including customers, competitors, suppliers, etc. The major features are all about the integration of the company's internal innovation practices and systems with the external factors. Additionally, the fifth generation models are defined by the introduction of ICT systems in order to speed up the innovation processes and communications throughout the networking systems in terms of increasing the development effectiveness and speed-to-market via strategic alliances. Moreover, the networking processes of the fifth generation are quite similar to the ones found in the fourth generation with an addition that is the time/cost tradeoff. Typically, being a fast innovator is regarded as a crucial parameter increasing the firm's competiveness especially in areas where rates of technological transformation are high and product cycles are short. *(Buyse, 2012). (Ipacso, n.d).* Rothwell has stated on the matter: *"many of the features of 5G are already in place in innovators that have mastered the 4G process; parallel and integrated operations, flatter structures, early and effective supplier* *linkages, involvement with leading customers and horizontal alliances. The most radical feature of 5G is the use of a powerful electronic toolkit to enhance the efficiency of these operations. While electronic measuring and computational devices and analytical equipment have for many years been important aspects of industrial innovation, 5G represents a more comprehensive process of the electronification of innovation across the whole innovation system." (Rothwell, 1994).* Figure 10 shows the fifth innovation generation model.

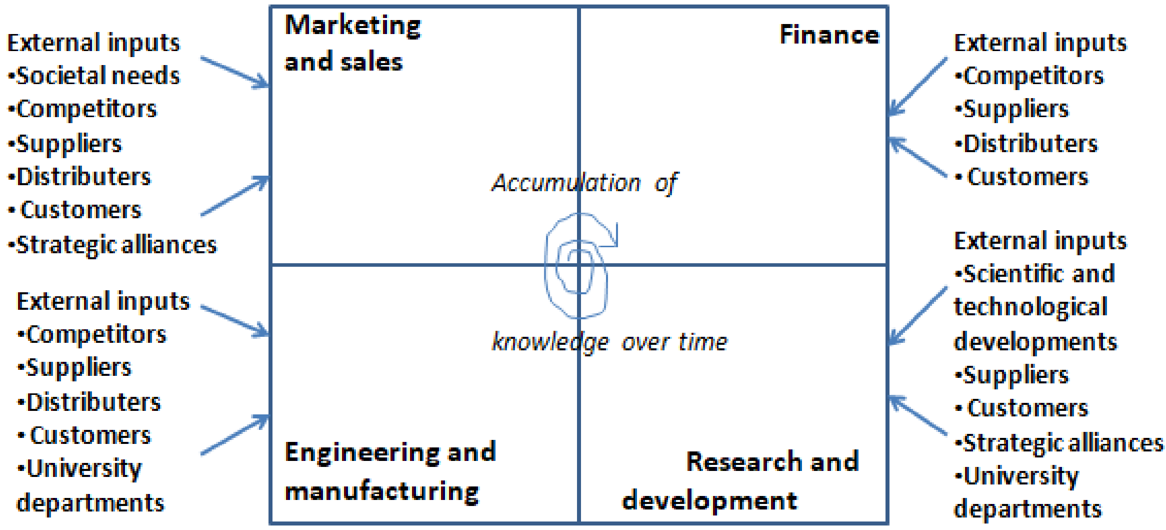


Figure 10: The fifth innovation generation model (Ipacso, n.d)

➢ *Sixth generation: open innovation*

Following on the seminal work of Rothwell, innovation generation model typology researchers and specialists have indicated that open innovation is considered the latest version of innovation models. Representing a controlling orientation to the previous network models of innovation, the open innovation approach isn't just restricted to internal idea generation and development, since internal and external ideas in addition to internal and external ways to the market are promoted throughout the innovation development chain. Open innovation is regarded therefore as a paradigm shift by which competitive advantage can be the consequence of leveraging inventions beyond the boundaries of a single internal R&D unit and can evenly benefit from depending particularly on their own internal paths to market through working with external firms that could be better placed to advertize a certain technology. On this matter, Enkel has determined therefore the existence of three major processes in open innovation:

- ❖ The outside-in process: it includes improving and expanding a company's personal knowledge base through the integration of customers, suppliers and external knowledge sourcing.
- ❖ The inside-out process: it refers to ensuring commercial/revenue advantages by introducing ideas to the market faster than internal development through licensing IP and/or multiplying technology, joint ventures and spin-offs.

- ❖ The coupled process: it integrates co-creation with partners via alliances, cooperation with the outside-in process (to acquire external knowledge) and the inside-out process (to bring ideas to market). *(Ipacso, n.d)*

The following figure demonstrates the sixth innovation generation model.

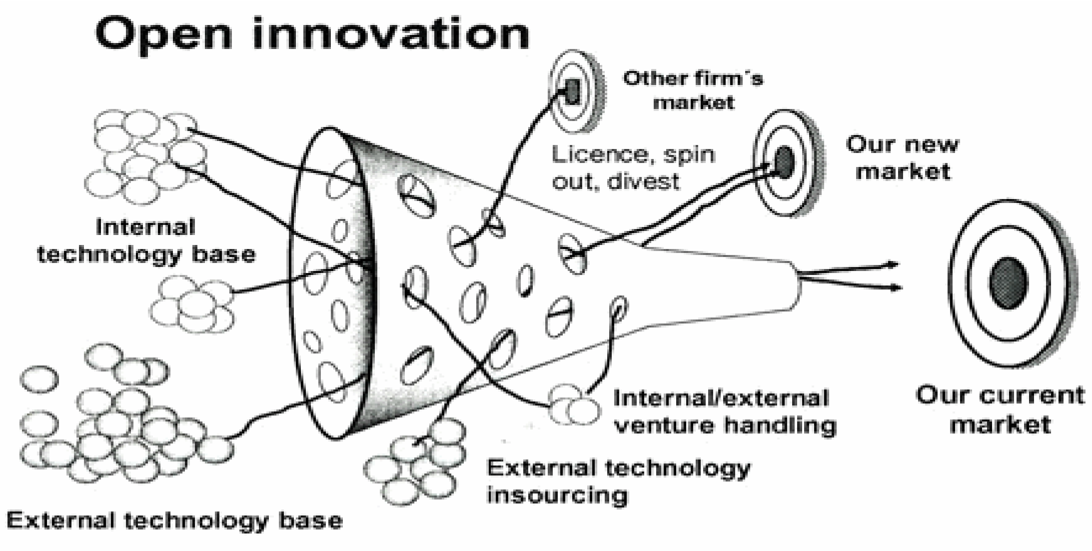


Figure 11: The sixth innovation generation model (Ipacso, n.d)

Concerning the first and second innovation generation models, they have been greatly condemned due to their exceedingly simplistic linear, discrete and sequential nature of the innovation process. These two generations had multiple weaknesses including the absence of feedbacks, the lack of networked interactions and technological instruments. Subsequently, the third generation illustrates how the numerous business functions interact through the innovation process in addition to combining the importance of technology push and market pull aspects. However, the major disadvantage of the third generation models is that they don't describe in details and enough mechanisms for communicating and interacting with the external and environmental parameters. As for the fourth and fifth generation models, there is a lack of evidence to show the influence of these models. Still, we can affirm that they went a long road in emphasizing the external linkages through the usage of integrated systems, advanced technological tools and extensive networking mainly for the fifth generation. Based on all the above and considering the variety of practices and approaches within a specified historical period, the concept of a generalized, prescriptive and isolated best approach can be quite puzzling and misleading. Lately, companies have started to invest more heavily in open innovation. Unlike closed innovation where innovation practices are performed within a single company, open innovation procedures are known as spanning firm confines demonstrating opportunities to diminish risk and commercialize both external ideas and internal ideas externally. *(Ipacso, n.d).*

In conclusion, we can confirm that there is not a single choice that regroups all solutions for designing and establishing a successful innovation process since innovation management and engagement is simply unique to its related organizational environment. However, there is a large set of information about innovation practices including the models involved, the array of rules, the details about R&D, the interactions with the market forces and the usage of knowledge as well as the advantages and disadvantages of the strengths and weaknesses of the numerous generations of innovation models. *(Ipacso, n.d).*

Section 5: Connections between innovation, CM and PdM

The various industrial markets are rapidly changing; we may call it industry 4.0 or the fourth revolution or the industrial Internet of Things. Whatever the name is, the result remains the same; operations are performed efficiently, on time, with a larger flexibility, in a safer and much more environmentally friendly way. The technologies and advanced products and services developed within the industry 4.0 are reforming the industrial applications and remodeling their related environments. Factory initiatives addressing artificial intelligence, cloud computing, automation, smart predictive maintenance and other innovative tools which are creating new opportunities for key players and new entrants to the industrial markets alike so as to work on suitable and novel solutions that would be capable of revolutionizing the industrial businesses.

All companies share therefore the same goal that is running their factories with optimal speed, high effectiveness and increased performance while maintaining their machines in a good operational health status. This signifies that the firm in question has to provide a considerable attention to the servicing, maintenance and repair tasks of its equipment through the wise and smart choice of the right maintenance and monitoring strategies and programs. The simplest approach is to plan maintenance activities at fixed intervals no matter what the condition of machinery is. A smarter approach is applying predictive maintenance which predicts equipment or component maintenance requirements in advance. According to a study by McKinsey, the usage of predictive maintenance would decrease downtime by up to 50 percent and save between 10 and 40 percent on machinery maintenance expenses. *(Faulisi, Janousek, Neumann and Tomarchio, 2018).*

It is important to underline that at the beginning, condition monitoring has appeared as a distinct technology application effort as industrials were only and simply employing its techniques and tools to monitor the condition of a certain parameter or parameters of machinery so as to indicate the existence of a significant change that could be the sign of an emerging failure. Following that, condition monitoring began to be combined and fused with predictive maintenance concepts and models for a better and faster prediction of potential failures. At this stage, it wouldn’t be possible for industrials to use PdM approaches without involving CM tools. Next, companies started to notice that this equation needed another ingredient which is innovation strategy. Consequently, they worked on improving both CM and PdM procedures and systems by adding innovation in order to create a solid and profitable business impact on its operations and structures. The following figure illustrates the gradual progression of CM and its combination with PdM and innovation through different stages.

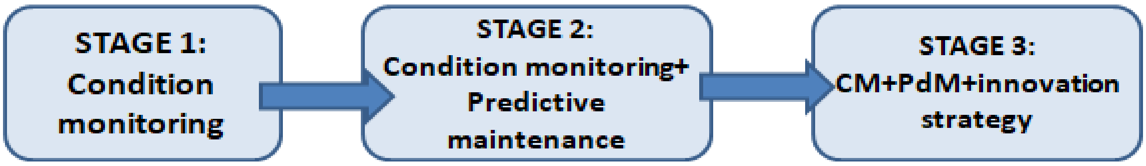


Figure 12: Gradual evolution of industrial application of CM and gradual fusion with PdM and Innovation

Predictive maintenance combines condition monitoring with dynamic predictive models for detecting failures modes and patterns ensuring by that a maximum level of protection and productivity of machines without having to increase the overall systems complexity. Condition monitoring is therefore an essential part of predictive maintenance meaning that PdM cannot exist without CM. Predictive maintenance relies therefore on condition monitoring and its various techniques through the measurement, analysis and assessment of the physical parameters or characteristics such as vibration, sound, temperature, visual inspection results and others.

During the second part of the thesis, we have detailed the benefits and advantages of PdM as it is regarded today for most industries as a "must maintenance strategy" for achieving successful business. We have also talked about the various challenges facing PdM tools and approaches and how innovation plays an essential role in helping companies to overcome and often solve these issues. We can therefore conclude that PdM is already in itself a suitable solution for many of the maintenance problems, though when adding to the equation technological innovative aspects such as sensing, connectivity, security, power management and embedded processing through cloud computing, IoT and AI capabilities, we will acquire all the necessary ingredients for developing a highly advanced sophisticated and high performance mechanisms that will eventually deliver the full benefits of PdM applications. This implies that when innovation's principles and practices are used as a rigorous, determinate and well defined array of explicit strategies having the objective of leading PdM and CM systems' progression, PdM and CM can more concretely achieve higher levels of quality, effectiveness and performance. For this to be accomplished, innovation has to be considered not only as a group of novel tools, systems or strategies but above all as a new way of thinking. In fact, adopting an open, still, decisive mindset allows the company to easily deploy novel, intelligent and smarter technological applications in relation to CM and PdM systems. Only in this case, innovation would constitute a key enabler of the establishment of smart factories and a core driver for enabling connected, secure and well managed innovative solutions to construct a solid and advanced future of CM and PdM mechanisms.
Following so, we will establish a relational diagram that will show more concretely the connections and interactions between innovation, CM and PdM within industrial environments.

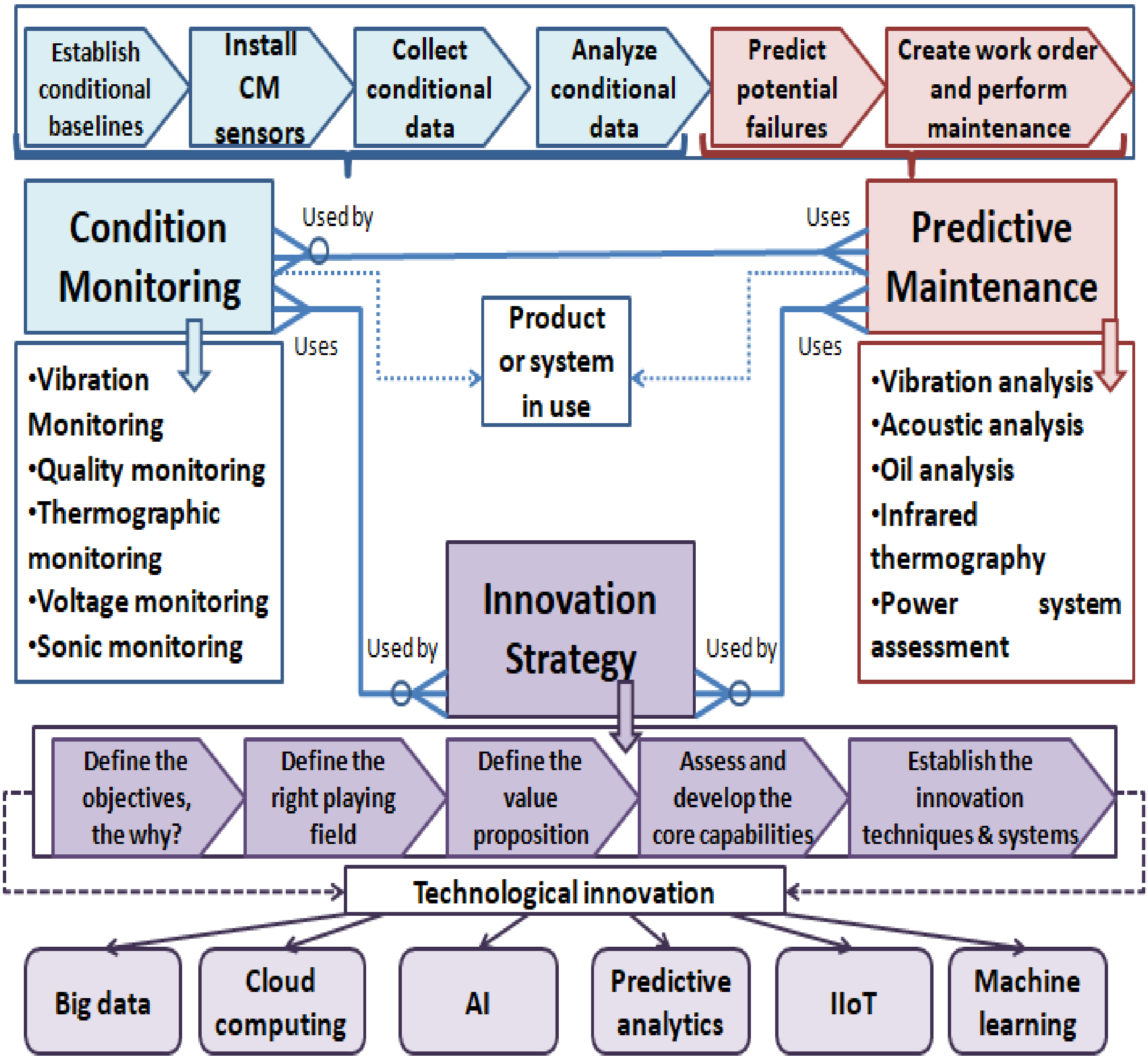


Figure 13: The relational diagram between CM, PdM and innovation

The figure above demonstrates the relational diagram between the key concepts of our project, that are condition monitoring, predictive maintenance and innovation, which shows the existing connections among these entities.

In industrial contexts, condition monitoring and predictive maintenance come hand in hand and are regarded as complementary concepts that are made to ensure an operational safety at every level. As illustrated through the process situated at the top of the figure, predictive maintenance is using condition monitoring techniques in order to predict the service life of the relevant equipment and the potential failures of its components that might occur based on the data that has been gathered and assessed through CM systems and on system-specific knowledge. Typically, the multiple CM approaches including vibration monitoring, current & voltage monitoring, thermographic analysis and others allow the controlling and monitoring of key parameters (vibration, temperature, electrical levels…) and the collecting of the related information so as to identify changes that indicate the existence of certain anomalies or damages leading to potential failures. This data is therefore considered the base for the PdM tools to undertake the examination tasks of information gathered from hundreds or thousands of sensors in order to ultimately perform maintenance repairs before a failure gets the chance to actually occur. However, there are multiple challenges and problems that might hinder the process combining the CM and PdM activities that we have detailed previously. The major obstacles revolve around the complexity and huge volumes of collected data. This is where innovation strategy interferes as an optimal solution to the imposed issues. Indeed, a well defined and clear strategy of innovative tools' usage would facilitate the CM and PdM operations and improve their effectiveness and performance through the deployment of connected, advanced and well managed systems. However, innovation strategy isn't about setting innovation tactics but much more about laying out the company's mission, vision and value proposition for designated customer markets. It establishes the relevant borderlines to the innovation performance expectations through streamlining and assembling the innovation work so as to achieve the desired output. Following this logic, innovation strategy can be defined as an explicit and rigorous roadmap for achieving the desired future and best possible outcome related to PdM and CM in our case. Therefore, building innovation into this clear-cut strategy starts by making a thoughtful choice on concentrating on the best ways to accomplish the set objectives and justifying the reasons behind that particular choice. For this reason, it would be adequate to firstly establish some precise steps to follow as a way of turning the image of innovation strategy from a complicated or confusing process to a simple and systematic exercise. As illustrated on figure 13, there are five main steps for developing a suitable innovation strategy capable of upgrading the expected future of PdM and CM systems. Obviously, the first step is about defining the objectives and strategic approach of innovation. It is essential to take a step back and consider the long term goals and know exactly what we would like to accomplish through innovation introduction. Secondly, we must determine the right playing field as in knowing the market we're targeting and would be operating in including the competitors and above all the customers that we are offering value for. If a company wants to truly improve the CM and PdM systems, it has to know what's already out there in the market and what is actually needed. Next, and probably the most crucial step is to describe that specific and unique value proposition. Since innovation's ultimate objective is to bring a solid competitive advantage, the company should focus on creating value that would make the CM and PdM tools more durable, affordable, efficient and able to provide a higher benefit through their usage. Subsequently, these three phases come down to one particular point that is the necessary capabilities needed for succeeding at the innovation initiatives. In other quarters, for the introduction of the technological innovations to be fruitful, the company must acquire the required values, knowledge, skills, behaviors and an overall innovation culture to be capable of building that. The ability to connect and structure these abilities accordingly is the ultimate key to innovation success. As for the final step which is about establishing the innovation techniques and systems, it is executed in order to apply the innovation strategy in a scalable and integrated way by finding out what systems exactly should be put in place. The company ought to define therefore which innovation techniques are needed to be able of bringing the innovation infrastructure components all together and also determine the most crucial systems that support and enable the measuring of innovation strategy's results. Once the strategy of innovation is established, the company would be easily capable of producing, developing, installing and evaluating novel CM and

PdM systems with a clearer vision on the potential opportunities and a greater ability on overcoming the possible challenges. *(Myllylä, 2018)*. As shown all above, technological innovation, which we are focusing on, is deployed through both the CM and PdM entities and implemented through their techniques so as to overcome the common mistakes made mainly through the gathering and analysis of information as well as the elaboration of predictions. To accomplish so, technological innovation presents through the fourth industrial revolution multiple innovative tools that all share the common goal of facilitating the PdM and CM operations and improving their overall performance while respecting the environmental and safety standards. We have mentioned through the presented figure some of these major solutions such as artificial intelligence, cloud computing and cloud platforms, Big data and predictive analytics, machine learning algorithms and industrial internet of things.

The three concepts; innovation, CM and PdM, all rotate around a central element that is the product, service or equipment in use as illustrated on the figure. This shows again that the ultimate goal of the combination between these concepts, their tools and their approaches is to upgrade the quality of the product or system in question and boost its efficiency constituting by that a strong competitive advantage for the firm and leading eventually to the its economic growth and increase of its market share.

Section 6: Presentation of innovation as a business concept

In most organizations, there is a limited number of individuals who can think through novel business concepts or develop adjustments to existing business models. In order to be part of this election of people, formal education is a must but the equation cannot function without an important ingredient that is imagination. Indeed, it is imagination and creative vision which drives motivation and it is motivation that fires execution. At last, a good and proper execution can easily outweigh a good idea. *(RMIT, n.d).*

It is crucial to make the difference between invention and innovation. Invention is completely a new creation, a new idea that has never been before introduced to the world. Innovation on the other side can be defined as the commercial application and the successful exploitation of the relevant idea. The process of innovation can therefore generate an invention, but the term is much boarder and wider in the scope involving the establishment of an existing notion or practice in a novel manner, or the application of a new technology to an existing product or system or process to enhance upon it; for instance the telephone is an invention while the Smartphone is an innovation. Typically, innovation signifies introducing something new into the business through upgrading or replacing business processes so as to increase efficiency and productivity and allow the business expand the range or quality of existing products or services. This could be also performed through developing entirely new and improved products or services or by adding value to existing products in order to differentiate the business from its competitors. Consequently, innovation is regarded as a catalyst for the growth and expansion of the related business enabling the company to easily adapt to the current changes and trends and grow significantly in the marketplace. For this reason, innovation ought to become an in-built part of the firm's business strategy where it would be possible to develop a solid innovation culture and encourage an innovative thinking and creative problem solving through its structures. *(Infoentrepreneurs, 2009)(Rouse, 2017) (Business.gov, 2018).*

In today's and tomorrow's economy, the measure of a good and profitable innovation is not essentially a new service or product but instead a new business concept. A business concept is the foundation of a business. It determines exactly why people need your service/product, how they can assess it and eventually pay for it and how the business will become competitive, effective and ultimately beneficial and profitable. *(RMIT, n.d).* A business concept is an idea for a business that involves basic information such as the service or product, the target demographic, and a particular selling proposition that offers the firm a competitive advantage. In other terms, a business concept might refer to a novel product or simply a new approach to marketing or delivering an existing service or product. *(BusinessDictionary, n.d).* Thereupon, a business concept represents the foundational idea behind a business. This is meant to procure significant direction for the process of coming up with a business plan and launching a company. What business concepts do capture is the unique and single value proposition of the related business in the context of a crowded market. *(Spacey, 2018).* Based on these definitions and analysis, we can easily come to the conclusion that innovation can be defined as a business concept.

Business concept innovation aims therefore to determine and indicate entirely novel approaches or ways of delivering a certain product or service to customers that they already need or want. Obviously, by doing so, the game on the market changes completely so at so become ready of welcoming new systems and practices that would be eventually capable of enhancing the related companies' performance, profitability and economic growth. We can for instance give the simple but clear-cut example of online learning as a business concept innovation. Indeed, it brings teaching tools and materials in an entirely different format and without all the problems or challenges and limitations that are usually linked with university studies. For example, students can log on and study texts, perform research via links, post material on discussion boards and deliver assessments and assignments from the comfort of their couches at home. Typically, the product being transferred that is the course hasn't changed; the change resides majorly in the delivery system and the interaction with customer which is the student. Consequently, the reason that justifies the success of online learning is that it procures the flexibility and ease that student are looking for. Moreover, the argument that says that online learning is restricted by the level of student interaction and networking is proved wrong through networked video discussions and tutorials. *(RMIT, n.d).*

As we have long defined before, innovation is the process of developing or creating something new or performing something in a new manner. When talking about business, innovation must go further to tackle the subject of improvement. In other quarters, to innovate in a business context isn't just about executing a task differently by further doing it better and more efficiently. Naturally, developing new products or upgrading existing technologies, procedures, designs and marketing will enable solving issues, increasing effectiveness, gaining new customer bases and ultimately reaching high levels of profitability and growth. In the business world, innovation often tends to become more than just a synonym of research and development. As the OECD states; innovation "*goes far beyond the confines of research labs to users, suppliers and consumers everywhere – in government, business and non-profit organizations, across borders, across sectors, and across institutions".(Ward, 2018).*

Innovation has therefore become today the absolute business concept that most companies are focusing on. Innovation when regarded in this context, would allow the accomplishment of business objectives through the entire organization with sights established on achieving core business aims and initiatives. The ultimate objective of "business innovation", as we may call it, is to create value for the organization. This value can derive from developing new revenue opportunities or creating more revenues and profits through existing services and products; from driving efficiencies that save time, money or both; or from improvements to productivity or performance. Thereupon, when companies concentrate on the business aspect of innovation, it makes it much easier for them to set up clear-cut and precise strategies and goals which would eventually provide them with better opportunities for achieving them. Looking at innovation from a purely business perspective has more benefits to the relevant company than potential drawbacks, still, the firm has to assess equally the risks and weight them against the respective profits so as to acquire a broader image of the implementation and introduction processes of innovation. *(Rouse, 2017)*

Innovation when implemented and introduced properly could represent a significant break-through for the related company whether it is a totally new product or service or an improved one, or whether it is a single major transformation or includes a series of small, incremental enhancements. Moreover the ideas in question can be produced from inside the business (from employees, managers, in-house researchers or development workers…) or generated from outside the business (market reports published by other companies, universities, suppliers, media research reports, customers, suppliers or other sources of novel technologies…). Whatever form innovation adopts or source it comes from, innovation remains at the end a creative process and its success depends on filtering these novel ideas adequately by determining the ones that the business will be concentrating on and applying the needed resources for exploiting them eventually. Business innovation would enable therefore to boost the total productivity of the business, decrease the costs, increase the profitability, establish new partnerships, open doors for new relationships and opportunities, build up the overall value of the business and upgrade its competitive advantage. Obviously, this would be impossible to achieve if the firm doesn't study thoroughly the market (its trends, competitors…) and comprehend exactly what it needs so as to identify the existing opportunities and potential risks. *(Infoentrepreneurs, 2009)*

Although, there isn't a unified formula for successful business innovation, firms that are succeeding at business innovation follow usually a repeatable process. It all begins with articulating and formulating ideas about key areas (products, services, marketing, process, business models…). The cycle moves towards discovery then into development and delivery. Business innovation can be categorized in multiple divisions such as product or process innovations. We can also name business model innovation involving the development and implementation of novel and unique concepts backing up a corporation's viability; industry model innovation which signifies the development of a new industry or the company moves towards a new industry; revenue model innovation including the enhancements and changes done to an organization's framework for producing revenues. Business innovation can also be classified as revolutionary or evolutionary. Evolutionary or incremental business innovation involves smaller and more constant enhancements that even they could essential aren't extreme enough to drive the firm or the market into a new paradigm. On the other side, revolutionary business innovation also known as radical innovation, involves a radical transformation in the related product or service ending by that the existing business model. *(Rouse, 2017)*.

It has been important to show how innovation can be perceived as a business concept so as to facilitate the comprehension of how innovation is a must in today's industries and how it can actually serve companies to achieve a significant economic growth and gain a competitive advantage. We will therefore illustrate some examples of business innovation in the upcoming part.

PART 4: Study cases of technological innovations in relation to condition monitoring and predictive maintenance practices

Figure 14: Technological Innovation in various industrial fragments (APRISO, 2018)

Introduction

The fourth part of the thesis will be composed of two main sections. The seventh section will illustrate some concrete examples of technological innovative approaches, in relation to the condition monitoring and the predictive maintenance practices, applied in industrial contexts. The major sectors that will be the subject of the presented study cases are the aerospace and defense sector, the automotive sector and the oil and gas industry. These industrial segments would be the subject of our analysis because they are regarded as the most impacted by the technological innovations and also because they are the ones that mostly put in use these advanced tools into their production and operational lines. For that, it will be essential to name the companies that have been selected to demonstrate the adopted inventive methodologies and systems according to degree of importance of these tools as well as their affiliation to a certain industrial field.

This part will also exhibit in its eighth section the technical, financial and organizational improvements that have been observed after the implementation of the technological innovations in some of the mentioned industrial companies presented as study cases on the fourth section. It is crucial to outline the degree of impact of innovation in concrete situations from the current market so as to comprehend the true objective of this thesis that is demonstrating how it is essential nowadays to create and innovate in order to achieve the short and long term objectives of the industrial organizations in terms of performance, profitability and competitiveness.

Section 7: Study cases of industrial companies adopting technological innovative approaches in their CM and PdM practices and systems

Innovation has been regarded as a central factor impacting the transformation and prosperity of industries, the rate of entry, survival and progression of companies. Going back and looking at the last twenty five years of research on these matters, we must admit that the growth has been tremendous and largely impressive on the theoretical and practical levels. Innovation has touched several market segments and has involved considerably in the industrial contexts mainly when it comes to the condition monitoring and the predictive maintenance activities. Still, sectors differ significantly in terms of the market share and the organization of the innovative breaking through practices. In fact, in some industries, the innovation concept is restricted on a limited number of firms; stability of innovators is a common thing while the apparition of new innovators can be quite unusual. In this case, it could be observed the existence of barriers to the entry of new innovators while the large corporations would dominate the innovation race. Oppositely, in other fields, innovation patterns are dispersed across a diversity of numerous industrial organizations with a high turbulence in innovation movements and new innovators would come from every quarter thanks to the easy entry of technological improvements. Moreover, another aspect differentiates between sectors and technologies as well that is the knowledge base and the learning processes. Indeed, for a number of sectors, science is the leading and driving power that pushes the knowledge growth while for others learning by doing, redoing and cumulating the advancements is somehow the methodology for creating or being/becoming innovative. It seems therefore crucial to comprehend closely these distinctions so as to know how, where and when exactly innovation could be introduced into the company's plans and strategies. Furthermore, to acquire a deeper perspective on the matter, looking at the motivation behind these innovative installations; demand. Demand has been constantly the ultimate driver for the industrial revolution for centuries and economic analysts have claimed for a long time that demand procures the necessary incentives for innovation. The size, the structure, the growth, the orientation and the composition of demand, product differentiation and market segmentation influences greatly the introduction of innovation into the relevant industrial context.

Despite all these differences, industrial companies regardless of their activities' nature, size, structure, market share or their CM and PdM policies, they do share the goal of optimizing the performance of their technological innovative practices and making the best out of them in terms of increasing their profitability and competitiveness.

Therefore, to illustrate adequately this picture, it appears vital to display distinct and concrete examples of companies with different characteristics that have chosen to implement innovative systems and programs so as it make it easier for us later to draw the required conclusion for this study in terms of importance and impact of these inventive tools and systems on the economic, technical and organizational enhancements of the relevant firms.

4.7.1 Study cases from the Aerospace and Defense Sector

According to a new research published by Polaris Market Research, the global aircraft health monitoring system (AHMS) market size is predicted to reach USD 7.55 billion by 2026. The aircraft health monitoring system is a gathering of multiple tools and procedures which operate all together in order to control the lifecycle of the aircraft components. This technology is therefore capable to forecast when a certain component or process would break down. Over heating machinery, extremely high vibrations, low oil pressure, difficult landings are some of the examples of the urgent cases that demand attendance and thorough inspection. The technology allows by that advanced proactive maintenance of the relevant aircraft along with its engine and other complicated parts. The growing government regulations and commandments concerning safety and the increasing aviation accident cases have mainly driven the market expansion. Moreover, the rising volumes of air traffic and spreading safety concerns, majorly from the defense sector, have elevated the need for real-time fault management and the demand for predictive maintenance and performance monitoring promoting by that the growth of aircraft health monitoring system industry. Other elements contributing highly to the aerospace and defense sector growth include growing adoption of connected aircraft solutions, increasing necessity of automation and reduction in operation costs, technological improvements and rising appliance of the Internet of Things into CM and PdM practices and systems. New emerging markets, the enhancement and replacement of traditional or old-fashioned aircrafts by the new generation of aircrafts as well as the considerable investments in research and development would procure various advancement opportunities in the aircraft health monitoring system industry during the upcoming period. *(WiseGuyReports Website, 2019).*

Multiple players in the aviation sector feel therefore the need for innovation, sometimes even the urgency. They are mainly driven by the necessity to reduce the growing costs of labor and materials; thereby they aim to decrease the inventory and the unplanned aircraft maintenance interventions. In order to properly address these issues and achieve the desired objectives, the aviation industry focuses on everything related to automation, aircraft health monitoring, the Internet of Things, digitalization, cloud platforms and smart predictive maintenance. Nevertheless, the steps towards a full innovative aerospace and defense sector can be quite slow. This is why; more companies, especially the big players in the industry, should start implementing inventive approaches and programs into their structures and surpass the limitation of their current processes created by the traditional mindset and start thinks like startups.

- **Boeing study case**

Figure 15: Boeing airplane picture (Lynch, 2018)

Boeing is an American multinational corporation that is considered as one of the largest aerospace companies and leading manufacturers of commercial jetliners, defense, space and security systems and service providers of aftermarket support. As America's biggest manufacturing exporter, the corporation supports airlines and U.S and allied government customers in more than 150 countries. Boeing products and elaborated services involve commercial and military aircraft, satellites, weapons, electronic and defense systems, launch systems, advanced information and communication systems, and performance-based logistics and training. *(Boeing Website, 2019).*

The company says that it undergoes innovation developments today more than any time in the past 101 years of its history. One of the examples of its innovative designs and products include the first flights of the 737 Max 9, 787-10 and T-X among other achievements like the launching of Boeing AnalytX and Boeing HorizontX. Professionals across the global company's network work hard in order to enhance the ways they design and construct their products so as to enable the systems to operate more efficiently and upgrade the environmental performance. With more than $ 3 billion invested annually for research and development, Boeing drives innovation that will transform aerospace and defense as we know it and will solve difficult and real worldwide problems. *(Boeing Website, 2019).*

Condition monitoring and predictive maintenance are no single tools but a group of tools and approaches aimed at a goal according to Boeing. "*For us, predictive maintenance represents an umbrella of activities to help operators turn unscheduled maintenance into scheduled activities,"* states Dawen Nozdryn-Plotnicki, director of advanced analytics for digital aviation and analytics at Boeing. The analytics executive leader confirms that the approach is already well along, *"yet with new advances in bigger data, more powerful analytical methodologies and newer airplane designs, we continue to have more to do."*Indeed, the Boeing's predictive maintenance practices involve several axes of actions including advanced maintenance strategies and planning, reliability analysis, maintenance and post-operations monitoring for feedback and enhancement. According to Nozdryn-Plotnicki, predictive maintenance can actually impact both the transformation of aircraft design and the change of scheduled maintenance plans. They are many examples where smart predictive maintenance can be accomplished at individual airplanes. For the example of Boeing, it actually presents self-service analytics, consulting services to respond to certain requirements or needs, digital solutions that would contain both analytics and expertise and obviously its turn-key maintenance, engineering, and supply chain program, **Global Fleet Care.** No matter how or where these advanced predictive instruments are employed, it seems that they are absolutely working and achieving the desired goals; *"When customers tell us our predictive algorithms helped reduce 80% of maintenance burdens on a problem, that makes our day,"* Nozdryn-Plotnicki certifies. Boeing has invested in further profits as we have mentioned earlier in the design of the 737MAX and the development of the 777X. Another extremely crucial investment for the multinational corporation is the development of better algorithms, cloud computing programs and digital platforms in order to process and exploit more accurately larger amounts of aircraft data. Boeing offers these smart PdM services to a wide range of clients. The point of these services in to pinpoint at problems and failures prior their occurrence that have a large potential to occur with high accuracy and technical reliability normally above 99%. For instance, **Airplane Health Management (AHM),** is one of the smart PdM services of Boeing in which is performed over two million calculations each hour for over 100 airlines flying 4700 aircrafts. *(Canaday, 2018).* AHM is therefore an information instrument created by Boeing and airline users that gathers in-flight airplane data and delivers it in real time to the ground. The performance Monitoring Module within AHM procures automated monitoring and fuel utilization and calculation of carbon dioxide (CO_2) emissions. Boeing would provide this tool to the airlines clients so that they use this information to upgrade and optimize the operation of individual airplanes as well as the entire fleets. AHM is considered as a maintenance decision support capability which employs real time airplane information to provide improved failure detection and forwarding, troubleshooting and historical fix success rates to decrease schedule disruptions and advance maintenance effectiveness. It transmits data whenever and wherever it is requested; the data is received from airplanes and delivered by Boeing through the web portal MyBoeingFleet.com. AHM integrates the remote monitoring, gathering, and assessment and analysis of airplane information to indicate the status of an airplane's actual or future serviceability or performance. In fact, an airline's maintenance or engineering professional teams can deploy this analyzed data to take economical, timely and repeatable maintenance decisions that can aid enhance the total fleet operations. Aircraft Health Management contains three major modules or three kinds of decision support that are: the performance monitoring module, real-time fault management and service monitoring. *(Maggiore and Kinney, 2009).*

Typically, the Boeing's AHM is available via the Internet. Currently, as part of the Boeing AnalytX Self-Service Analytics portal, the information is accessible from a cloud-based, scalable infrastructure. Subsequently, Boeing is constructing more early-warning programs or systems into its most recent aircraft. In this sense, the analytics chief director Nozdryn-Plotnicki asserts: *"Boeing integrates predictive maintenance expertise into the systems design process, ensuring new aircraft types have predictive maintenance concepts designed in, increasing the use of data analytics onboard the airplanes over the next few years*". Going beyond predictive maintenance, data is used in order to develop optimal maintenance programs. Instead of performing rigorously heavy checking operations giving the standard maintenance planning report, airlines can actually utilize data in order to conceive a work scope that would respond fitly to their needs and enable the establishment of more effective shop visits and better-timed check intervals. The first advantage of this optimization is instantly identified when a certain unexpected fault is detected during a heavy check and there's no stocked component to actually rectify it. To avert such delays, data analytics give maintenance planners the capability of forecasting the occurrence of possible deficiencies or damages so they can order the needed parts in advance. Hence, engineers and maintenance specialists can more thoroughly model and make up for the existing uncertainty decreasing by that the operational risk and reducing the maintenance costs. *(Derber, 2018).*

We have already mentioned earlier that one of the essential modules of AHM is the Performance Monitoring Module which uses the Boeing airplane performance monitoring (APM) and health management technology to procure automated monitoring of fuel consumption and CO2 emissions. The module improves observing, handling and researching of, and responding to, aircraft performance information to upgrade airplane operation and endorse maintenance decision-making. Moreover, the module elaborates a connection between maintenance and performance segments creating shared toolset that analyzes the system's health state and fuel performance. It contains usually the following specific information: performance comparisons across airline and the larger monitored Boeing fleet, flight planning factors, per-flight and fleet CO2 emissions, exception-based alerting and integration with engine OEM condition monitoring alerts. The following figures (figures 16, 17 and 18) illustrate the data displayed by the Boeing's AHM. *(Maggiore and Kinney, 2009).*

Flight Leg Details

Airplane Information

Airplane Identifier	Operator	AHM Fleet	Tail Number
ZGCA088	ZGC	777 Demo Fleet	ZGCA088

Flight Information

Flight Leg	Flight Number	Leg Date	Departure / Arrival
Leg 0	GC836	10-Apr-2009 : 08:59	SIN / PVG
Current Status	**ETA**	**Elapsed Flight Time (Mins)**	**Average Flight Time (Mins)**
IN	10-Apr-2009 : 13:54	286	284.0

Flight Leg OOOI / Fuel Information

OUT	OFF	ON	IN
08:53 : 10-Apr 43400 kgs	09:11 : 10-Apr 42800 kgs	13:57 : 10-Apr 10100 kgs	14:06 : 10-Apr 9700 kgs

Fuel Consumption Summary:	Taxi Out (Out-Off)	Flight (Off-On)	Taxi In (On-In)	Block (Out-In)
Current sector (kgs)	600	32700	400	33700
Sector mean (kgs)	200	33700	2000	35800
Current sector (kgs/hour)	1999	6860	2666	6460
Sector mean (kgs/hour)	500	7500	12100	6900
tonnes (1000 Kg) of CO2	1,893	103,168.5	1,262	106,323.5

Great Circle Distance (km)	Available Seats	g CO2 / seat-km
3,800.3	313	89.4

Figure 16: The gathering of fuel usage data and the measuring of CO2 emissions by the Boeing's AHM (Maggiore and Kinney, 2019).

As shown in the figure 16, the Performance Monitoring module automates remote monitoring of aircraft CO_2 emissions through the automatic calculation of fuel-used data. Aircraft Health

Management employs an industry-accepted multiplier in order to exactly measure the resulting CO_2 emissions. The recap of emissions in metric tonnes for the relevant flight and kilograms of CO_2 per seat-kilometer give the necessary airline perceptibility so as to address properly the environmental initiatives.

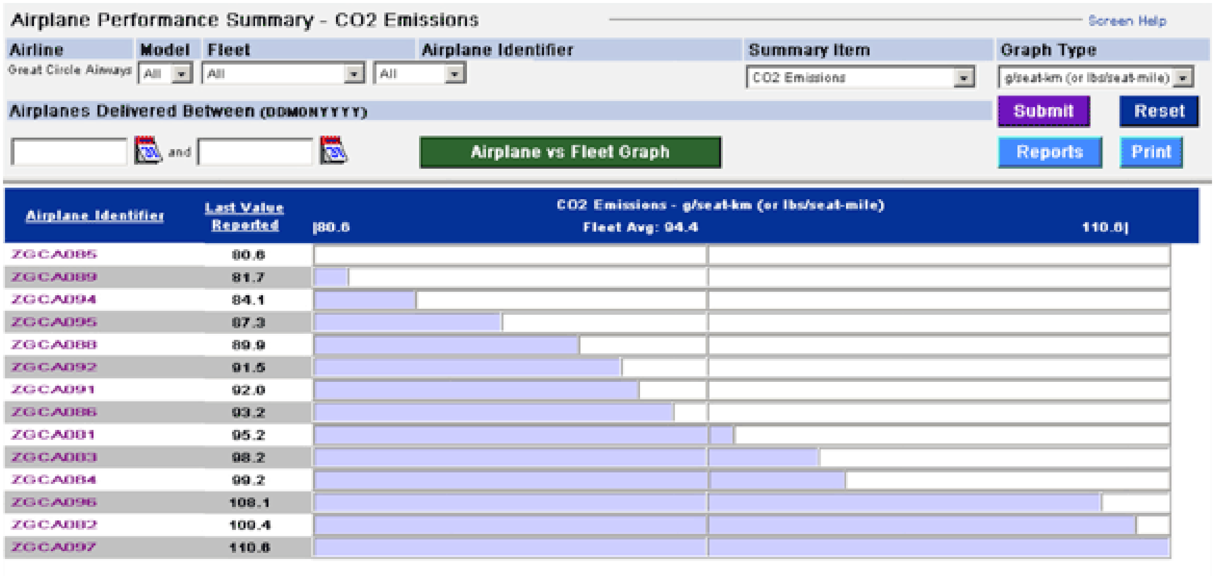
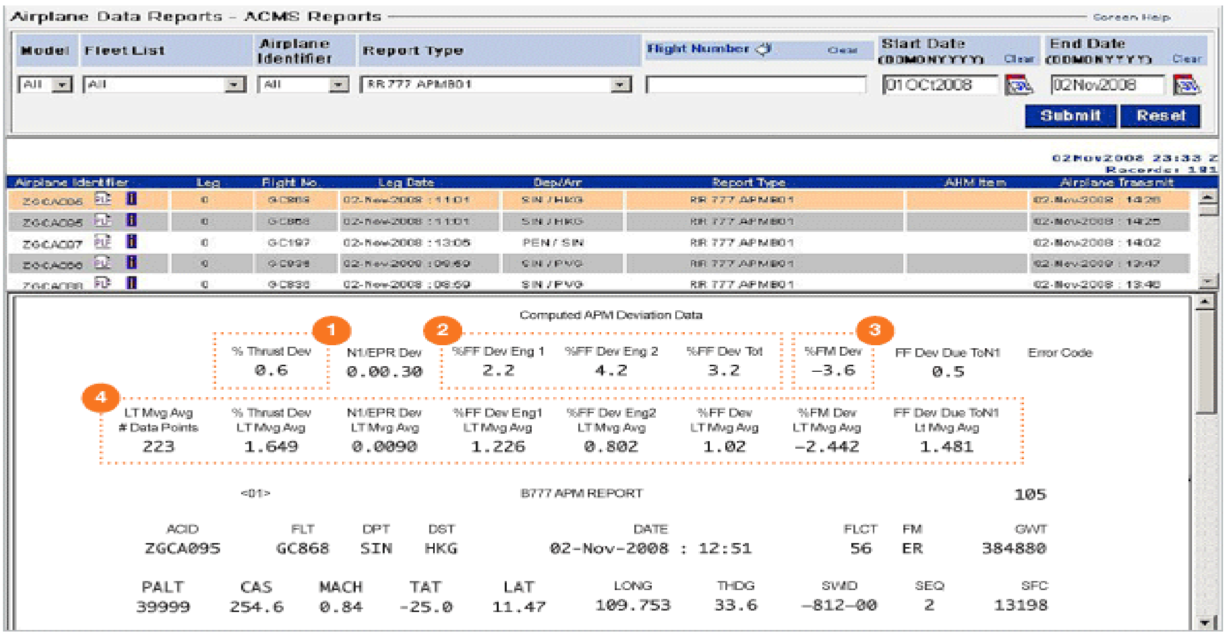


Figure 17: CO2 emissions for individual flights and across the fleet. (Maggiore and Kinney, 2019).

The AHM's summary gives details on the total CO2 emissions for fleet or sectors in order to acquire a complete perspective on the flight's performance.



1 % Thrust Required Deviation
2 % Fuel Flow Deviation — All Airplane Per Engine
3 % Fuel Mileage Deviation
4 Long-Term (90-Day) Moving Average Statistics

Figure 18: The Performance Monitoring Module (Maggiore and Kinney, 2019).

As demonstrated on figure 18, the module provides the technicians and engineers with timely warnings of performance deterioration signs that can be difficult to detect by illustrating certain diversions within the fleet.

Typically, the performance monitoring process involves five major steps:

1. Recording the cruise data: when tight atmospheric and airplane parameters for stable flight are attained, the airplane condition monitoring systems (ACMS) register air data, engine and airplane performance variables during few minutes. The outputs can be transmitted to the ground in a summary report or the summary itself can be kept on the board the aircraft.
2. Translating data to a format that can be read by the Boeing's APM software: the conversion of data into the digital standard interface record format.
3. Analyzing the data with Boeing's APM software: APM performs off-nominal data modifications to make sure that the data and database are consistent. It compares outputs for each data point in order to pick baseline levels for the same flight circumstances, and flowing so averages the outcomes for all data points into chosen time periods perceiving by that diversion patterns as functions of time.
4. Interpreting the results: Once the fluctuations in fuel mileage, fuel flow and thrust needed have been estimated, the aircraft's performance engineers can actually interpret the information. They assess the data for reasonableness and inspect whether modifications are required in flight scheduling and flight management computer (FMC) factors. These elements are essential to insure that the adequate quantity of fuel is loaded for every single flight and to decrease the amount of emissions. AHM automatically determines the trends or patterns that surpass airline already described thresholds. Additionally, AHM controls the information for sudden alterations and isolates the root cause in order to correct it rapidly and efficiently. This advanced process would allow the early identification of issues long before the old-fashioned analysis procedures take place.
5. Taking the necessary and adequate courses of action: After a total and successful interpretation, airline performance engineers can update if required the flight planning and FMC parameters for enhanced reserve and complete fuel loading. The performance data can as well determine a requirement for scheduling maintenance operations like flight monitoring rigging checks for instance. *(Maggiore and Kinney, 2019).*

Furthermore, Boeing is taking other innovative initiatives as it is also collaborating with universities in order to discover and develop novel technologies that would be capable of controlling and monitoring accurately the airplanes health status. Boeing has been also interested in detecting faults in coatings, surfaces and materials for maintenance assurance, quality control, structural health and product safety. It has been as well interested in disruptive innovations that can be applied in future AHMS technological solutions, such as photonics to control in real-time the system's conditions, vibration and structural health if the airplane and its components. *(Basu, 2019).*

- **Bombardier study case**

Figure 19: Bombardier's C-SERIES Aircraft (CBC Canada, 2016)

Bombardier is a multinational company and a global leader in the transportation industry, developing innovative and game-changing planes and trains. Headquartered in Montréal, Canada, Bombardier has production and engineering sites in 28 countries across the segments of Transportation, Business Aircraft, Commercial Aircraft and Aerostructures and Engineering Services. The corporation states that its products and services procure world-class transportation experiences that set new standards in passenger comfort, energy efficiency, reliability and safety. *(Bombardier Website, 2019).*

Bombardier is creating its future with the C-Series aircrafts. Profiting from a clean-sheet design that involves highly advanced technology and systems integration, leading edge-materials and the latest generation of aerodynamics, the C-Series present 15% cash operating cost benefit, a 20% fuel consumption advantage, remarkable operational flexibility and a unique environmental comfort. *(Bombardier Website, 2015).*

The AHMS developed by Bombardier, is constituted of on-board and ground system parts. The on-board maintenance equipment placed on the airplane handles the fault messages derived from all the aircraft mechanisms and the high-capacity recording and transmission Health Management Unit provides airlines with a special level of customization to process the aircraft data. Indeed, the unit gathers broad stream aircraft operation as well as performance information from every single system during the relevant flight. This involves typically flight controls, fly-by-wire, landing gear, braking systems, environmental monitoring systems, avionics, engines, electrical instruments and others. As for the AHMS part situated on the ground, it offers a detailed assessment of the communicated on-board information so as to address a large diversity of operational decisions. *(Bombardier Website, 2015).*

Fast data communication and steady information transmission are the lifeline of an AHMS application. Multiple vendors have been developing and proposing proprietary data transmission innovative and technological solutions as a service to aircraft manufacturers, which are starting to employ **Aircraft Communications Addressing and Reporting Systems (ACARS)** as an intermediate to send huge volumes of data by the integrated series of software systems to the ground. For the example of Bombardier, it has utilized Pratt & Whitney's **eFAST data transmission technology** for the AHMS functions on its C-Series aircrafts. *(Basu, 2019).* Concerning Pratt & Whitney, it is a world leader in the design, the manufacturing and the service of aircraft engines and auxiliary power units, providing high-tech systems and services to the aerospace industries. The eFAST aircraft health monitoring system, created, designed and evolved by Pratt & Whitney, is an on-board, near real-time data acquisition and transmission entity that automatically downloads, processes and stocks information then transmits it to the client portal. This unit allows by that the technicians and engineers to catch considerable volumes of crucial airplane system information for usage so as to optimize the operational and maintenance costs for the relevant aircrafts. *(Bombardier Website, 2015).*

Bombardier has announced on the 15th May 2015 on its collaboration with Pratt & Whitney to create and establish a data management service for the C-Series aircraft as an important segment of the total Bombardier Aircraft Management system (AHMS) able of communicating real time registered data from the airplane. The AHMS will simplify remote troubleshooting and transmit effective and precise diagnostics for usage by flight and maintenance personnel. Through this agreement, Pratt & Whitney's eFAST system will be the base and infrastructure entity employed to execute data transmissions from the C-Series airplanes on-board Health Management Unit (HMU) to the ground. Teaming up with Bombardier, they will be capable of constructing a solid data acquisition structure in order to accurately download, process and store information that would be later accessible for upload to the relevant customer portals. *(Bombardier Website, 2015).* In other quarters, Pratt & Whitney AHMS system downloads information and the aircraft team sends it to the ground sources via the ACARS. Concerning the C-Series, Bombardier's FlightLink transfers the recorded data from the aircraft to the ground, and in turn to the customer. As the operator, he/she used a web-based interface in order to analyze and assess the data while the airplane is airborne, so the crew can take the required preparations to respond properly to the presented issues as soon as the airplane lands. *(Basu, 2019).* In this same context, Graham Webb, the Vice President of Pratt & Whitney Commercial Engines has stated *: "C-Series operators will be able to immediately review the performance of their aircraft, allowing them to make smarter business decisions related to their PurePower® engine fleet. This is truly revolutionary and will enable operators to maximize their fleet performance, while optimizing their maintenance and reliability expenditures."* On the other hand, the Vice President of the Bombardier's C-Series Program Commercial Aircraft, Rob Dewar shared the same point of view; *"We congratulate the teams at Pratt & Whitney and Bombardier that together have developed a service that will provide real-time monitoring of all critical aircraft systems for use in optimizing flight operations and lowering maintenance costs,"* confirming by that that this advanced technology which was mainly made for the C-Series airplanes, has actually the ability to enhance the way maintenance teams manage their tasks reducing the mechanical delays and failures and increasing the overall equipment reliability. *(Bombardier Website, 2015).*

AHMS can furthermore offer significant opportunities for service providers with expertise in cloud platforms, huge data technological solutions and advanced sensors etc, and the perfect example for that is the partnership between Bombardier and Tech Mahindra for the development of the Aircraft Ground Support System (AGSS) for its C-Series product line. (*Basu, 2019).* In fact, Bombardier and Tech Mahindra, which is a leader in digital transformation, consulting and business re-engineering, have declared on the 15th October 2015 that they have concluded an agreement through which Tech Mahindra will develop the AGSS for Bombardier's AHMS for its C-Series aircrafts. The AGSS allows and supports real-time monitoring of the airline and post-flight registered information management, diagnostic reporting and deficiency identification for ground and on-board system parts. By leveraging the huge volumes of recorded information and sent from the C-Series, the AHMS will enable the crew to take adequate decisions on aircraft operational efficiency and maintenance. Lakshmanan Chidambaram, Head of North America, Tech Mahindra Ltd said on the subject: *"Our digital tools will support efficient analysis of the data, so that it can be quickly captured and shared with operators. We are aligned with Bombardier's vision around 'connected aircraft' and the core of our digital strategy will focus on converting information into insight, to impact operators' business efficiency and profitability".* As for Rob Dewar, he clarified that they are working in collaboration with Tech Mahindra in order to upgrade first of all the aircraft availability and reduce the maintenance costs, *"Specifically designed for the C Series aircraft, the AHMS will help operators manage their activities, resulting in superior dispatch reliability."*, he confirmed. It is therefore obvious to conclude that Tech Mahindra's digital solutions for the Bombardier's AHMS will put in advance highly developed Cloud platforms, cutting-edge sensors, the IoT and Big Data technologies in order to apply deep and accurate analytics of the airplane's operational and health status. *(Tech Mahindra, 2019).*

- **Airbus study case**

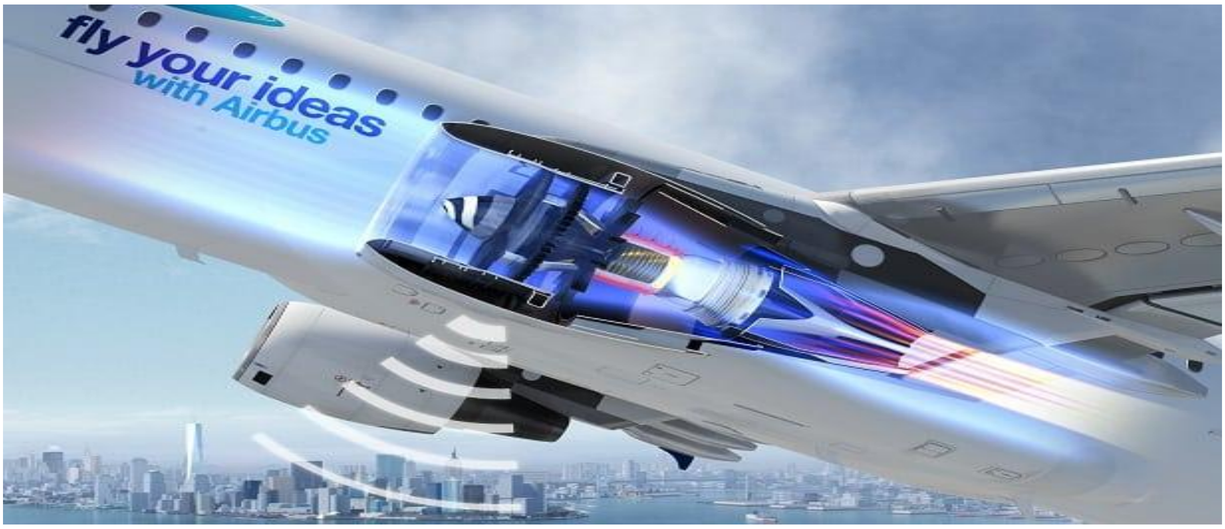


Figure 20: Innovation at Airbus (eTurboNews, 2018)

Airbus is an international reference in the aerospace sector. The company designs, manufactures and delivers industry-leading commercial aircraft, helicopters, military transports, satellites and launch vehicles, as well as providing data services, navigation, secure communications, urban mobility and other solutions for clients on a global scale. With a forward-looking strategy based on cutting-edge technologies, digital and scientific excellence, the multinational aerospace corporation aims for a better-connected, safer and more prosperous world. *(Airbus Website, 2019).*

Airbus provides aircraft health monitoring for their customers through its Airman system which is an online solution that allows effective management of unscheduled maintenance, procurement of real time information and recommendations and enhancement of aircraft dispatch reliability optimizing by that the maintenance tasks and the aircraft availability and reducing the overall maintenance costs. *(Services By Airbus Website, 2019).* Airman users can therefore access to all types of real-time data via a web portal for Airbus aircraft supplied with an on-board maintenance system and air-to-ground communication system communicating and transmitting the needed information. The central unit of Airman-Web holds the function of controlling aircraft events, including systems, while an optional unit is linked to the maintenance information system and enables aircraft information requests. Subsequently, newer aircraft assimilates better technology that affords a larger variety of data and interactivity. For instance, the Airbus A350 and A380 have the Aircraft Condition and Monitoring System (ACMS), which gathers and stores parameters upon identification of trigger conditions. Norman Braker, Airbus Senior Vice President for digital solutions declares: "*With these collected parameters, it generates ACMS reports—the basis of the aircraft-monitoring function—which allow users to get advance indications of initial-stage system failures and to support system performance trending." (Derber, 2018).*

As multiple aircraft manufacturers are aiming to establish standardized approaches for AHMS through their global fleet and implementing open data platforms seems the right way to achieve so, Airbus works thoroughly on following the same path. Indeed, Airbus plans to develop open data platform Skywise as an end-to-end aircraft health management solution for Airbus operators. The Skywise platform will allow access to the Airbus Customer Service digital suite as well as the Airbus flight operations and maintenance exchanger (FOMAX) instrument, involving sensor data for the A320 and A330 product line. *(Basu, 2019).* The Skywise Health Monitoring will be created to leverage the huge amount of data gathered through the open data platforms in order to assist airlines manage the maintenance activities more effectively. Detailed information about this innovative service can be quite limited, although Airbus confirms that it will facilitate efficient and rapid troubleshooting and provide supplementary functions like prioritizing corrective tasks for instance. *(Derber, 2018).*
Airbus is therefore developing this platform to harness huge data for indicating to the airlines in real time where exactly the possible maintenance issues can occur and how to decrease the fuel consumptions and the CO2 emissions. For that, it has teamed up with Silicon Valley data cruncher Palantir Technologies to extract the necessary data from participating suppliers and airlines and employ it to enhance directly the engineering, performance, operation, maintenance and even the design of the new aircraft. The German-French aircraft

manufacturer states that it has 30 airlines with 3000 jets already enrolled for the platform. Marc Fontaine, an executive member of Airbus and the head of the digital project, expects that by the end of 2019, Airbus will hold 60 to 70 per cent of the world's jet air, some 23,500 passenger planes, on the platform. Typically, Airbus offers participants the access to the collected information for free, so that the airline could actually ask some operative questions like why a certain altimeter for instance doesn't function properly on its plane than on other airlines. Nevertheless, for special maintenance problems, Skywise charges an adequate price with what it costs to ground the plane. Still, some firms seem absolutely satisfied with that price. Easyjet, for example, has succeeded to reduce its downtime with 20 percent, a result that appears to be tremendous especially in a business that fights for every single small improvement. Moreover, fuel savings are regarded as another major advantage of the Skywise platform since the actual in-flight performance of each engine can be accurately calculated instead of depending on averages. Additionally, Airbus demanded that all Skywise data would be kept in Europe so Palantir had the obligation to set up in France and Germany. If Airbus achieves the quantum leap expected by Marc Fontaine at the end of this year, which signifies that it will have information from various Boeing aircrafts also feeding into Skywise, it will become the most important data hub for commercial air travel, the one that you can't operate without. *(Hanke, 2019).*

Furthermore, Airbus plans on incorporating structural sensors in order to predict and prepare adequately for forthcoming damages or failures in wings and fuselages. OEMs already employ a diversity of similar sensors in testing and research and have confirmed the viability of installing strain gauges into materials such as carbon fiber. Airbus states that reliability and durability are crucial when it comes to structural sensors. On the same matter, Norman Braker expresses that: *"New-generation sensors are coming on the market which could replace traditional non-destructive inspection equipment used for specific maintenance tasks, and Airbus is continuously evaluating possible use cases on both metallic and composite structures." (Derber, 2018)*

- **GE Aviation study case**

GE Aviation, an operating unit of General Electric, is a world-leading provider of commercial, military, business and general jet engines, components and integrated systems such as avionics, electric power, and mechanical systems for aircraft with an extensive global service network to support these products. GE Aviation recorded revenues of $20 billion (US) in 2012. Headquartered in Cincinnati, Ohio (USA), GE Aviation employs about 40,000 people and operates manufacturing, overhaul, and repair facilities worldwide. About 25,000 jet engines from GE and its partner companies (CFM International and The Engine Alliance) are in airline service. An aircraft powered by GE or CFM engines takes flight every 2 seconds. GE Aviation invests more than $1 billion (U.S.) annually in jet propulsion Research & Development programs. *(GE Website, 2019).*

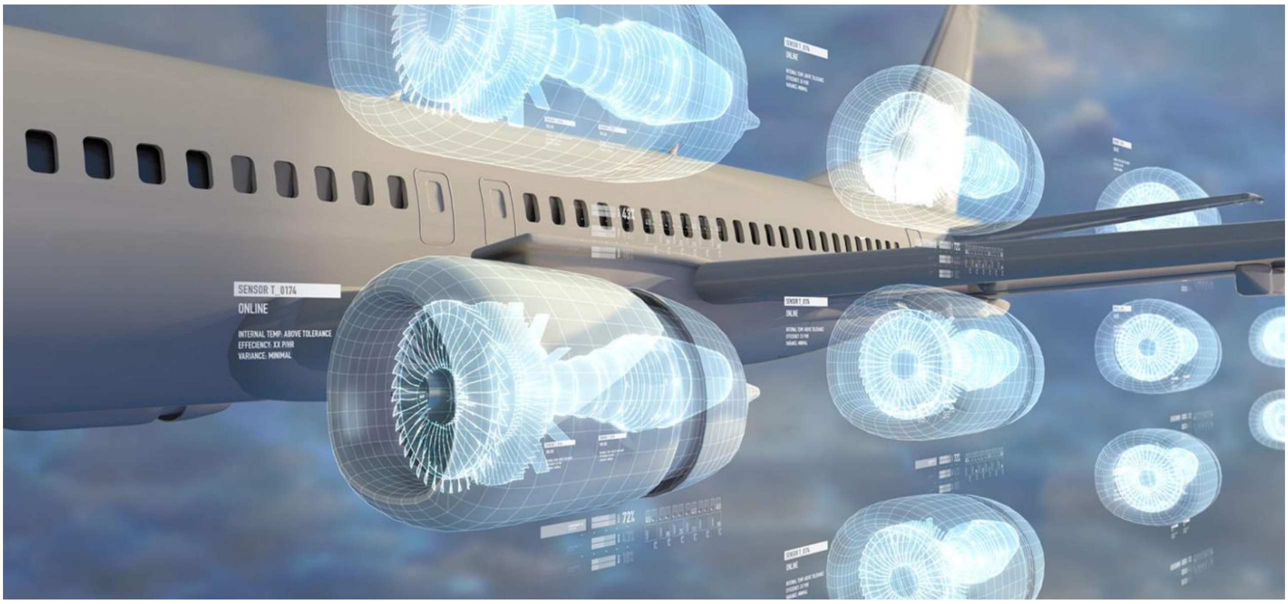


Figure 21: Digital Twin at GE Aviation (GE Digital, 2018)

One of the latest IFS (Industrial and Financial Systems referring to the multinational enterprise software company) studies about commercial aviation challenges, clarifies that operational availability is one the most significant issues nowadays in the aerospace industry. The director of IFS aerospace defense, Mark Martin, says on the matter: *"No matter how quickly operators can turn around a plane between flights, the disruption of having an aircraft on the ground has drastic ramifications, with parts and time potentially costing millions of dollars,"*. This signifies that aviation companies must take serious initiatives into bringing innovative procedures so that the issue of limited availability can be resolved. The solution resides then on the analysis of reliability data and IFS forecasts that digital twins will have a central part in this task in commercial aviation. As for GE Aviation, the construction of this technological solution has already begun. According to Martin, GE has contributed in developing the world's first digital twin for an aircraft's landing gear. As the sensors planted on common failure points on the equipment, like hydraulic pressure and brake temperature for instance, they can procure real-time data and contribute in predicting early malfunctions or diagnose the remaining lifecycle of the landing gear. GE strongly believes therefore that digital twinning is the future of condition monitoring and predictive maintenance to upgrade the overall reliability of the aircraft. *(Canaday, 2019).*

Digital twins according to GE are defined as software representations of assets and processes or digital replicas for those physical systems that are used to comprehend, forecast, and optimize performance so as to accomplish enhanced business outputs. Digital twins contain major three components: a data model, a set of analytics or algorithms and knowledge. The point of developing digital twins is to increase the availability and reliability, reduce the risk, decrease the maintenance costs, improve the production and elevate the profits. As for the operational aspect of this technology, digital twins consume historical and performance information in order to assimilate the past, utilize indirect and direct data to consider present circumstances, and execute machine learning and knowledge to foresee the future. At GE, the digital twinning can be performed majorly on components, assets, systems or and processes. By figuring out the actual and current conditions and knowing the future state of a digital twin, the company can more efficiently control, simulate and monitor the relevant asset or process and optimize through that the lifecycles whether it is online or offline. *(GE Digital, 2019).*

Other companies are also developing digital twins such as Lufthansa Technik and Siemens. The technique of twining itself can be quite expensive so it would potentially applied at first for major systems and components mainly. But as companies would gain wider and better expertise in the field, the technology would be performed on a larger range of aircraft parts.

On the other side, we can discuss the involvement of TPSs (telecommunication service providers) that are gradually getting implicated in the AHMS value chain. GE Aviation has teamed up with AT&T, an American telecommunication multinational company, in order to connect the on-board and off-board portions of the Aircraft Health and Trend Monitoring System (AHTMS) driven by the aircraft manufacturer Gulfstream; which utilizes its proprietary PlaneConnectHTM (Health and Trend Monitoring) on its G500, G650 and G650ER business jets. AT&T leveraged its connectivity solutions (AT&T Control Center and AT&T Global SIM) to enter the AHTMS on landing and transfers the information wirelessly to Gulfstream Technical Operations and Gulfstream Operators. The data is transferred via AT&T's secured linkage with a custom MPLS/VPN network, connecting by that mobile assets distributed in the world. The combination of data gathered from the global fleet can be leveraged by Gulfstream Technical Operations to transmit improved services, such as time-specific information for individual aircraft. The concluded insights can be employed to rise transparency and accelerate and facilitate resolution through the global fleet. *(Basu, 2019).*

- **Southwest Airlines study case**

Figure 22: Preparation of Southwest aircraft (Seidenman and Spanovich, 2016)

Southwest Airlines is a major American airline headquartered in Dallas, Texas. It is considered as the world's largest low cost airline, and carries the highest number of domestic passengers in the Unites States of America. The firm started a rebrand towards the end of 2014, launching international flights for the first time. Regardless of a major redesign, Southwest has been quite rapid to ensure its passengers that the quality of the flight remains the same. Currently, Southwest Airlines isn't a member of any global alliance, but as they continue to target larger markets, it's very possible for them to join a partnership in the near future. *(Skycanner, 2019).*

In order to upgrade the monitoring of aircraft's engine function, Southwest has decided to implement bleed-air temperature monitoring sensors on its 737NG fleet. Southwest Airlines are therefore rebuilding their entire 583 Boeing 737NGs with special sensors provided by Honeywell to acquire supplementary data points to enhance the Boeing's Airplane Health Monitoring (AHM), which is implemented on that fleet two years ago. According to Ross MacArthur, fleet chief in the Dallas-based carrier's Technical Operations Organization, Southwest has identified through AHM that poor performance of the bleed air system was engendering severe service disruptions. The majority of data, approximately 95%, that is required for the engine bleed air monitoring will be accessible from the AHM. However, some key pieces of data will be still missing. He states that the company decided to install the sensors because of the additional data they could bring which would appear to be ultimately of a critical importance in relation to the monitoring of the bleed air system. For each engine, the sensors would monitor the bleed air temperature as it comes from the engine. MacArthur explains that the Southwest is getting a total of four (two per engine) data points of the bleed air temperature data from the sensor implementation as well as of the bleed air pressure data which they were already capable of monitoring thanks to the existing software. The resulting four data points are providing the company with the necessary insight on the state of health of the complete bleed air system and what could actually go wrong with it. The sensor upgrade project necessitated the establishment of supporting wiring and is being performed under essential checkups, under a Boeing service bulletin. Furthermore, MacArthur has indicated that the airline would expand sensors to the 7373NG cabin environment and has been working on with Boeing on a cabin temperature monitoring cabin assuring by that Southwest will gain significant competitive advantage and a leading edge through this innovative step. The source of this initiative was the realization that even for a commercial jet, the data procured by the AHM was far from being enough to acquire the perfect and entire vision of the aircraft's state of health and a deeper study of its components has to be carried out; this is where appeared the value and importance of adding adequate sensors for the job to be completed. *(Seidenman and Spanovich, 2016).*

Companies that usually handle the Maintenance, Repair and Overhaul (MRO) of airplanes, involving MRO service providers and OEMs that are concentrating exponentially on the aftermarket business and searching constantly for innovative ways to reduce aircraft downtime and maintenance costs. Through all the study cases that we have analyzed, we can easily conclude that Aircraft Health Monitoring Systems (AHMS), which employ real-time information via sensors installed on airplane's systems to upgrade the overall reliability and security, are regarded today as a promising business opportunity for the service providers and OEMs and airlines. AHMS can optimize MRO expenses by removing the costly and exhaustive maintenance strategies and replacing them by non-invasive maintenance work and inspections that determine exactly the aircraft's condition and reduce its downtime. The AHMS field can be regarded more or less as a cross-over that brings various services all together from information and communication technologies (ICT), chemical materials, structural and mechanical engineering etc. Accordingly, it acts as a launching platform for the upcoming generation predictive analytics algorithms that will mostly facilitate the maintenance tasks and decrease the total downtime for the relevant aircraft. Today, as we have mentioned aircraft manufacturers are aiming at expanding the aftermarket services especially that the machine learning methodologies are developing and the fuel prices are considerably increasing. On the other side, airlines are looking for new solutions that can actually enable them to install the AHMS into their old fleets smoothly with a better integration. Some of the engineering service providers are concentrating on outcome-based, risk-sharing pricing models that could be appealing to the capital-exhaustive, small-margin commercial aerospace market. This will allow the manufacturers and service providers to seek innovative solutions for a faster, larger and more rewarding expansion of the AHMS market. *(Basu, 2019).*

4.7.2 Study cases from the automotive sector

The automotive industry is one of the industries that are currently undergoing intensive transformations and tremendous developments from autonomous driving, smart sensors and artificial intelligence (AI) to electrification or electric vehicles (EV) and 3D printing or adding manufacturing. The automotive sector requires therefore state-of-the-art technologies. Mechanisms of integrated machining centers, transport systems and industrial robots allow cost-optimized large scale productivity and at the same time permit to answer adequately the individual equipment demands. Every step in the entire process of automotive manufacturing including press shop, body-in-white, paint shop, power train and final assembly must operate with high levels of accuracy, reliability and availability of the involved equipment and installations. Moreover, the driving experience itself must be well monitored and followed with precision so it can be completely safe and efficient. To accomplish so, the automotive companies have started to understand that their vehicles need reliable and effective sensors, systems and programs that are capable of supporting the production with innovative technologies and high quality standards.

The expected change in the automotive industry in the upcoming years, unlike what has been occurring in this past, will be mainly getting the inspiration from "looking outside the box"; as marking a considerable leap from the old-fashioned and traditional workings of a vehicle. The introduction of automation, connectivity and shared economy and the increased penetration of electric power and EVs into the market will greatly remodel the total commuting models in the automotive business.

While these transitional changes occur, the automotive market is expected to jump from $3.5 trillion in 2015 to $6.7 trillion in 2030 in total size and it is estimated that 30% of this revenue will be derived from new services that don't even exist today. *(Desjardins, 2018).*

- **Tesla study case**

Tesla Motors, Inc is an American automotive and energy storage company that designs, manufactures, and sells electric cars, electric vehicle powertrain components, and battery products. Tesla Motors is a public corporation that trades on the NASDAQ stock exchange under the symbol TSLA. During the first quarter of 2013, Tesla posted profits for the first time in its history. *(Wirawanrizkika Website, 2016).*

Regardless of the fact that the automotive industry is one of the sectors where manufacturing processes are demanding in terms of regular maintenance, quality inspections and condition monitoring, vehicle recalls still present a serious challenge for the key players and manufacturers of the industry costing them millions of dollars and severe reputational damages. And Tesla doesn't make any exception on the matter. The firm has indeed recalled, back on March 2018, 123,000 Model S cars over faulty steering components and its shares have fallen 4% right after the announcement. As technology transforms vehicles into platforms of innovative approaches and tools via the usage of security, efficiency and computing power performance as essential pillars, it has become obvious for manufacturers that they must be "smarter" when it comes to employing the right technologies throughout the production and post-purchase lifecycle of vehicles. This is where artificial intelligence, machine learning and predictive analytics can allow the involved corporations acquiring full access, visibility and control over the manufacturing processes. *(Phukan, 2018).*

Tesla is though still considered at the front race of the industry's transformation and innovation. Indeed, Tesla has in somehow showed the world how electric vehicles can be considered more desirable than ICE (Internal Combustion Engine) vehicles as they appear to be safer, faster, greener and require far less maintenance. Still, Tesla is aiming to become and remain the ultimate source for innovation in the automotive industry whether it is in relation to the operational, monitoring or even the maintenance aspect. To achieve so, it came a long way to comprehend to that it is not the hardware or the software that makes the sale, but it is the right combination and integration between the hardware and software. Tesla has been an early pioneer in gathering and processing big data and employing it in ways to improve its business. It is now seeking to further use it so as to streamline and customize the user experience. Tesla has been producing highly technologically advanced electric vehicles as various leading edge technologies are implemented inside the automobile even an autopilot can be installed in it. Moreover, the company has been one of the main auto-manufacturers known for instrumenting cars with IoT devices and accurate sensors and sending the entire collected information to the central hub or mother ship for analysis and assessment using the Apache Hadoop® cluster, which is a group of open-source software or framework designed for distributed storage and processing of very large data *(MapR Website, 2019),* to gather the required data. The usage of big data and the relevant sensors for the monitoring and the software for its collection and analysis has the ultimate objective of improving the company's R&D operations and the vehicle's operational performance and upgrade the reliability of its predictive maintenance tasks as we have already mentioned on earlier sections large amount of information are an essential basis for fast and accurate detection of potential failures. The related data is moreover utilized to enhance the customer satisfaction and also the future products development processes' quality. The electric car manufacturer, which produces the most connected car on the market, the Tesla S, a model built with all-electric and high-strength architecture designed to provide high levels of protection and safety *(Tesla Website, 2019)*, gathers huge volumes of data from its vehicles purely for research and development and for better CM and PdM performance enabling by that its IT specialists, analysts and engineers to solve the presented issues and send back the corresponding solutions through its over-the-air (OTA) software updates. For example, the company would be informed if the car doesn't function properly and clients can be actually advised to get the adequate service, subsequently actions can be taken according to the presented situation. These capabilities have allowed Tesla to create an important market share in a difficult industry. The company's CEO, Elon Musk, has already stated in various occasions that the major innovative advantage of Tesla, is the usage of huge predictive analytics to seize the client's real time data. The usage wouldn't only enable the company to increase its profits but also enhance its visibility to foresee what's ahead of them. Consequently, the company gains better insights about the most repeated failure types, the driving patterns, the driver's behavior trends etc. As the electric car produces large volumes of information through downloadable log files and the company employs sophisticated IT tools including Big data technologies to combine and analyze these log files, it seems important to recall the tools that Tesla uses to handle properly the related data. We can name for instance SAS Enterprise Miner which is defined as an advanced analytics data mining tool designed to aid users in quickly developing descriptive and predictive models through streamlined data mining processes in order to acquire better insights that drive for better decision making. *(Reifer, 2019)*. They also use Tableau tool from the Tableau software for a better visualization and comprehension of their data. Another technological tool the company employs into its predictive and monitoring tasks is the SPSS predictive analytics software that enables the company predict with consistency what will occur in future so it could make better decisions, solve issues and enhance the outcomes. Additionally, it works with other programs like for example the Zoho analytics (previously called Zoho Reports) which is a data analytics software that allows creating appealing data visualizations and insightful dashboards *(Zoho Website, 2019)* and further online reporting. The company employs moreover, NodeXL as a powerful and easy-to-use interactive network visualization and analysis tool that integrates the available MS Excel application as the platform for displaying generic graph data, executing advanced network assessment and visual exploration of networks. For its CM and PdM analytical tasks, it uses programming languages including python and the database management system SQL. Another factor that distinguishes Tesla on other car manufacturers is its real-time connection with the driver to transmit vital information and receive relevant data not only for analysis but also for immediate warnings in case of urgent situations. Thusly, Big data plays here an important role as it gathered from the vehicles, and will be concerning primarily the essential parameters such as the electrical, mechanical and of the engines etc. Accordingly, Tesla will develop the raw data into meaningful information for the user and will be analyzed properly to inform the driver. This information is meant to enhance the customer service and increase its satisfaction but above all ensure high levels of equipment reliability and overall safety. Unlike any other car manufacturer, Tesla instruments entirely its vehicles by default connecting them wirelessly to their corporate offices for analysis and assessment. *(Wirawanrizkika Website, 2016).*

Figure 23: Tesla's Autonomous Vehicle Technology (Shutterstock Licensed Photo by metamorworks, Matthews, 2018)

A major innovative step taken by Tesla was the last Autopilot update on August 2018 enabling the introduction of full-self driving vehicles in the market. The autonomous vehicle technology adopted by Tesla allows the establishment of multiple features:

1. Sense-plan-act: the vehicle's machine learning algorithms and IT programs would be capable of accurately predicting the outcomes based on high volumes of data.
2. Mapping: the ability of the vehicle's computer to acquire highly detailed and comprehensive maps will facilitate the monitoring tasks and the capability to detect any potential hazardous situations or items.
3. Early detection: through the implementation of advanced IoT and wireless sensors, the vehicle would be capable of creating an accurate and complete readout of its surroundings in real time and transmitting it to the central hub.
4. Vehicle to vehicle communication: this option isn't running yet on the autonomous vehicles but it is expected to be integrated in the future projections of the Tesla self driving cars by 2021. *(Matthews, 2018).*

The installed sensors would be also capable of informing the computer if they are defective which is called graceful deterioration. Moreover, the predictive analytics would indicate with extreme precision when and how a certain future event is about to happen and how it shall respond to it, like for instance when a pedestrian is about to cross the street, the vehicle has to know exactly how to react adequately. If the vehicle's protocols recommend following the laws with no exception what so ever, there's still must be a reverse function that orders to do the opposite if someone's life is in danger. Still, the establishment of this reverse function still relies on the human driver's reaction; this signifies that the autonomous vehicle in Tesla hasn't accomplished its complete version. Still the last and current updates imply that Tesla is getting closer in achieving its goals for the fully self-driving car. As for LIDAR, which stands for Light Detection and Ranging and refers to a remote sensing technique that applies light in the form of a pulsed laser to measure ranges (variable distances) to the earth *(NOAA Website, 2019),* Tesla doesn't have it meaning that Tesla doesn't possess any LIDAR data to instruct its autopilot. This is why a large number of analysts believe that Tesla isn't any close of getting a fully successful driverless operation and Tesla is at a total disadvantage against companies that do acquire LIDAR, which procures a huge volume of data to the car to work with, such as Waymo. Regardless of these opinions, it is a fact that Tesla stands strong against its competitors and has a solid opportunity in developing its autonomous vehicle project as its autopilot relies on eight cameras, 12 ultrasonic sensors, and a forward-facing radar to procure information. As for Waymo, it operates with cameras, radar and LIDAR. However, Tesla has something Waymo doesn't have: real-world data from vehicles out on the road. By July of 2017, Tesla's fleet logged 5 billion miles. Tesla is therefore capable of gathering data on speed, acceleration, braking and battery usage and the company can actually access short videos from road incidents. Tesla gets large amounts of autopilot data on a daily basis, and even when the vehicle is not on autopilot, it can still go through the shadow mode and procure hypothetical data on what the vehicle would have reacted if it was indeed on autopilot mode. Furthermore, Tesla has been gathering information from more than 300,000 vehicles around the world and the Tesla's sensors have allowed the collection of data from all kinds of environments since the autopilot is semi-autonomous. As for the cameras that we have mentioned, they can actually collect information at a range of 250 meters in all directions and provide by that increased visibility. With the recent update established in August 2018, the onboard computer will provide a quicker processing of data approximately 40 times faster than before. The Tesla site states that; *"The system is designed to be able to conduct short and long distance trips with no action required by the person in the driver's seat".* This would eventually reduce the risks of road accidents engendered by human error, decrease the insurance costs and insurance rates, improve the condition monitoring and predictive maintenance tasks' performance and gain the total customer satisfaction and above all the customer's safety. *(Matthews, 2018).*

- **Nissan Study case**

Nissan Motor Co., Ltd is a Japanese multinational automobile manufacturer that sells more than 60 models under the Nissan, INFINITI and Datsun brands. The corporation has started on the project Nissan M.O.V.E. to 2022, a six-year plan aiming a 30% rise in annual revenues to 16.5 trillion yen by the end of fiscal year 2022, along with cumulative free cash flow of 2.5 trillion yen. As part of Nissan M.O.V.E. to 2022, the company intends to enlarge its leadership in electric vehicles. Nissan's global headquarters in Yokohama, Japan, handles operations in six regions: Asia & Oceania; Africa, the Middle East & India; China; Europe; Latin America; and North America. Nissan has a global workforce of 247,500 and has established a partnership with French manufacturer Renault since 1999. In 2016, Nissan has gained a 34% stake in Mitsubishi Motors. Renault-Nissan-Mitsubishi is considered today the world's largest automotive partnership, with combined sales of more than 10.6 million vehicles in calendar year 2017. *(DATSUN Website, 2019).*

One of the major innovations of Nissan is definitely the intelligent mobility. The intelligent mobility perspective of Nissan is regarded as an initiative that was put in place to make vehicles smarter and safer. It concentrates mainly on how the cars get their power, how they drive, and how operate in roads. The point of this technological solution is to eventually make the driving experience better, easier and more efficient. In other quarters, it allows the driver to know what’s happening around him/her and keep him/her as much as possible out of danger. The intelligent mobility presents therefore some features such as the forward collision which is a monitoring system that doesn’t only keep track of the a vehicle in front of the driver but of two vehicles ahead so as to give the driver a better vision of what to expect further down the road. Another tool is the blind spot warning and intervention which detects the existence of vehicles in the blind spot preventing by that any potential accidents if the drivers misses to see something on his/her blind spot. The intelligent mobility presents further solutions including the lane departure warning and the lane departure prevention in order to maintain the driver in his/her intended lane and take the necessary corrective actions if he/she drives out. Nissan gives moreover the capabilities to see around the vehicle and also know if something is moving directly behind the vehicle through the intelligent around view monitor and the moving object detection; these two tools that use cameras for accurate detection and monitoring. *(Nissan Website, 2017).*

Nissan has taken an enormous step towards the establishment of predictive analytics programs and systems in its vehicles by teaming up with artificial intelligence firm Senseye. Senseye is the leading cloud-based software for predictive maintenance and essential provider for PdM analytics. The company allows manufacturers avoid downtime and save financial resources by automatically predicting machine deficiency without the need for expert manual analysis. Its intelligent machine-learning algorithms enable it to be employed on any equipment from any manufacturer, taking data from existing industrial IoT sensors, devices and platforms to eventually diagnose failures and determine exactly the remaining useful life of machinery. Senseye has announced on the 11th of February 2019 its partnership with the North East Automotive Alliance (NEAA) in order to provide its predictive maintenance software to the automotive sector in the North East of England. The AI company, which has headquarters in Southampton and an office in Sunderland, has therefore provided to Nissan scalable predictive maintenance capabilities which allows the industrial firm to monitor the condition of thousands of vehicles remotely, identify automatically emerging problems and potential deficiencies likely to occur, and forecast thoroughly when and how controlled components

and machinery would possibly fail. Indeed, more than 200 maintenance users at Nissan's Sunderland plant use Senseye's software to enhance maintenance operations and perform repairs months before forecasted equipment breakdown. Over 3,000 Nissan assets such as robots, conveyors, drop lifters, pumps, motors and press/stamping machines, are monitored through various production sites where models including the Qashqai, X-Trail, Leaf and Infiniti are fabricated. Thusly, this has helped Nissan reduce the unplanned or unexpected downtime and cut down the maintenance costs by approximately 40 per cent. And thanks to the innovative program, Nissan can actually move from a state where predictive maintenance is regarded and executed as an exhaustive and money and time-consuming approach that only focuses on critical points of failure only to a state where PdM permits a faster, less expensive and more effective monitoring of the machinery automatically so as to prioritize the maintenance tasks according to the actual need. *(Sewell, 2019). (Senseye Website, 2019).*
As Nissan is already gathering large amounts of data from their machines for the purposes of accident logging and historical analysis, it can more facilely and rapidly deploy automated predictive maintenance analysis through all of their monitored equipment by connecting to technological advanced instruments. Typically, the automated algorithms utilized by the automobile manufacturer consider thoroughly data from a range of outputs like electrical current or vibration levels for example. Accordingly, this would enable the company's systems to develop a detailed understanding of all the components' condition, and identify trends and patterns or unusual situations that could actually signify that a specific part or parts are getting closer to failing. Therefore, by adopting Senseye's programs, Nissan has started to deliver tremendous improvements in throughput, margin and quality. *(Kampa, 2018)*

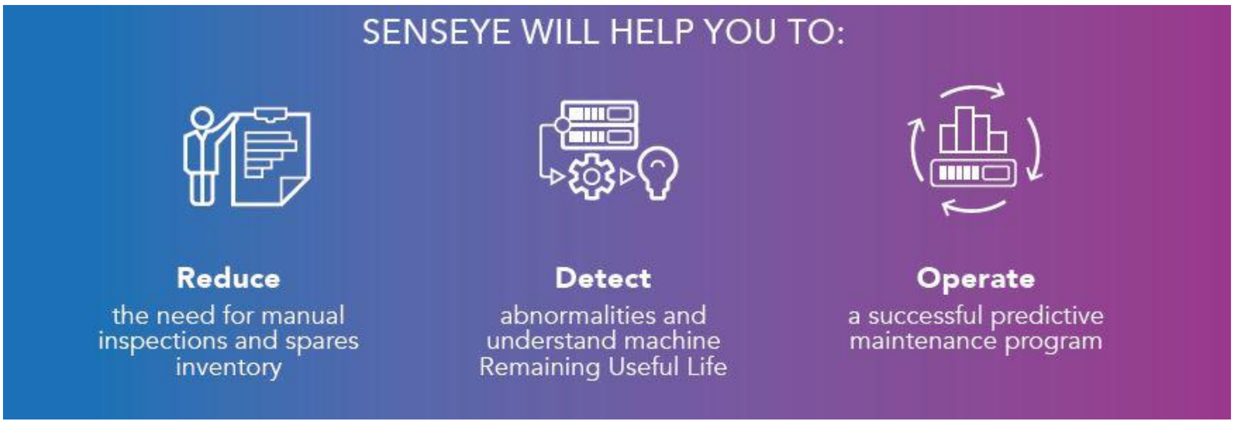


Figure 24: Predictive maintenance scheme provided by SENSEYE and adopted by Nissan (North East Automotive Alliance Website, 2019).

As we have mentioned earlier, Nissan is collecting huge volumes of information to as to upgrade the performance and efficiency of its condition monitoring activities and predictive maintenance tasks. The company is today capable of storing these large amounts of data much easily and deploying by that a diversity of data cross-functionally. Nissan has embarked on a Big data journey in order to solve the issues caused by the increased growth and diversity of data. The corporation has turned to Hadoop as a solution to the Big data challenge. After a detailed and meticulous competitive evaluation, Hortonworks Data Platform (HDP) involving

Apache Hadoop was chosen so that it can power Nissan's information lake infrastructure by eventually storing, processing and analyzing the relevant data. The major reason behind the partnership with Hortonworks is the open source model. Moreover the technological solution is known for its numerous engineering capabilities in the market, its flexibility to easily get adapted in case the condition of work change and more importantly the fact that it doesn't necessitate the installation of any proprietary or non-open source modules; for all these factors the open source technology seemed the right choice for Nissan and had an enormous appeal to the company. On the other side, the connected car is a shared vision strongly pursued among a large number of automobile manufacturers. HDP has consequently allowed Nissan to gather information across the whole business, majorly data linked to driving quality and vehicle performance. The company is capable today of employing information applications that demand cross-functional data assessment like analyzing for instance the battery usage in electric vehicles and quality management to make sure that customers have an enjoyable driving experience. Long before, Nissan didn't acquire the necessary infrastructure to stock, analyze and assess all these volumes of information especially on a long term. As part of Nissan's attempts to completely install HDP, it engaged seriously in the construction of a data warehouse in 2017. Such implementation has allowed the introduction of a data lake able of stocking all kinds of corporation information to be processed. In this matter, Satoshi Kitsuki, General Manager, Nissan Global IT Division states: *"HDP proved very effective in managing the large volume of quality data we had. Thus, HDP was deployed to other functions in order to meet internal demand"*. Nissan is working constantly on exploring new areas and expanding its business through the investment of innovative programs and applications for its valuable data. Thereupon, the company is encouraged to establish partnerships such as with Hortonworks for a better and smarter future. *(Spillar, 2017).*

No other manufacturing industry has worked hard enough to seize the value of partnerships in delivering high quality products and great customer experiences than the automotive sector. Likewise, in the software industry, Microsoft is considered to be the most suitable candidate for the partnerships with automakers around the world thanks to its heritage and technological cutting edge position. Instead of choosing to construct its own connected cars, Microsoft is procuring auto-manufacturers with a solid platform that does all the heavy work across various areas of connectivity empowering partners and customers with the cloud-based instruments in order to connect services and information together. Consequently, this will endow automakers in focusing more on their operations of creation of innovative vehicles that bring better and safer driving experiences. Employing Azure IoT Hub, to link and communicate between the vehicle and provided services such as Cortana Intelligence, the Microsoft Connected Vehicle Platform takes advantage a group of cloud services and productivity technologies that grant improved navigation, advanced predictive maintenance, remote condition monitoring of vehicle features, in-vehicle productivity and intelligent and personal assistance for drivers. Nissan, which sells one in ten cars around the globe, is regarded as the first automaker to actually commit to the Microsoft Connected Vehicle Platform. Nissan would be utilizing this platform in order to empower its next-generation connected services in their vehicles. These vehicles would be able to provide advanced navigation and driver support through Cortana Intelligence and above all offer predictive maintenance assistance using remote monitoring of vehicle features. During the company's CES (Consumer Electronics Show), the annual trade show, on the 5th of January 2017, the company confirmed that they have committed to the innovative platform mainly because of Microsoft's flexibility, multi-OS and programming language support, enterprise-grade safety and strong engagement to conformity. *(Microsoft IoT Website, 2017).*

- **BMW Study case**

BMW which stands for Bayerische Motoren Werke AG or Bavarian Motor Works, is a German multinational automaker headquartered in Munich, Bayern. Today, the BMW group, with its 30 production and assembly facilities in 14 countries as well as a global sales network, is the world's leading manufacturer of premium automobiles and motorcycles and provider of premium financial and mobility services. The BMW Group sets trends in production technology and sustainability as an innovation leader with an intelligent material combination, a technological shift towards digitalization and resource-effective production. At the same time, flexibility and continuous optimization of value chains guarantee high levels of competitiveness. With Efficient Dynamics, the BMW Group constantly establishes the principle of sustainable mobility and is firmly decreasing its vehicles' fuel consumption and CO2 emissions. *(BMW Group Website, 2019).*

BMW creates some of the most high-tech vehicles in the automobile market. The German auto-manufacturer produces 2.5 million vehicles annually and sells them entirely worldwide. However, the technology isn't just restricted on the cars built; the company's business model is primarily based on Big data which drives everything it does across design, engineering, production, sales and customer support. Supported by Artificial Intelligence, information-based predictive analytics systems and other advanced technological solutions, BMW is capable of constructing the cars of today while still planning and designing the cars of the future. As a the majority of automakers today, BMW has serious plans in making driverless vehicles a reality and takes intensive initiatives in this directions seeking to accomplish by the end of 2021 level 5 autonomy for its cars. Level 5 autonomy exceeds the scale defined by the US department of Transport indicating that the vehicle would be absolutely able of driving with no human intervention, input or supervision. Further information on how this could be executed on real ground started to emerge in the beginning of 2017 when BMW declared its partnership with Intel which has already acquired Mobileye; a leader in computer vision technology. In fact, computer vision is built on the basis of teaching machinery to see in the same manner humans do, employing cameras instead of eyes, and to analyze and interpret data in the same way our brains do. The computer vision applied in autonomous driving would be capable therefore of reading all the input data produced by the vehicles' cameras and sensors and analyzing it in real time rapidly enough to take the necessary action. With a manufacturing activity as huge as BMW's, enormous volumes of information are brought about through design, production, logistics and distribution. In order to coordinate the work, decrease the operational and maintenance expenses and improve the overall efficiency over 30 industrial facilities spread over 15 countries, BMW has teamed up with Teradata, a provider of database management systems and analytics, so as to automate data flow and upgrade decision-making. Systems were designed to pursue the journey of any given component from the point it is fabricated to when the vehicle is sold. This would create amazing efficiencies in logistics when large numbers of components are being shipped around the globe and aids making sure that every part gets to the convenient place with the minimum usage of resources. Predictive maintenance is empowered through production lines, so worn parts can be replaced and mistakes are displayed before they engender operational issues. Also, if stock levels of particular components are too high or too low in certain locations or too low or specific transport resources are under or over-resourced, this can actually be immediately corrected. *(Marr, 2017).*

Another example of partnerships of BMW Group is the collaboration with IBM (International Business Machines Corporation). Indeed, BMW is utilizing IBM's big data and analytics technology in order to solve the imposed vulnerabilities in advance on the production processes and is counting on the offered software to address the big challenges presented in the automotive industry in relation to maintenance, repairs and customer service. Through the use of predictive analytics, BMW can determine possible failures and issues at early stages of new models being launched. BMW will deploy the platform to collect and assess information all across its global warranty, diagnostics and repair entities to enhance the design and production of novel vehicles. A process that used to last for months can be nowadays performed and fully achieved in days. Being capable of analyzing various sources of data allows the auto-manufacturer to identify the exact trends and patterns that will recognize the possible flaws. Such abilities will make the company surpass easily any repair issues, decreasing by that the number of workshop visits and accelerating the inspection and repair times. We can talk for instance about the IBM's SPSS predictive analytics software adopted by BMW Group and through which the German automaker can actually combine and analyze data from multiple prototype test runs, an average of 15,000 faults registered by vehicles and recent workshop reports. The insight deduced from the analysis is channeled back into the operational procedures and processes. Errors are quickly and accurately pinpointed permitting new models to be corrected before even they reach series production. Fixing problems in advance diminishes the necessity for costly and time-consuming repairs for later phases. BMW has as well automated some 250 analytics applications enabling more than 500 users at BMW to manage a range of requests and analyses on a self-service basis according to IBM. *(Datanami Website, 2014).*

Building a vehicle produces tremendous amounts of information through the value chain. The BMW exploits its Smart Data Analytics digitalization cluster to analyze this data accurately and improve its operational systems. The outputs of intelligent data analysis make an efficient contribution towards upgrading quality in all areas of production and logistics. Subsequently, data-based enhancements to procedures and equipment contribute in reducing lead times and maintenance and operational costs. These novel solutions are implemented in all BMW industrial facilities allowing by that the auto-manufacturer to take advantage of more innovations so as to include more options for more flexible processes. Additionally, BMW uses an access-protected intranet-of-things platform to connect the huge amount of sensor and process data from production and logistics rapidly and more easily. Smart Data offer high potentials that enable surpassing the old-fashioned or traditional analysis possibilities. Another advantage is that the speed with which novel solutions can be established is quite significant. Simultaneously, new industrial IoT sensors, integrated with cloud and big data technologies are decreasing the technical complexity and the overall related costs. Christian Patron, head of innovation and digitalization in production system in BMW says: *"Smart Data Analytics is setting new standards for our production system. By combining the experience of our staff with new possibilities for efficient processing of large data volumes, we are able to create accurate forecasts and proactively optimize processes. This speeds up continuous improvement of our production system in line with the basic principles of lean production." (Wienstroth, 2018).*

Smart data analytics applications adopted by BMW provide furthermore new opportunities for expanding the availability of machinery in automated locations of manufacturing sites and maximizing the accuracy in forecasting the risks of failures reducing by that significantly the unexpected system downtime. The resulting predictions will allow by that the maintenance personnel to schedule targeted maintenance interventions to restrict downtimes to the minimum. The smart PdM that we are discussing is enabled mainly by the executed intelligent assessment and analysis of considerable volumes of real production, sensor and process information that make it feasible to indicate precisely when and where to replace wearing parts. Obviously, if the replacements are established too late, the risk of production stoppage increases, and if the changes are made too early then important resources are wasted. Data-based solutions for PdM are deployed at various and practically all phases of car body production in order to forecast wear in robots. Sensors in welding tongs alert ahead of time when faults or quality issues are more likely to happen. Wide-scale sensor also enhances the reliability of the electrical drives utilized in a diversity of systems including turntables and lifts. Robots and control technology are fitted with the established sensors making it easier for the maintenance teams to assess the gathered data and take the right decisions. The intelligently networked systems established in the BMW facilities improve the stability of process sequences facilitating the PdM tasks and ensuring high levels of quality for users. As for the online process control, it adds the advantages of algorithm-based analysis of large amounts of data to the solid personnel expertise engendering by that a better concentration among the maintenance and production teams since the needed information is already sorted and thoroughly prestructured for them which reduces again the error percentage and eliminates the rework operations. In May 2017, the BMW Group has started using entirely automated quality control for the first time at its Munich facility, with robots scanning the whole outer vehicle surface. The installed system would be able of identifying faults that the biological eye cannot detect. Such information would offer important feedback about the accuracy of the manufacturing processes allowing constant optimization and timely determination of potential deficiency. Concerning the assembly processes, a great number of conveyor systems are supplied with various sensors that control multiple parameters such as temperature, electric power, vibration etc. The installed sensors are cost-effective enough to make them widely used across the industrial processes and in all the facilities. Data coming from these sensor kits and other processes is streamed live through the BMW IoT platform so it can be visualized and assessed in real-time. In case the resulting data indicates the exiting of a disparity from previous breakdowns, the platform warns the maintenance staff. As a result, the team can actually decide if the hanger should be removed for maintenance. In this manner, it would be possible secure lasting and reliable operation of the conveyor system through numerous years. Patron has confirmed that in the automobile sector, every minute is crucial and when a certain component or system is not available on time or fails, the production cycle is interrupted or delayed which affects directly the value chain. He then adds: "Intelligent use of production data ensures a stable and efficient process. We see tremendous potential in Smart Data Analytics for incorporating feedback from our customers into development and production even faster." *(Wienstroth, 2018)*. This only proves how much BMW has worked and still working harder to introduce constantly innovative CM and PdM systems and approaches into its industrial structures.

- **Volvo Study case**

The Volvo Group is one of the world's leading manufacturers of trucks, buses, construction equipment and marine and industrial engines. In addition to that, the Group provides complete solutions for financing and service. The Volvo Group, with its headquarters in Gothenburg, employs about 100 000 people, has production facilities in 18 countries and sells its products in more than 190 markets. In 2018 the Volvo Group's net sales were approximately about SEK 391 billion (EUR 38.1 billion). The Volvo Group is a publicly-held company. Volvo shares are listed on NASDAQ Stockholm. *(Volvo Group Website, 2019).*

Volvo's commitment to innovative initiatives isn't a new thing; the auto-manufacturer has started to engage innovation into its production and maintenance activities since the late 90's. Still, the company is constantly working on introducing novel technological tools and procedures into its various processes in design, production, assembly, distribution and customer service. Indeed, Volvo Trucks is deploying new approaches to monitor and analyze critical parts in real time so as to handle any possible breakdowns or malfunctions prior their occurrence. For that, a new tyre management service has been launched in Sweden along with a test pilot for advanced monitoring of trucks in Europe. Besides, the application of machine learning systems will enhance the accuracy of predicting unplanned or unexpected stops. Markus Efraimsson, Vice President Uptime, Volvo Trucks, expresses that the new technologies for monitoring and analyzing truck information in real time are presenting new opportunities for forecasting potential deficiencies more accurately and further into the future, *"It's all part of our continuous effort to keep our customers' trucks on the road".* As for the new tyre management service, it calculates precisely the tyre pressure and temperature in real time. Following that, the resulting outputs would be monitored through an application, allowing the driver and the owner to single out slow punctures and avert any possible tyre explosions that could lead to unplanned breakdowns and costly repairs. Moreover, since the new service insures the correct pressure and the right temperature, it is expected to reduce the fuel consumptions and more mileage from each tyre. The tyre management service will be therefore rolled out successively in the European markets. Concerning the test pilot adopted by Volvo, it provides a better monitoring and analysis of information in real time through thousands of trucks enabling by that various types of deficiencies and faults to be avoided and enhancing consequently the total uptime and overall productivity. The main objective is to forecast with high accuracy the components failures before they take place and before they interfere with the customer's business providing the clients with optimal service planning. When a potential problem is identified by a Volvo Truck Monitoring Center, the customer's local workshop is warned so that the necessary actions can actually be taken. On this context, Efraimsson says: *"We're looking at uptime from a customer perspective. Our focus is really to secure that the customer has no unplanned stops".* The next natural phase would be to gradually implement machine learning. This form of artificial intelligence enables to gather and analyze huge volumes of truck information for the purposes of research and development. In other quarters, it makes it possible for Volvo Trucks to learn more and more about the health status and the performance of the relevant truck, and thousands of other connected trucks on a daily basis. Thereupon, through the intensive usage of computer modeling and IoT analytics, the objective is to be capable of detecting hidden trends or patterns to foresee part failures at early stages and maximize the truck's uptime upgrading the related CM and PdM operations. *(Volvo Trucks Global Website, 2018).*

With the aim of upgrading uptime for its clients, Volvo Trucks is teaming up with SAS technologies in order to assess more information from IoT-empowered trucks and the environments they function in, while also starting to execute artificial intelligence to the relevant data with the goal of ameliorating the predictive maintenance abilities. The innovative breakthrough of the automaker in this case is that is can easily solve possible technology problems and grant the needed improvements through the appliance of over-the-air software updates, remotely program software that enables parameter updates without taking the truck off the road, according to Conal Deedy, the director of connected vehicle services for Volvo Trucks North America. With SAS technologies, Volvo Trucks in actually succeeding in extending and processing the information in relation to uptime in the best way possible, and also concentrate on putting in action its gained knowledge and expertise as a vehicle builder and accordingly organize to draw the maximum benefit of it instead of drowning in the huge amount of collected data. Volvo Trucks has announced the launching of its so called Remote Diagnostics platform and services in 2013; coupling telematics boxes implemented into trucks along with SAS technologies to allow the exact and real-time monitoring of components, data and trouble codes. Subsequently, the agents operating in the related centers do employ this data to inform the customers who have chosen this service of the possible problems or failures. The Volvo Trucks can currently assess seven or eight distinct scenarios in order to make the adequate maintenance recommendations. For example, it can couple defect codes with data on oil temperature and cooling levels, the software version of the engine control unit and data on the altitude and what humidity levels the truck was working at to examine the state of the truck and its degree of vulnerability to getting potential breakdowns. Deedy states: *"We need to be on top of that as an OEM. We want to be the best. We have to leverage that data and information to be much more precise and support our trucks".* According to Deedy, enlarging Volvo's remote monitoring and diagnostics abilities on average enables decreasing diagnostic time by 70 percent and repair time by 25 percent. Also, remote programming of software and parameter updates saves time over the 2.3-day industry average. On the subject, Deedy confirms: "The reason our customers buy a truck is to deliver and do a job. The most important thing for the customers is uptime. We can react in a much quicker way than we ever could before." *(Bjorlin, 2018).*

The common description of a connected car is a vehicle that can access online data and deploy it to facilitate the operational and maintenance tasks of the vehicle and improve as well the comfort and convenience of passengers and drivers. Volvo Group has a solid reputation for safety so it focuses mainly on reducing the influence of mechanical, electric or system failures and identifying what features and functionalities its customers want to have exactly on their connected cars. Volvo's director of business intelligence, Jan Wassen, says *"We are trying to coordinate both creating and enabling tools for analytics, as well as making sure it is being triggered within areas where we should be active."* Obviously, indicating the areas where analytics could bring the most profits is a part of Wassen's job. Volvo has been actually working non-stop on improving its data strategy and analytics since it has introduced to the market its first vehicle with internet connectivity in 1998, through initially mixing warranty claim information with telemetry to forecast when components would fail or when vehicle would require servicing. The increasing complexity of this dataset and the abundance of the knowledge and insights incited the company to develop furthermore its analytics technological tools and currently Volvo is teaming up with Teradata, a leading provider of pervasive data intelligence, data and analytics solutions and hybrid cloud products *(Teradata Website, 2019),* in order to carry out predictive, machine-learning based analytics across petabyte scale datasets. Their early warning system examines over one million events per week so as to study their relevance to breakdown and failure rates. In addition to forecasting these failures and breakdowns rates, the company uses Big data and IoT analytics in order to maintain its strong reputation in delivering highly safe vehicles. The ultimate goal of Volvo here is the control of vehicles' performance in hazardous conditions like for instance when roads are icy etc. Hence, information is uploaded to the company's Cloud and ultimately shared with the Swedish highway authorities. As the previous study cases that we have discussed on this section, Volvo is strongly interested in autonomous vehicles and of course focuses on the safety aspect above all. A National Highway Safety Administration report has found in 2016 that 90% of US road accidents are majorly caused by human errors. This has confirmed again to many automakers including Volvo that by removing the driver from the equation, driving can be better and much safer. On this matter, Wassen declares: *"We believe that one of the major contributors to road safety will be autonomous vehicles. We have very ambitious plans here, that are very much dependent on connectivity and IOT."* Thusly, Volvo is walking the line with the key players of the automotive industry towards the future where driverless vehicles become the reality; and to accomplishing so, is developing AI algorithms in house, enhancing its IoT tools and bringing innovative PdM and CM systems and approaches into its operations and structures. Wassen says *"I believe that this is really an important step for us. The next step with autonomously driven vehicles is to work out what the transportation service will look like. Will everyone have their own vehicle which is parked 95% of the time? Or will there be fleets of vehicles which you join? Clearly this is something which is already starting and we want to be on top of it and Big Data and analytics is how we make sure we reap the benefit of this development."(Marr, 2017).*

- **Toyota Study case**

Toyota Motor Corporation is a Japanese multinational auto-manufacturer headquartered in Toyota City, Japan. Toyota manufactures and sells vehicles and spare parts globally. Currently, the company operates its business worldwide with 53 overseas manufacturing companies in 28 countries and regions. The company's vehicles are sold in more than 170 countries and regions. Toyota became the world's largest automaker by volume in 2008, surpassing General Motors, the largest US automaker, for the first time. *(Marketrealist Website, 2018).*

Toyota has been taking lately some serious initiatives when it comes to implementing technological innovations in its operations and structures. Jeff Moore, Senior Vice President, Unit Plants/Lexus Leader of Toyota Motor North America, has said that the auto-manufacturer has been in the process of establishing Toyota New Generation Architecture, a shared platform system to be installed in every North American facility in the upcoming years. Moore says that it is awaited to cut down the costs and ameliorate the vehicle performance, and considers it as a crucial opportunity to insert production technology as he describes it *"beyond the normal plant projects and upgrades".* Few years ago, Toyota started to comprehend that it wasn't making enough improvements when it comes to the IT contributions to manufacturing processes and to the core business. Therefore, the automaker has established a program called Advanced IT for Manufacturing in order to integrate other fields of the business. By 2016, the program's North American steering committee has installed 32 smart manufacturing systems. Tim Platt, group vice President and chief divisional information officer, has explained that in the company's operations and maintenance area, they are gathering information from the plant floor and featuring them on dashboards and reports and mobile instruments, he says *"We're pulling it in that an industrial big data share so we can do cross-pillar predictive analytics."* Among these systems, we can name the Toyota Operations Availability System (TOAD), which has saved 40,000 minutes in a single plant for a total of $6 million in avoidance and savings. Moreover, the company has established a big data control tower for its dashboards which procures a complete examination and following up of the parts through the supply chain; the solution has saved $187 million per year of downtime, Platt has as well stated: *"We recently had a a bridge closing that affected in the ballpark of 200 routes. With the new capability, getting those routes going in a better direction was a matter of a few minutes."* The installed technological solutions have further allowed the company to run various product types on a production line, acquiring data mechanisms which catch conditions in real-time so production and maintenance staffs can actually react rapidly and applying at the same time the flexibility concept in relation to the volume without crushing the productivity. Trever White, divisional information officer, noted that his team has had the challenge to construct a containment system in order to easily and effectively determine and contain a quality problem when it comes to the surface. White has confirmed that currently his team members can actually carry their iPhones with scanners on them, and no matter where the containment is placed, they can rapidly perform a scan, they can examine it to see if it was impacted and following that they can repair the vehicle and confirm the operation, unlike before where, as he says, *"the members were going to*

*Starbucks, they were logging in, trying to figure out where the cars were at that particular time. Now we know where they are—we can contain the issue and reduce the time."*On the other side, Platt states that Toyota considers that there's a crucial opportunity in placing sensors on machinery. He adds talking about a concrete situation in the company: *"We were talking about an example we had in paint. Our engineers were manually collecting data, it was taking weeks and weeks to validate a problem, we brought in one of our strategic vendors, put in a predictive maintenance tool to show proof of concept. One of the paint engineers came back and said you know it's taken me eight weeks to figure out that was a problem; you guys did it in two hours."* Moore also stated that in North America unlike in Japan, they spend too much time on data collection and analysis instead of issue solving and kaizen. He declares therefore that developing a system while employing IoT in order to capture data in real time, apply automated analysis and conceive visualizations for personnel has contributed in compensating the gap in experience level and "it's been a game changer". *(Putre, 2016).*

Toyota Motor Corporation has also announced its collaboration with Hitachi, Ltd., to conceive a high-efficiency production model utilizing an IoT platform. Both of the firms have already conducted on 2017 verification at Toyota's model plants. Through this verification, they have established a platform using Hitachi's IoT platform "Lumada", which deploys digital technologies like AI for instance and big data analysis. The usage of this platform to help solving problems at manufacturing plants will enable the PDCA (plan-do-check-act) cycle to be performed more rapidly and new issues to be accurately pinpointed and solved from the point of complete optimization leading to higher enhancement of quality and productivity levels. A plant IoT platform deploying "Lumada" will be implemented in each of the model plant for units and vehicles. The platform contains multiple layers including a data acquisition layer, a data accumulation layer and a data utilization layer. The sites, instruments and connected mechanisms at different manufacturing facility in the model plant will be linked to the platform in order for the relevant information acquired from them to be actually reinforced and assessed. This would enable both firms to swiftly utilize IoT in numerous manufacturing processes for enhancement actions leading to a faster and more efficient PDCA cycle. Another advantage of this solution is the fact that it permits a total analysis not of a single process but of all the processes in question, resulting in the construction of new findings and the improvement in production effectiveness and performance. As a special theme of this verification, Toyota and Hitachi plan to install a system that avert unplanned or unexpected facility deficiencies through big data analysis and expand the related system to other processes so as to upgrade the effectiveness of predictive maintenance activities and monitoring tasks. The goal of Toyota behind the usage of this IoT platform is to accelerate the PDCA cycle, apply the necessary verifications and inspections throughout the entire processes to control the potential impacts so that operational and maintenance actions can be ameliorated and quality and productivity can be boosted. *(Trego, 2017).* The following figure illustrates the features of IoT platform of Lumada solution.

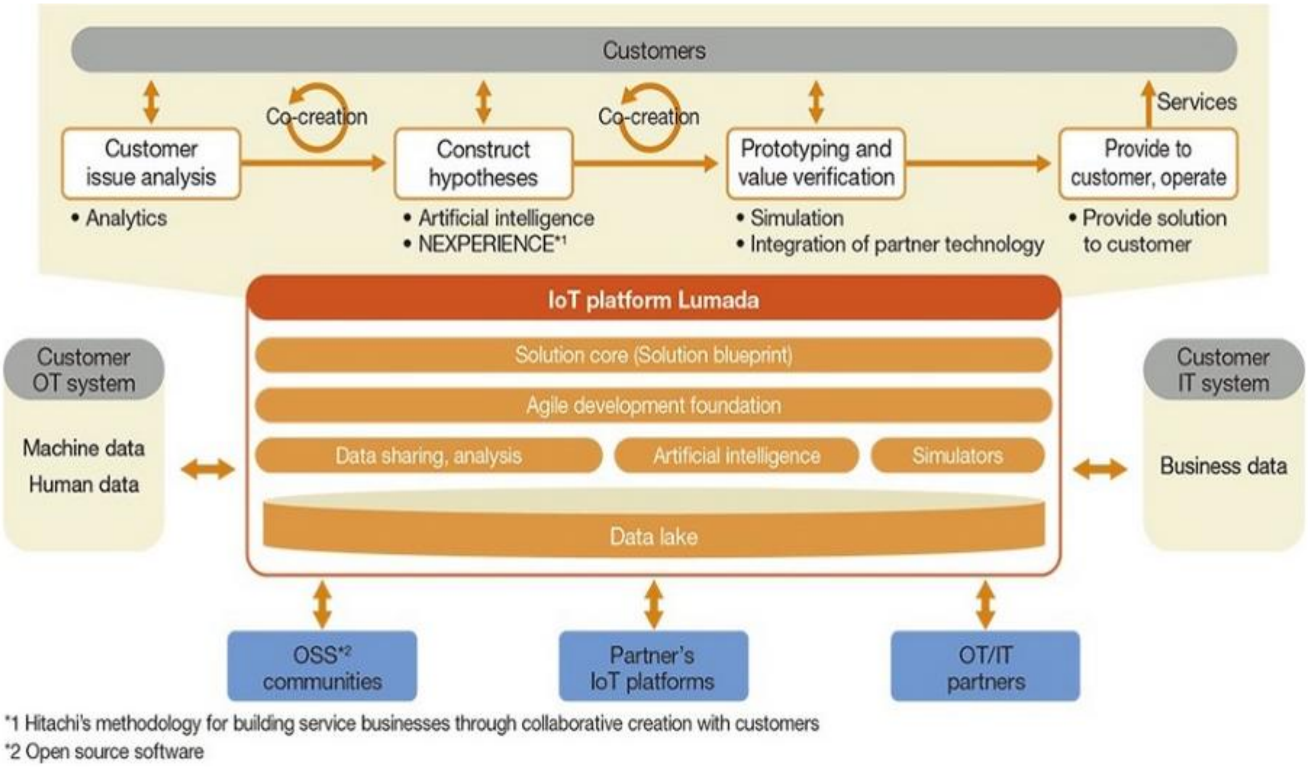


Figure 25: Features of IoT platform, LUMADA (Trejo, 2017).

4.7.3 Study cases from the Oil & Gas sector

The oil and gas sector can be considered as a complex sector with some demanding requirements. Adding to the fact that equipment, installations and operators are working under unfavorable sometimes even hazardous conditions, it is becoming more and more complicated, costly and time-consuming to extract energy. Companies have therefore obliged to find innovative ways and look for new opportunities to maximize investments, reduce operational and maintenance costs and mitigate risk. The recent technological and digital developments in predictive maintenance and condition monitoring have enabled industrial corporations to facilitate the maintenance and monitoring tasks and elevate their overall performance and effectiveness. The advanced condition monitoring and predictive analytics which combine data science, computing platforms and engineering allow the potential failures to be accurately forecasted and the maintenance activities to be scheduled only if needed. In adopting smart analytics, it follows that Artificial Intelligence would find its way into the oil and gas sector, permitting companies not only to concentrate on their operations' effectiveness but moreover on employee's safety and environmental accidents rates. As the oil and gas sector, along with aerospace and power generation industries, was one of the earliest adopters of smart predictive maintenance, it has accumulated a large experience into developing novel approaches into its activities and systems, leading by that to diminished unscheduled downtime, increased machinery efficiency, reduced costs and enhanced safety even in the most hostile tasks and environments. *(Peycheva, 2018). "We are now poised for a* *second digital age that could further reduce costs, unleash unparalleled productivity, and boost performance significantly—if executives can harness the right technologies to support their business strategy,"* McKinsey & Co. oil and gas industry analysts write in a recently released research report. *(Burger, 2019).*

- **Shell Study case**

Royal Dutch Shell, known as Shell, is an international energy company with expertise in exploration, production, refining and marketing in oil and natural gas, and the manufacturing and marketing of chemicals. Royal Dutch Shell was formed in 1907; still, its history can be traced back to the first half of the 19th century. Its headquarters are in The Hague, the Netherlands, and its Chief Executive Officer is Ben van Beurden. The parent company of the Shell group is Royal Dutch Shell plc, which is incorporated in England and Wales. It operates in more than 70 countries and has an average of 82,000 employees and produces 3.7 million barrels of oil per day. Its revenue in 2018 was estimated at $388.4 billion. The company's main strategy is to endorse its position as a leading energy corporation by procuring oil and gas and low-carbon energy as the world's energy system changes. Moreover, Safety and social responsibility are fundamental to its business approach. *(Shell Website, 2019).*

Shell has been an early adopter of Artificial intelligence working intensively on speeding up its digital transformation. From machine learning to cloud computing, deep learning to virtual assistants and autonomous vehicles to robotics, Shell has been concentrating on a wide range of technological solutions to support AI advancements. Satya Nadella, CEO of Microsoft has said: *"What's happening at Shell is pretty amazing. They have a very deliberate strategy of using AI, right across their operation… from the drilling operations to safety in… Shell Retail stations."* *(Shell Website, 2019).*

Through the strategic usage of analytics, numerous oil and gas companies are capable today of creating strong intelligence from new data sources and make revolutionary and beneficial decisions with extreme confidence and Shell is exception. Indeed, analytics remodel big data and transform it at Shell Exploration and Production into thorough exploration decisions, high quality wells, diminished environmental influence and reduced operational and maintenance expenses. Shell utilizes SAS Predictive Asset Maintenance software in order to expand machinery lifespan and run times, which can account for millions of dollars in raised oil and gas production. Impacting all segments of activities, analytics enable Shell improve its overall efficiency and effectiveness maintaining the firm on top by boosting the bottom line. *"SAS eliminates guesswork from our business processes,"* states Tom Moroney, manager of Technology Deployment and Geosciences at Shell Exploration and Production, Upstream Americas, Deepwater. He confirms that the company analyzes huge amounts of real-time data in order to upgrade process and asset efficiency, well performance and reliability and explains that when its SAS alerts indicate a performance gap, the teams can rapidly diagnose it, interrogate the system and prevent or mitigate critical upsets. *(Analytics magazine Website, 2018).*

Shell is also enlarging its work in the same direction through the collaboration with Microsoft Corporation. This partnership will enable the firm to accelerate industry transformation and innovation, to increase efficiencies across the corporation from drilling and extraction to maintenance and monitoring, as well as safety of the personnel and retail employees. Shell has therefore chosen C3 IoT with Microsoft Azure as its artificial intelligence platform to allow and speed up digital change on a global level. Shell awaits to score important economic enhancement by quickly scaling and reproducing AI and machine learning applications and solutions throughout the upstream and the downstream structures and upgrading operational performance. The collaboration with Microsoft offers Shell a strong digital technological platform so as to turn its core business into a more efficient one and more importantly gives the oil and gas company the necessary means to generate better and cleaner energy solutions through advanced technology, confirmed Yuri Sebregts, executive vice president for technology and CTO of Shell. Leveraging the C3 IoT Platform on Microsoft Azure for a large group of artificial intelligence applications, Shell will begin mainly with predictive maintenance for a tremendous number of significant assets globally. Subsequently, the company will extend then to support other machine learning, equipment vision and natural language processing-driven use cases. The shell arrangement builds on the expanding power of the C3 IoT and Microsoft collaboration to hasten enterprise AI and IoT application improvement. With C3 IoT on Azure, Shell will apply enhanced work on tier-one transactional information in the Azure cloud, involving predictive maintenance, maintenance optimization, telematics, production optimization, and in the future machine vision. It is crucial to signal that Shell has made some considerable progress in two major aspects of the business through the usage of AI tools. Shell Geodesic was developed in order to ameliorate the precision, accuracy and consistency of a horizontal well's directional control to attain the most fruitful layers of rock holding oil and natural gas. Hence, the solution provides drilling information and processes algorithms that produce real-time decisions and help predict accurately their outputs. And to secure the safety of workers and customers in retail plants, Shell has created a novel cloud-based, deep learning application based on Microsoft Azure that employs closed-circuit camera footage and Internet of Things technology to rapidly and automatically determine security hazards and alert personnel, so they can properly react and quickly eliminate any potential issues. *(Wells, 2018). (Telecoms Business Website, 2018).*

The adoption of technological solutions from C3 IoT and Azure has enabled Shell to effectively handle the cost of goods sold (COGS) and exploration/drilling costs in the short term while still ensuring high levels of safety. And through this planning, Shell has announced the launching of its deliberate strategy of deploying machine learning across its total operation as affirmed by Satya Nadella's keynote speech at Ignite 2018. On the short term, Shell leverages predictive maintenance and production optimization to decrease COGS. By first of all gathering large volumes of sensor data from the machinery on the industrial plants, Shell can actually forecast when the equipment will possibly fail and perform the needed replacement before it breaks down. Averting unexpected downtime of its assets has reduced costs and saved approximately 3.5million barrels in lost production since the installation. Second, as stated by Craig Walker, CIO of Shell Downstream, Shell leverages machine learning for demand predictions and for feedback selection, which adds significant benefits and a huge value to refineries by making sure that the multiple blends from all the fields won't engender any operational issues. The company would consequently comprehend market trends or patterns more effectively and works harder on better planning its production so as to optimize the value produced by an oil barrel. In order to decrease the exploration/drilling expenses, the corporation utilizes real time information generated by the drill bits to plan more effective course for wells to upgrade productivity and diminish drill wear and tear. In the medium term, Shells schedules to apply and spread machine learning largely into its activities in the objective of enhancing safety in retail facilities. For instance, inadequate fueling and smoking can actually put at risk the safety of customers and workers. Daniel Jeavons, General Manager of Shell data science, says that with computer vision, Shell has evolved machine learning models that employ labeled footage of threatening behaviors to constantly improve instead of spending hours and hours into the analysis of CCTV footages manually. This will allow the company to interfere immediately with elements representing serious risks to the overall security. Shell would consider extending the usage of machine learning systems and tools to health, safety and environment. For short term, Shell could apply its predictive abilities to handle in a better way its carbon footprint. Through machine learning, Shell can actually indicate the major parameters that lead to emissions and thusly forecast emissions at earlier stages and adjust emissions prior the occurrence of any violations. This will as well aid the firm in reducing the additional costs caused by environmental regulations. In the medium term, Shell could disperse its safety enhancement initiative in retail plants to non-customer facing operations like in exploration or refining for example. Using image recognition mechanisms to eliminate dangerous conditions, Shell can interpose with safety problems for its personnel. Predicting the level of corrosion in pipelines and pipes within a facility, Shell would have the chance to replace pipes prior the start of hazardous liquids leakage. Due to the abundance of relevant information, all these uses of machine learning tools that we have explained all above can be considered therefore applicable. *(Johnson, 2018).*

Moreover, Shell supports novel projects that seek to develop further the existing predictive maintenance systems and come up with new technological solutions that can help overcoming the oil and gas industry challenges. Indeed, Akselos, predictive digital twin pioneer, has announced on September 2018 the completion of a $10 million investment round directed by Innogy Ventures and Shell Ventures. The financing round will have the goal to upgrade the sustainability of crucial assets in energy business, through the empowerment of predictive maintenance with structural analysis software, machine learning and big data analytics. "*Today's announcement underlines the value we will bring to the energy sector and is a huge vote of confidence from two of the world's most progressive and innovative energy companies. Our technology will not only help maximise efficiency and returns in the oil and gas industry in an increasingly competitive market, but it also has a crucial role to play in accelerating the energy transition. To tackle the many challenges humanity is facing, we need to think beyond incremental innovation and move towards next generation extreme engineering – that's what Akselos is all about*", have stated Thomas Laurent, Akselos co-founder and CEO. Akselos presents a digital technology to the market through a limited license with MIT. The technological solution, over 15 years in the development, was further advanced at the Swiss Federal Institute of Technology. In fact, it reproduces identical virtual replicas or digital twins of huge mechanical assets, deploying data to develop precise and accurate living, learning and predictive twins. This technology is regarded to be the first of its kind to be compatible with the IoT and digital solutions like for instance sensors, machine learning and big data analytics. This application which much faster and more precise than the industry standard itself when representing large scale assets, will permit the workers to have real-time access to the exact condition of the asset in question from any location and at any time and facilitate by that to take the necessary initiatives towards predictive maintenance. On this matter, Peter Van Giessek, Investment Director for Shell Ventures have expressed that Akselos enables the company to better monitor the integrity of their most complex assets, whether they are production vessels or wind turbines or other. With this technology, Shell's engineers, according to him, can currently perform analysis at the speed of thinking almost. *"When integrated with real life sensors on the assets, the technology creates a responsive system, enabling cost reduction and enhanced safety."* He furthermore confirmed that they are extremely proud to support "the brilliant" work of Akselos team and can't wait to see this being employed in their activities and operations. *(Akselos Website, 2018).*

During the " EMEA Users Conference" organized in Berlin on 2016 by OSIsoft, which is the provider and creator of an open enterprise infrastructure to connect sensor-based data, operations, and people to allow real-time and actionable insights, called the PI system *(Bloomberg, 2019)*, John De Koning, Shell Smart Solutions Technology Manager, has explained how it has transitioned from a reactive to a proactive and even a predictive company nowadays. The corporation's goal has been to change the operating model from a local reactive approach to a enterprise predictive approach. Although, to achieve this goal there's am main challenge that Shell faces which is how to migrate an entire company from a state of reactivity to proactivity taking into account multiple aspects including; operational performance, asset integrity and reliability, disciplined delivery and empowering the people. According to De Koning, the only solution to accomplish the company's objective is to create one-stop-shop for data and solutions. He confirms that they had to start treating data as an asset in order for them to make improvements in the process, as he says "You have to manage the data properly; treat it like a baby" and construct following that a platform approach so as to incorporate data and integrate capabilities while leveraging industry standards tools such as OSIsoft's PI system. Furthermore, De Koning has confirmed that the results of such enhancements have been quite tremendous as the model adopted by the company has indeed changed from a reactive to a proactive one leading to a higher performance, a better return on investment and an increased reliability. Shell would be capable therefore to detect and avert operational issues before they happen, reduce unplanned downtime and lower operational expenses across their organization. The following figure shows the long road that Shell has went through in the past years and where they are positioned today as a predictive operations' company. *(OSIsoft LLC, 2016).*

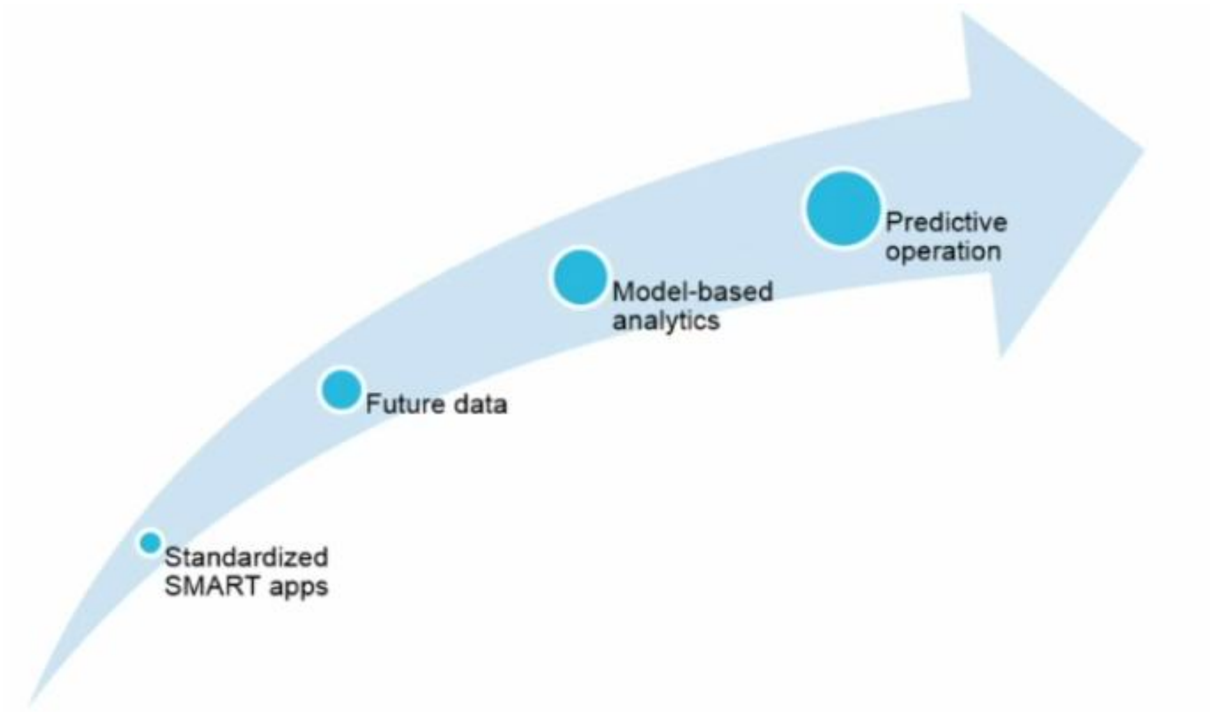


Figure 26: The road to the future for Shell's journey (OSIsoft LLC, 2016).

During the conference, De Koning has also discussed how Shell has gone from a tag-based user of the PI System to one that is currently making exhaustive use of Asset Framework (AF). He has affirmed that it has taken the company extensive efforts, lot of hard work and endurance to translate all the individual data points into an asset structure with the definitions on how their equipment types should look like. He has also given some recommendations based on Shell's personal experience including taking the necessary time to elaborate the required changes and having a clear vision about the adequate ways to process the data. Through the conference, De Koning has presented briefly their adopted approach to gain a total predictive aspect of their operations. The process obviously begins by gathering the required amounts of data and bringing it together through the super collective concept that involves primarily the standardization on way of working and the establishment of templates for equipment definitions and for analytics. Following so the adding of the necessary functions through the smart solution platform. And here comes the introduction of OSIsoft capabilities in building the adequate portals throughout the proactive technical monitoring and the complex analytics. Figure 27 illustrates the strategy approach adopted by Shell on its usage of OSIsoft PI system for its predictive maintenance and its smart monitoring. *(OSIsoft LLC, 2016).*

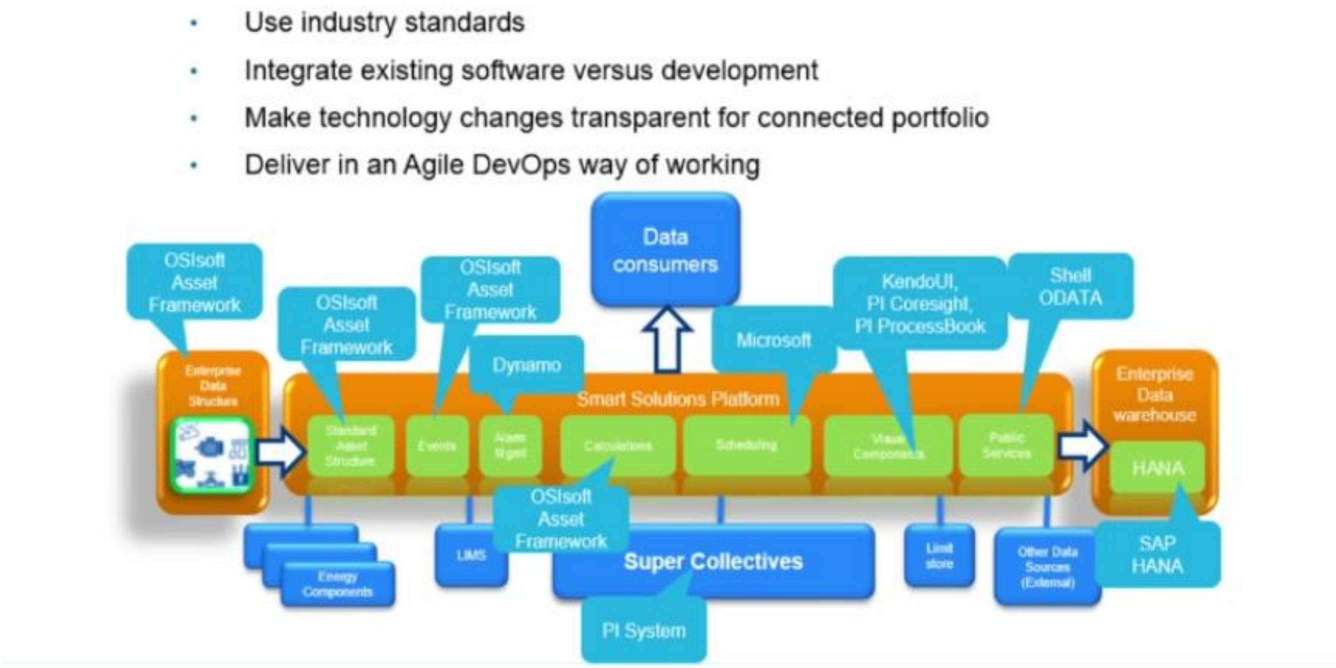


Figure 27: Strategy approach of Shell for the PI system implementation (OSIsoft LLC, 2016)

- **BP Study case**

BP PLC, the British Petroleum Company, is one of the world's leading oil and gas companies, providing customers with fuel for transportation, energy for heat and light, lubricants and petrochemicals. The company had its roots in the Anglo-Persian Oil Company, which was founded in 1909. As of 2018, BP was the sixth-largest oil and gas company worldwide based on market value. In 2018, BP reported around 298.8 billion U.S. dollars of revenue, which also placed it in the top ten within the whole industry. BP employs around 73,000 people all around the world and operates in 78 countries worldwide. *(Statista Website, 2019)*. Technology is constantly present in all the company's operations and activities from safely discovering and recovering oil and gas, to renewable energy, digital and lower carbon fuels and products. And digital, big data and advanced technologies, as well as an innovative mindset, are driving rapid development of new ways to tackle emissions and improve efficiency at BP. BP's professional teams operate at the furthest possible edge of digital innovation, working with academic institutions and start-up companies, among others, to scan the horizon for just such possibilities. The corporation's current focus areas involve primarily cognitive computing – the most sophisticated form of artificial intelligence, advanced distributed ledger technologies (including blockchain) and robotics. *(BP Website, 2019).*

Morag Watson, chief digital innovation officer at BP confirmed that Artificial Intelligence "would be one of the most critical digital technologies to drive new levels of performance" in the oil and gas sector. This is why the company is heavily investing into big data analytics, AI, digitalization, machine learning and automation in order to enhance its operations and the usage of its resources, security and reliability of oil and gas production and refining. It is estimated that more than 99% of BP's oil and gas wells acquire sensors implemented that actually develop data to aid BP's professional teams comprehend the true conditions of each site or facility no matter where they are located and help them furthermore optimize the performance of machinery and monitor maintenance requirements so as to prevent failures or breakdowns which would eventually enable the firm to score some enormous cost savings. Back in June 2017, BP has invested around $20 million in Beyond Limits, a start-up that integrates software, initially created for robotic exploration of space from NASA and the US Department of Defense, for commercial usage. Beyond Limits' cognitive computing mechanisms concentrate on how to automate properly decision making processes and go even to the extent of filling in lacking parts from data series. This has been affirmed by Beyond Limits' CEO, AJ Abdallat who told ZDNet : *"Our AI can work with unknown or missing data and figure out hypothetical scenarios and fill in the missing pieces—much like humans with experience do,"*. BP expects Beyond Limit's software to procure the necessary operational insights allowing the enhancement of predictive maintenance and monitoring techniques. This will ultimately offer the company better opportunities in locating and develop reservoirs and improving how it produces and refines crude oil, upgrade processes' automation and operational effectiveness and moreover optimize business tasks including how it handles the marketing of the relevant products. Another vital advantage of this technology is to develop the decision making approaches and ameliorate the management of the imposed operational risks. *(Marr, 2019).*

On July 2017, the Financial Times has published an article on the front page of their Companies and Markets section asserting that BP has made $7 billion annual savings between 2014 and 2017 by investing in Big data technologies. This is an enormous benefit even for a corporation with an $87 billion market capital. The oil and gas sector is asset-sensitive acquiring large numbers of critical assets including drilling rigs, off-shore platforms, wells and pipelines etc. As for BP, these represent approximately 50% of its total assets, with management and maintenance implying a considerable operational cost. The financial times article illustrates how BP applies a wide range of sensors in its oil and gas wells (99% as mentioned above), and are therefore aiming to elevate their data capacity by 5 fold by 2020. The resulting information along with predictive maintenance approaches enable BP to better optimize its assets and schedule maintenance interventions only when needed or perform replacements of systems or components at the right time saving by that, huge amounts of resources. *(Carr, 2017).* In addition to BP's High Performance Computing (HPC), a supercomputer with significant data crunching ability, and nearly 2,000 kilometers of fiberoptic cable that can bear 5m data points every minute, BP has invested in big data technology for improvements to its data streaming, storage and processing abilities. Moreover, the company has been in the middle of a significant extension that will upgrade its data capacity from 1 to 6 petabyte by 2020 and has invested more in data sensors in order to gather large volumes and multiple types of information about temperature, chemicals, vibration and more from oil and gas wells, rigs and facilities. *(Marr, 2019).*

There has been a tremendous innovation in three major segments that helped BP improve its predictive maintenance tasks and its monitoring activities and furthermore has permitted the firm to save all that money; principally storage of data, streaming of data and processing of data. Indeed, storing large amounts of information whether in a data lake architecture; holding the raw data in its native format until it is needed, such as Hadoop or in a scalable data store such as Cassandra; a distributed database for handling large volumes of structured data through several commodity servers, while offering highly available service and no single point of failure *(DataStax Website, 2019),* has never been simpler. There is considerable number of significantly adept technological solutions that conform to the use case of time series event or sampled data that BP's various sensors generate. For managing the large data sets that the sensors create, BP uses scalable data stores such as Parquet Files on Hadoop Disk Filing System (HDFS). In fact, HDFS is a virtually large filing system that can be run over various machines or nodes. It is actually conceived and constructed on the hypothesis that equipment develop defects quite easily, and the virtual Filing System ought to be capable of facilely handling a loss of a node. Under these conditions, HDFS stocks a replica of each portion of data a predefined number of times, usually an odd number like three so that during recovery a voting process can be established in order to conclude what was saved. In order to decrease the imposed loss of time when stocking or saving everything three times, it has been more useful for BP to apply highly optimized compressed files on HDFS, with Parquet being one such file format. Typically, Parquet files are compressed column conformed files which could be referenced in a compatible manner to SQL tables by technological applications such as Apache HIVE; a data warehouse system designed on top of Apache Hadoop that simplifies facile data summarization, ad-hoc queries, and the analysis of huge datasets saved in multiple databases and file systems. *(MAPR Website, 2019).* Among the solutions that BP employs to access its data in the Parquet files is Cloudera Impala; an open source for querying data, and a faster, more improved SQL entry on HDFS files. This would allow developers interacting with the storage in the same way a traditional SQL data store or warehouse would, saving by that on development time. Naturally, this approach is becoming quite popular and more widely used for stocking huge amounts of data for analytics processing and this can be explained mainly by the compression sire of files, the simplicity of scaling out mixed with the throughput pace for processing those files. This is considered a greatly beneficial technology for analytics over exhaustive amounts of historical unchangeable information. Additionally, BP deploys Cassandra for storing time series data; another popular choice for historical time series data, where we usually have huge volumes of data. Typically, Cassandra scales out and is both datacenter and rack conscious so it can be optimized for both reading and storage. The vast volumes of data gathered by BP's sensors don't only cause a challenging storage issue, but further a demanding data gathering issue. The novel implemented technological solutions in streaming technologies have greatly helped the process of moving the information from sensors on oil rigs to the data store, prepared for processing. In other terms, they have offered BP better ways of transmitting data from sensors to storage, or process in near real-time enabling the required actions to be taken in a well-timed way. It is vital to mention that BP has made a huge investment in enhancing their monitoring techniques in order to get hold of problem alerts at early stages prior the occurrence of any disasters. Technologies applications such as Kafka which is a distributed log, Apache NiFi (a bi directional streaming system), Apex, Amazon Kinesis, Google Pub/Sub are all acquiring considerable power removing older messaging and streaming technologies and aiding to get large quantities of information from source systems or sensors to their destined locations ready for timely processing. The fact of sending the relevant information to the destination with low to absent discontinuity would be a vital element for monitoring equipment and systems to detect extremely early the alarming manifestations of problems developing. Once data has been gathered and stored, it demands to be processed and acted upon in order to generate the awaited benefits such as cost saving and operational and maintenance effectiveness. On this matter, BP couldn't be capable of scoring any important savings without the appliance of Machine Learning algorithms to those vast datasets. And luckily for the company there have been some significant innovations on the subject and breaking through technological solutions including Apache Spark, Flink, Samza and Apex. Some of these are primarily streaming technologies like Apache Flink and Samza, which can be low latency. While, applications like Hadoop or Spark in batch mode have usually higher levels of latency. As for BP, it does utilize some technologies for its machine learning involving Apache Spark and Hadoop. Apache Spark has actually became recently the most popular open source processing engine and is therefore capable of processing information in a much easier way than ever before with the integration and incorporation of out-of-the-box machine learning algorithms. We can therefore conclude that BP has been using and is still using a wide diversity of technologies and digital solutions that have helped it to enhance considerably its predictive maintenance approaches and monitoring tools. These solutions, who mainly involve a combination of open source technologies that are accessible to everybody, have moreover helped the firm accomplish some impressive costs savings. Such applications have indeed evolved to a degree where they can easily allow anyone who knows how and when to deploy them, pay back their investment so rapidly.*(Carr, 2017).*

Another innovative approach adopted by BP is the digital twin where its maintenance and production engineers can check critical engineering work via virtual or digital reality before doing so on actual plants. This technological solution has enabled the professional teams to actually take their time to make the right decisions based on accurate and valuable predictions and early detections of faults and potential deficiencies ameliorating by that the reliability of its exploration and production facilities. *(Marr, 2019).*

BP has been also investing in the making of its wells connected to the industrial IoT. GE Intelligent Platforms Software has announced a novel production enhancement project that aims to connect all BP's oil wells globally to the Industrial Internet. Through the usage of GE's data management software, the field engineers of BP will acquire real-time access to all of the equipment and operations data sets throughout all BP's wells gathering by that all the necessary information to take the right decisions, avoid failures, eliminate unplanned downtime, and reduce costly repairs. The project will be initially applied to 650 of BP's wells and will expand following so to 4,000 wells worldwide for the next upcoming years. Kate Johnson, GE Intelligent Platforms Software CEO and GE Chief Commercial Officer says that by connecting BP's oil wells around the world, they're offering them better and deeper insights that would eventually lead to new efficiencies in their oil fields and raise oil production. BP's move to license this software was majorly guided by its ability to drive effectiveness and performance through improved standardization, increased oversight and decision-making. Such solution will enable the oil and gas company to catch, stock, contextualize and perceive information in real time making it accessible for the right people through the right channels and at the right time, so they can eventually make the right informed decisions. Peter Griffiths, BP System Optimization Strategist stated: "*This project highlights BP's commitment to deploying technology that can not only improve efficiency and reduce the complexity of our operations, but that can also make them safer and more reliable". (Pat research Website, 2018).*

In a global operation like BP, making the necessary and enough data available for engineers, scientists and decision-makers about the actual state of operations worldwide is vital. This would allow detecting problems prior their escalation and enhancing business outputs, increasing by that, benefits, diminishing costs and optimizing production and maintenance operations. The increased reliability of BP's exploration and production plants going from 88% in 2012 to 95% in 2016 is mainly due to the introduction of technology in the company's activities and structures, and even if investment is a must when it comes to supporting big data and AI technologies, as BP as shown, the return on that investment can be quite tremendous. *(Marr, 2019).*

- **Baker Hughes Study case**

Baker Hughes, BHGE, a GE company is the world's first and only fullstream provider of integrated oilfield products, services and digital solutions. Drawing on a famous heritage of invention and innovation, BHGE mobilizes the passion and experience of its people to upgrade productivity throughout the oil and gas value chain. BHGE aids its customers to acquire, transport and refine hydrocarbons more effectively, productively and safely, with a smaller environmental footprint and at lower cost per barrel. Backed by the digital industrial strength of GE, the corporation deploys minds, machines and the cloud to break down silos and decrease waste and risk, applying breakthroughs from other industries to advance its own. With operations in over 120 countries, the company's global scale, local know-how and commitment to service infuse over a century of experience with the spirit of a startup, inventing smarter approaches to bring energy to the world. *(LinkedIn, 2019).*

The oil and gas sector still has to overcome some serious challenges involving mainly the expenses of maintaining it aging equipment and infrastructure. On average, 42% of offshore machinery is more than 15 years old and has around 13% downtime, the majority of which is unexpected or unplanned. For the past years, the main goal of oil and gas corporations was to focus on massive data collection and analytics. The numbers are quite significant in that direction; pipeline inspection produces 1.5TB for every 600km controlled, ultrasound around 1.2TB for every 8 hours of scanning, process data gathered is approximately 6GB per plant per day and seismic surveys bring about around 10TB each. Still, collecting huge quantities of information isn't enough to achieve the desired levels of efficiency and performance and industrials are still struggling to deliver the necessary insights for this data. Indeed, 60% of operators are finding huge issues in generating the needed outputs from the amassed data as around 95% of it has never been utilized and analytics are too slow and don't scale properly. This can essentially be explained by the usage of traditional analytics procedures and a legacy

CPU compute infrastructure that doesn't acquire the required processing capabilities to assess the volume and diversity of information in a timely way. To solve the presented challenge, oil and gas data necessitates algorithms and computing programs that can actually scale to refine these large volumes of data and produce the awaited insights and maintain by that great effectiveness. Consequently, deep learning, machine learning, GPUs and digital twins present extraordinary advantages for predictive maintenance in the oil and gas industry such as the precise detection of defects at early stages, the exact prediction of remaining useful life of assets, and the description of guidance advice on work scope for the field service staff. We have earlier mentioned the importance of the usage of digital twins as constantly learning mechanisms that represent the digital copies of certain assets, systems and processes that can be interrogated automatically, or even by voice, for certain results. A digital twin can therefore forecast asset equipment behavior and power to generate specific outcomes within given variables and cost restrictions. The equipment doesn't go to sleep and the digital twin indicates what you ought to do with the asset on the physical twin so as to accomplish the desired result. In fact, deep learning along with domain specific physics-driven modeling approaches, are at last transforming the idea of digital twin into a reality throughout a variety of industrial fields. *(Modi, 2018).*

Baker Hughes is actually teaming up with NVIDIA, a world leader in visual computing technologies and the inventor of GPU, in order to work together on end-to-end platforms for constructing full stream artificial intelligence based services for the majority of oil and gas operators through the globe and allow by that the realization of digital twin concept. Baker Hughes GE is seeing enhanced data processing capabilities at 100 times higher resolution at the data source, data scientist productivity 50 times faster model-constructing and training, and non-productive time availability (NPTA) with a more solid and rapid deficiency forecasting. Arun Subramaniyan, Vice President Data Science and Analytics at BHGE GE, has affirmed: *"Deep learning, enabled by GPU-accelerated compute, is instrumental in realizing the potential of industrial digital twins."* In order to put in execution the digital-twin perception for the oil and gas sector at scale, Baker Hughes GE has adopted edge-to-cloud GPU accelerated compute. At the 2018 Unify Conference in Houston, BHGE has showed predictive maintenance abilities multi-well field improvement on an array of 500 wells in 90 seconds, which equals one million times faster than what's feasible on the market nowadays. This breaking through innovation is exclusively offered by BHGE through their edge-to-cloud deployed Artificial Intelligence platform motorized by NVIDIA GPUs, and is evolving today to become a central part of their fit-for-purpose digital development applications such as IntelliStream™. Once any given business starts establishing this technology, its value rapidly appears on the company's assets management; for instance high producing electric submersible pumps (ESPs) can be controlled at less than 5% false warning rate while indicating deviations at 93% with up to 60 days of lead time leading to cost-avoidance profits of $300K per year and per well. The oil service firm as also teamed up with technology providers and leaders like Google Cloud, Microsoft, Accenture and KBC to bring digital technologies and energy worlds together providing by that the convenient solutions for the industry's challenges. It has been proved thusly, that smarter, faster AI-based solutions and digital twins would significantly upgrade the predictive maintenance practices in the oil and gas sector. Furthermore, it will permit AI and GPU infrastructure powered edge-to-cloud abilities to enable full-stream outputs for production enhancement, automated drilling and also connecting silos throughout the entire operational streams from oil extraction and exploration to refining, processing and distribution. *(Modi, 2018).*

On the other side, GE Digital, a subsidiary of General Electric, has developed Predix, which the company affirms can help any given oil and gas business including BHGE, into creating automated analytics models that could enhance predictive maintenance procedures and tools of the industrial equipment or machinery in question employing machine learning. *(De Jesus, 2018).* Hence, GE's Predix platform is considered as the basis of Asset Performance Management (APM) which GE has itself confirmed to be the first Internet Of Things "killer application. *(Diaz Williams, 2017).* Predix demonstrates that the application's machine learning algorithms are capable of processing information that sensors gather including equipment or parts performance, environmental data and weather circumstances among others. Subsequently, the algorithms compare these against the optimal performance data existing in the database. In case, the algorithms detect any disparities between the actual and ideal state, the application is set off to send a warning to operators and technicians who in turn perform maintenance interventions or part replacement. *(De Jesus, 2018).*

Another agreement that Baker Hughes has made was with Emirates National Oil Company (ENOC) in order to develop VitalyX, a real-time lubricant monitoring system. VitalyX can actually be employed in various sectors utilizing huge equipment, and the advanced cloud-driven mechanism is created to determine and calculate crucial lubricant parameters in real-time while translating the data at the same time into actionable insights. ENOC, which will not only co-design but has signed as well the first order for VitalyX, declared the project along with BHGE leaders at BHGE's Annual Meeting in Florence on 30th of January 2019. Lubrification oil is considered as the lifeblood of a several assets and machines as it not only used to protect them but also to indicate their health state and overall condition. Real time monitoring of lubricants also contributes into securing end users' and workers' machinery by providing a whole new scale of predictive maintenance, improving effectiveness, decreasing downtime and increasing asset's remaining useful lifetime. Oppositely, the absence of continuous monitoring can lead to some cataclysmic failures due to fluid problems, for instance; the cumulative cost of a top drive gearbox deficiency caused by fluid loss can be up to $1 million. Here interferes VitalyX advanced cloud-based application which can compute key lubricant chemical and physical properties in real time through the operator's fleet and convert information into alarms and warnings to pinpoint possible problems. The user-friendly dashboard can therefore demonstrate fleet-wide data down to the individual asset level and stocked either locally or in a common cloud. *"Digitization is playing an integral role in driving the transformation of the energy sector, and has contributed significantly to enhancing operational efficiency,"* expressed Saif Al Falasi, ENOC Group CEO. *"We believe that our agreement with BHGE - will play a key role in revolutionizing lubricant quality testing and physical asset management. We at ENOC are pleased to have been able to work with BHGE on the development of this innovation and look forward to developing many other projects in the near future."* The CEO of BHGE's Measurement and Sensing business, Diarmaid Mullholand, has stated: *"Our joint focus on lubricant monitoring is a critical and* *essential element towards making industries safer and more efficient. Our co-development of VitalyX with ENOC not only ensures we deliver technology that works in real-world extreme conditions but also has proven experience in the field. This technology is a prime example of the Industrial Internet of Things in action – hardware and software working seamlessly together, taking sensor data to deliver new insights we could never achieve before. We are excited for this journey with ENOC and many more customers to come." (BHGE Website, 2019).*

- **Schlumberger Study case**

Schlumberger is the world's leading provider of technology for reservoir characterization, drilling, production, and processing to the oil and gas industry. Working in more than 85 countries and employing approximately 100,000 people who represent over 140 nationalities, Schlumberger supplies the sector's most comprehensive range of products and services, from exploration through production and integrated pore-to-pipeline solutions for hydrocarbon recovery that optimize reservoir performance. For 90 years, Schlumberger technological innovations have procured value for oil and gas operators by helping them elevate production and recovery from nonrenewable resources efficiently and with lower environmental impact. *(Schlumberger Website, 2019).*

Schlumberger is regarded as one of the major world leaders in the development and application of cutting-edge digital and innovative technological solutions. Indeed, Schlumberger software technology development concentrates on novel digital applications and capabilities in order to build the future of a multibillion-dollar industry. Although, the company doesn't only seek to make its operations more efficient through its technological enablement, but it aims further to transform completely how its business operates. To accomplish so, Schlumberger is using multiple tools including data analytics, cloud computing, digital oil fields, robotics, automation, smart predictive maintenance, artificial intelligence and machine learning. *(Hackerearth Website, 2019).*

In order to bring to reality its innovative vision of data analytics, the oilfield services provider has been working in partnership with Google Cloud on big data, software platforms, high performance computing (HPC), and on artificial intelligence to allow it interpret seismic and wellbore information. *(Paraskova, 2019).* For more than 90 years, Schlumberger has worked with a large number of customers in the oil and gas business generating vast volumes of information in order to safely and effectively handle hydrocarbon exploration and production. The company has therefore worked on developing a specific software environment that operates on GCP called DELFI*; a cognitive energy and production (E&P) environment that bridges from exploration to production. Thus, clients can amalgam DELFI with their own proprietary information and science for novel insights and faster outcomes. Ashok Belani, Executive Vice President of Technology, Schlumberger, has said*: "To improve productivity and performance, DELFI enables our customers to take advantage of our E&P domain science and knowledge, while at the same time fully using disruptive digital technologies from*

Google Cloud. This approach ensures that all data is considered when making critical decisions." (Hölzle, 2017).

The main challenge within the oil and gas sector is the complexity of operations and interactions and therefore the cost. Indeed, the relevant tasks are usually undertaken under difficult conditions so the potential occurring deferments or interruptions can be quite expensive. Therefore, industrials started focusing essentially on collecting larger amounts of data and installing a diversity of sensors in machinery to do so more accurately. Still, only a small portion of the gathered data is actually analyzed and assessed today due to the fact that analysis and interpretation can be a complex, time-consuming and sometimes even a repetitive operation. Schlumberger, as the largest oilfield service firm, is working on overcoming these challenges in the short and long terms through the usage of machine learning to optimize human decision making processes, cut down the costs and enhance the overall performance. An example of machine learning being deployed to upgrade procedures and processes is in drilling. The oil company is actually integrating machine learning tools to forecast drilling events such as extreme vibration or fluid loss on the basis on data inputs going from surface data to the wellbore geometry. Consequently, drillers would be aware of such events prior their occurrence and would adjust activities accordingly. The AI based process in drilling is therefore capable of saving costs by decreasing drilling times and equipment downtime through the establishment of smart predictive maintenance based on actual wear and tear instead of pure planning/scheduling. Another area where Schlumberger is employing machine learning is in well completion; ranging from a drilled well into a producing one. Typically, Schlumberger is exploring machine learning techniques that can provide models within a matter of hours which can predict the productivity based on a deviation in the completion design. This will allow field engineers to perform their assessment and evaluation in a faster and more accurate way across a larger array of choices that would basically change the entire process to well completion design enhancement. On the long term, Shlumberger seeks to incorporate processes throughout well scheduling and execution with back end mechanisms such as inventory management and logistics. Hence, machine learning allows this integration via driving automation and data-based decision making. Machine learning is an essential driver of process ameliorations that encourages generating new ideas of operating and adopting a proactive mindset instead of a reactive one. *(Sheep, 2018).*

In order to ensure that stimulation, completion and perforating machinery is ready to execute accurately and reliably for every activity, Schlumberger's new OneStim business, which is made to operate mainly in North America Operations, handles stimulation and completion equipment from an entirely centralized and digital facility in Denton, Texas. Thusly, service staffs utilize real time data analytics to forecast major part and machines deficiencies. In fact the status of the machinery can currently be monitored in real time and OneStim can easily indicate how and where the related machine is performing. For example, when monitoring the acoustic response of a pump, it can be identified when exactly the pump is on the verge of a failure stage and thus service the equipment as a proactive action and following so apply the required maintenance initiative. At the remote monitoring center, real time information from the equipment is gathered 24/7 where experts warn field personnel to remove machinery from operations executing by that maintenance before any failure takes place. As result of predicting deficiencies, the maintenance and operational costs would be significantly reduced for the company and operators. We can consider the example of a fluid end or power end failure during a certain operation leading to hundreds of thousands of dollars due to the operational stoppages or delays and the material damages. The established proactive approach thanks to OneStime enables to activate the predictive maintenance vision that reduces the costs and makes it possible to actually forecast the potential failures instead of having an unexpected accident at a critical point in the process. Furthermore, OneStim also manages the operational details of each completion process at one central location, with the usage of real-time information guiding logistical decision to streamline tasks. At the central operations planning control center in Sugar Land, Texas, Each completion program is supervised and executed with highly advanced technological applications involving mobile app logistics tracking. Real time information is employed to coordinate between equipment, tools, products and operators all under a unified vision. Through digitally empowered technologies like Automated Stimulation Delivery Platform (ASDP), OneStim adds more efficiency into the well site. The ASDP's automated process system monitors all machinery with a single-touch technique. The system uses actually monitoring and predictive health approaches in order to execute each job as designed and reduce downtime. In all, implementing innovative technology along with streamline processes and automation improves reliability, effectiveness and performance of all operations ensuring that smart predictive maintenance and advanced monitoring techniques would the base for making the processes run successfully. *(Shlumberger Website, 2018).*

- **Chevron Study case**

Chevron Corporation is a multinational energy company. This American company is involved in all aspects of the geothermal energy, natural gas, and oil industries. It is one of the largest energy industries in the world as it manufactures and sells a variety of products including petrochemicals, fuels, additives and lubricants. Since the company was founded, it has always been based in California. Even as it has grown into a multinational corporation, this is where the headquarters have always been located. *(Berman, 2018).* Chevron boasts more than 11 billion barrels of proved reserves, produces about 2.7 million barrels of oil per day, and has refining capacity for nearly 1.7 million barrels per day. The company sells refined products branded under the Chevron, Texaco, and Caltex names through nearly 8,000 gas stations in the US and almost 6,000 outside the US. In April 2019, Chevron Corporation announced plans to acquire Anadarko Petroleum for $50 billion (including debt), making it the sixth-largest oil and gas deal in history. *(Vault Website, 2019).*

Today, Chevron is employing artificial intelligence in order to determine novel well locations and simulation candidates in California. Since the firm' usage of AI software to assess the corporation's extensive collection of historical well performance information, it has been drilling in much better locations and has seen a significant rise in its production; around 30% over common techniques. Additionally, Chevron has been utilizing predictive applications or models in order to analyze the performance of hundreds of thousands of parts of rotating machinery to indicate deficiencies prior their occurrence. Thereupon, by addressing issues before becoming critical, Chevron has succeeded to avert large numbers of unexpected shutdowns and decreased considerably repair costs elevating by that the overall productivity, lowering the expenses and scoring higher profits. *(Srivastava, 2017).*

It seems essential to mention that Chevron has launched a significant effort in forecasting maintenance issues within its oil fields and refineries, a great ability that various corporations have been trying to develop for a long period and is today considered as a huge competitive advantage and source of high benefits. Developments in the functionalities and economics of sensors, artificial intelligence, cloud platforms and data analytics are the essential drivers of the rise of what it named predictive analytics, which Chevron executives consider would enable the savings of millions of dollars per year. Through its work with IoT services from Microsoft Corporation, Chevron seeks to empower large quantities of equipment and components with sensors by the end of 2024 so as to predict exactly when they will need to serviced or replaced. Chief Information Officer Bill Braun states: *"In the past, we had to figure out how equipment was performing. In the future, the equipment will tell us how it's performing. This represents a big shift."*Microsoft's $5 billion, four year investment in the sector was announced back in April 2018. According to recent research from Gartner Inc, it is expected that 25.1 billion devices will be connected to the internet by 2021 up from 6.3 billion in 2016. According to Gartner the total spending on IT, involving data center systems, connected instruments and enterprise software is estimated to attain $4 trillion in 2021, up from $3.4 trillion back in 2015. In 2017, Chevron has concluded a seven-year deal to make Microsoft's Azure its major cloud provider. Braun has confirmed that this collaboration will offer the company's engineers the required access to data in one single cloud repository instead of various silos in the corporation. This signifies that it would be faster and easier for them to acquire the necessary insights on a larger array of information including the gathered data from sensors linked to machinery on the site. In recent years, multiple enhancements have been made in sensors fabrication in terms of their accuracy, quality and affordability. Furthermore, it has become faster and easier to enable equipment with wireless sensors, while in the past, sensors needed weeks for wiring and installation. Chevron has already planned to equip its oil machinery with sensors for predictive maintenance by 2019 within a large-scale pilot program, with complete adoption for several of the machines awaited by 2024. Over the past year, Chevron has worked on a small experimentation linking additional sensors to a number of heat exchangers, which are vastly employed in processing oil and gas. The machines in question that go from large trucks to small buildings, resemble in a way to radiators that cool down car engines, and an expected interruption could take days to be solved, leading to huge financial losses, said Deon Rae, Head of Chevron's Industrial Internet of Things Center of Excellence. Previously, two sensors on the heat exchanger would gather data such as temperature of the cooling fluid and oil flowing through the heat exchanger, still with restricted sensor information, Chevron could only know about the past and current state of health of the equipment. In the experiment, four wireless sensors were implemented in critical locations along the equipment, which caught a larger dataset, involving information concerning temperatures and oil flow. Thanks to the additional data and Microsoft's cloud-driven predictive analytics applications, Chevron's data scientist can forecast when the heat exchanger will become dirty and require cleaning, Rae affirmed. He also said that it is expected that over the next years, sensors and data would be deployed to continuously control and monitor the health of the equipment in real-time enabling by that data experts to predict accurately when it is vital to repair or replace them, decreasing by that machinery downtime and unneeded repairs. Rae added: *"Savings could be in the millions if you can monitor and predict the health across all of our exchangers."* According to him, by 2024, Chevron would have sensors connected to high-value machinery that could considerably interrupt oil and gas activities and engender lost profit opportunities in case they fail. Similar equipment involves compressors that are employed to decrease the volume of gas by raising pressure, and pumps utilized to move liquids. *"The value creation is going to be from the combination of assets that we can monitor,"* Rae confirmed. *(Castellanos, 2018).*

We have analyzed during this section around fifteen industrial cases of companies from different sectors adopting innovative tools in their CM and PdM processes and systems. Each of these firms installed distinct inventive mechanisms whether created by the companies themselves or their respective partners or third parties. However, they are all sharing the same objective which is increasing their profitability and improving their operations' performance. The point behind these examples isn't to assess the innovation systems per se, but instead to indicate how organizations are working harder today to introduce the various technological advancements that we have talked about during the second part of our thesis. These cases would be therefore the explicit and concrete explanations of the theoretical ideas mentioned during the previous sections. Furthermore, they would present the foundation for our next results and analyses when it comes to studying the impact of these new implemented devices and procedures on the some selected corporations.

Section 8: The technical, financial and strategic improvements of innovative systems and practices in chosen study cases of industrial companies

Throughout the years, many have argued that innovation, technology and any other related concept to the term “change” is an absolute waste of time, money and energy. If we had followed this vision, we would be still using horses to get to our jobs and arriving to the moon would be still an impossible mission for humanity. In other terms, what made innovation possible today along with its benefits on society and human life is the fact that the individual has tried and gathered all its will and courage to actually innovate, create, and bring its own new ideas into life. He has failed and succeeded constantly but this hasn’t stopped him from following this path and focusing all the required resources and efforts into achieving the desired objectives. Typically, the majority of industrial corporations, despite of their business nature, capital, size or capital share are adopting today the same perspective by understanding that their ways of work are changing and adapting to this reality will make them score high savings for the future. These companies are investing millions of dollars annually in innovation-driven projects whether it is through their partnerships with key technology providers and start-ups or by internally creating new technological solutions for their maintenance and monitoring operations. By taking such initiatives, firms have come to the conclusion that innovation will bring extremely significant profits on the short and medium terms and especially the long one. In today’s markets, innovation is indeed cutting down operational and maintenance costs, extending machinery useful life, enhancing cross communication, increasing the return on investment and improving workforce safety and upgrading the reliability, availability and overall performance of equipment and processes.

We have already assessed during the seventh section fifteen study cases of industrial companies from the aerospace and defense sector, the automotive sector and the oil & gas sector that have adopted innovative systems and procedures within their facilities in relation to the condition monitoring and predictive maintenance activities. It seems therefore essential to determine to what extent these innovative and technological tools have changed the technical, financial and strategic aspects of these organizations. Subsequently, we will choose arbitrarily a single company from every sector to analyze in detail the resulting enhancements of its innovative taken approaches. The main objective here is to concretize the impact and effects of innovation in CM and PdM systems and tasks on the industrial structures.

4.8.1 Innovation’s improvements on a selected study case from the Aerospace and Defense Sector: Airbus

The French-German aircraft manufacturer Airbus has been selected as a study case for this subsection so as to discuss the enhancements engendered from its adopted innovative tools that we have already analyzed on the subsection 4.7.1.

One of the Airbus innovative systems that have been mentioned previously is the Airman online solution that is primarily designed to ameliorate the firm's PdM operations and is mainly deployed as an instrument for aircraft health monitoring in order to undertake efficient management of unscheduled maintenance, to provide real time recommendations and data and upgrade aircraft dispatch reliability. In other quarters, this technological solution allows the airline company to operate real time and optimized maintenance tasks and technical aircraft follow-up on the entire fleets in question. It appears to be the most reliable and economic solution among the technologies adopted by the corporation. The following table summarizes therefore the technical, financial and strategic advantages of Airman on Airbus.

Technical enhancements	Financial enhancements	Organizational & Strategic enhancements
• Optimizing the maintenance tasks; • Reducing the maintenance related delays and disruptions; • Increasing the aircraft and its components availability; • Reducing unscheduled maintenance actions; • Improving aircraft dispatch reliability; • Decreasing the aircraft turnaround time; • Providing a large number of in-service live data checks; • Procuring an accurate and automatic follow up of the predictive maintenance actions; • Representing a high simplicity and easiness in usage.	• Reducing operational costs; • Decreasing overall maintenance (direct and indirect) costs; • Increasing the expected revenues thanks to the higher availability of the aircrafts; • Decreasing the additional costs due to potential disruptions; • Decreasing the high up-front costs of predictive maintenance operations;	• Eliminating the risks of flight delays or cancellations; • Attracting new airline customers for the adoption of Airman solution; • Increasing the performance of the Maintenance Control Center and the maintenance strategies; • Making sure that Airbus will always be capable of responding to all airlines requirements, easily, rapidly and to the highest level of their expectations.

Table 2: The technical, financial, strategic and organizational enhancements of the Airman Program on Airbus.

Another innovative system that we have already mentioned was the open data Skywise platform considered as an end-to-end aircraft health management solution for the company's operators and enabling the leveraging of large quantities of information so as to help the relevant airlines manage their maintenance activities more efficiently. Skywise seeks to become the platform of reference employed by all key aviation players to upgrade their operational performance and business outputs as well as to assist their own digital transformation. Airbus has therefore the goal to extend Skywise to become aerospace's data platform of reference, with a service offering adapted not just to the aviation ecosystem but moreover to defense customers and helicopter operators. *(Airbus Website, 2019).* Skywise is considered therefore as a digital, hyper-connected and safe platform that permits users to optimize and forecast everything from engineering and maintenance to flight operations. Thanks to leading-edge data analytics and highly advanced artificial intelligence tools, Skywise offers its customers the access to deep insights previously lost in the noise. Before the implementation of Skywise, these masses of information have never been shared on this scale. Indeed, an airborne A350 generates around 800 gigabytes of data on an average flight, about the same quantity generated by all the cars over the course of an entire Formula 1 weekend, and this number is constantly rising as engineering tools get smarter. *(Euronews Website, 2018).* Moreover, Skywise procures all customers with one single access point to their enriched information by bringing together to aviation data from various sources throughout the industry into one secure, cloud-driven platform physically hosted in Europe. Typically, the more data is gathered from airlines or original manufacturers sharing it in the Skywise Core platform, the more the predictions and models are accurate. Additionally, data is anonymized so its sources remain confidential for a better sharing of the information and lessons. *(Airbus Website, 2019).* Skywise is therefore the most suited model on how crucial business ecosystem strategies are for manufacturers nowadays and how industrial data platforms can assist business ecosystem strategies. It is then believed that Skywise is the smartest move for Airbus to take; not only does it enable the aircraft manufacturer's clients to gain value out of sharing their information with the company, but Airbus also benefits from getting data from customers and transmitting this back to its product engineers to enhance the quality of their aircrafts. *(IDC Website, 2019).* Table 3 illustrates the multiple benefits of Skywise implementation.

Technical enhancements	**Financial enhancements**	**Organizational & Strategic enhancements**
• Decreasing fuel consumption; • Reducing CO2 emissions; • Reducing equipment downtime; • Lowering the	• Increasing fuel savings; • Increasing the operational and maintenance savings and revenue opportunities;	• Making the customers benefit from a supercharged and ever-evolving digital platform; • Reducing workload; • Organizing better the

component and systems failures; • Enhancing the efficiency of operations; • Reducing operational interruptions; • Leaving room for third-party services (mostly in maintenance); • Improving fleet operational reliability through predictive maintenance; • Engaging rapid and accurate root-cause analysis of in-service issues; • Optimizing each aircraft's performance via flight operations information analytics; • Facilitating the check up and the tracking of maintenance effectiveness over time; • Reducing data gathering lead-time; • Procuring best-in class aircraft connectivity; • Increasing the visibility of open tasks across maintenance shifts; • Providing more informed decisions in a quicker way; • Enhancing the inspection, monitoring and	• Lowering digital transformation investments; • Reducing the maintenance expenses; • Increasing the number of airlines joining the Skywise core due its efficiency and leading to more revenues.	maintenance operations; • Optimizing flight operations; • Lowering the delays and the cancellations; • Improving the communication channels between the customers and the company; • Providing one-click reporting workflows, involving complex reporting to regulatory bodies; • Benchmarking at aircraft, fleet and global level; • Enhancing team collaboration; • Simplifying the reliability analysis and reporting strategies; • Procuring a better and a more accurate prioritization of tasks based on the faults' potential impact of the aircraft; • Providing the necessary guidance based on aggregated data from various operators; • Optimizing the operation and the maintenance schedules through the assignment the right tail numbers to the right routes;

diagnostics tasks; • Finding adequate solutions to operational and maintenance issues; • Saving time by taking predetermined inspection and maintenance paths.		• Creating maximum hours and cycles without a deviating from the imposed schedules; • Optimizing the airline's operational and maintenance induction plans; • Powering other related innovation projects; • Maximizing the utilization of the company's assets; • Providing high confidentiality for the sources of the shared data.

Table 3: The technical, financial, strategic and organizational enhancements of the Skywise Platform on Airbus.(ICD Website, 2019) (Airbus Website, 2019) (Services by Airbus Website, 2019) (Euronews Website, 2018).

As we have noticed based on the table presented above, Skywise platform has brought some significant advantages to Airbus within various aspects and such benefits are expected to evolve rapidly in the upcoming period as technological advancements continue to grow and its related tools get smarter every day. Still, it appears important to underline that along with Skywise, operators of Airbus aircraft will be in position to leverage the cumulative knowledge of the 20,000 Airbus engineers that have followed closely the performance of every single individual aircraft through its whole entire operational existence. Until lately, this deep reservoir of knowledge and expertise has been only available during the periods of development and flight testing across the aircraft Entry-into-service. *(Airbus Website, 2019).* Airbus has still a huge vision for its Skywise platform and seeks to score higher objectives. Indeed, Airbus's long term ambitious for Skywise is to decrease operational interruptions by 30%. Since the best and most qualified engineers of the world concentrate currently on the huge amount of possibilities afforded by technology and innovation, Skywise is expected to be at the center of groundbreaking innovative systems for the upcoming years. (*Euronews Website, 2018)* For Airbus, this is only the beginning of a long successful ride towards better outcomes.

4.8.2 Innovation's improvements on a selected study case from the Automotive Sector: Nissan

Nissan, the Japanese vehicles manufacturer, has been chosen as a study case for this subsection in order to discuss and analyze thoroughly the technical, financial, strategic and organizational improvements of its innovative adopted tools and systems that have been already mentioned in detail on 4.7.2 subsection.

One of the main innovative tools adopted by Nissan that we have talked about earlier is Senseye's software which is a predictive maintenance software allowing Nissan to accurately monitor the condition of its vehicles remotely, determine its emerging issues and therefore predict the potential failures of the relevant equipment without the need for expert manual assessment or analysis. As explained previously, this software has greatly enhanced the maintenance activities and enabled the execution of the needed repairs long before the machinery would fail. The following table demonstrates the benefits of this software on the company's multiple segments.

Technical enhancements	Financial enhancements	Organizational & Strategic enhancements
• Reducing unplanned downtime up to 50%; • Delivering advanced predictive maintenance insights in an comprehensive and easy way; • Providing high accuracy for the likelihood and detection of future failure; • Not requiring any additional hardware or application-specific customization; • Presenting a quick installation with the operational benefits are realized immediately; • Procuring an ongoing evolution of the	• Cutting down the maintenance costs up to 40%; • Avoiding the upfront investment commitments required by costly platform products; • Avoiding the expenses of hiring third-party consultants to operate or interpret the results; • Scoring higher revenues.	• Improving continuously the intuitive user experience; • Requiring minimal personnel training or condition monitoring expertise to operate; • Encouraging the implementation and research of new features within the software; • Improving the communication channels among the maintenance teams and between them and the operational staff; • Focusing the maintenance and operational teams' efforts on specific

product's diagnostics and prognostic capabilities; • Covering all the machines and not the critical ones offering by that a general view on the relevant industrial site; • Reducing the necessity for manual inspections and spares inventory; • Offering high level of security to data; • Saving time.		targets.

Table 4: The technical, financial, strategic and organizational enhancements of Senseye's Software on Nissan.(ReliabilityWeb.com Website, 2018)

Moreover, Nissan has adopted Hortonworks Data Platform (HDP) as an open source data management platform based on Apache Hadoop that constitutes the foundation for its data architecture and used to power it data lake infrastructure by helping it to load, store, process, manage and analyze and eventually benefit from the growing quantities and diversity of information entering and flowing into the corporation's structures. HDP was made especially to facilitate for the companies installing, incorporating, handling and employing Apache Hadoop. The open source model captivated the interest of the Japanese auto-manufacturer due to the extensive number of engineering talents it contains and its impressive flexibility to pivot in case conditions change down the road. The relevant data platform has been therefore a considerable technological leap in the company's advancements history. In order to demonstrate this more concretely, table 5 will sum up some of the most important advantages of HDP 's implementation in Nissan.

Technical enhancements	Financial enhancements	Organizational & Strategic enhancements
• Improving the maintenance and operational activities reliability and performance; • Gaining easily the necessary insights	• Reducing maintenance and support costs (the annual cost of using HDP to manage a raw data terabyte could be as much as 100 times	• Simplifying the diagnosis strategies; • Allowing the company to be less reactive and gain a better and border view over their data

from huge amounts of information; • Avoiding the potential of data loss; • Not requiring the installation of any proprietary (non-open source) modules; • Making the data more available to nay applications that need it; • Enabling agile applications deployment; • Analyzing and storing data more efficiently; • Helping to build applications more rapidly and efficiently; • Enabling to create easily new features; • Testing new versions of business services without interrupting the existing old ones; • Indicating exactly which type of computer processor a business runs on; • Making more efficient usage of the computing infrastructure; • Offering highly accurate real-time predictive analytics; • Optimizing data architectures; • Increasing analysis efficiencies; • Providing high levels	less expensive than doing so with high-end storage arrays); • Eliminating the burden of cost certification and testing across multiple Hadoop distributions; • Avoiding upfront hardware costs; • Increasing the savings for data storage and data protection up to 50%.	and operations: • Simplifying their daily activities; • Organizing better their data management and saving a lot of time; • Improving resource utilization; • Increasing task throughput.

of security and governance; • Increasing the productivity; • Ensuring automated cloud provisioning so as to facilitate big data deployments while optimizing the use of cloud resources; • Eliminating the performance gap between low latency and high-throughput workloads; • Combining real-time and historical data; • Making deep learning faster and easier.		

Table 5: The technical, financial, strategic and organizational enhancements of HDP on Nissan. (Cleverism Website, 2019)(Buragohain and Fontaine, 2018)

Another advanced innovative system employed by Nissan is the Microsoft connected vehicle platform based on the Azure IoT Hub acting as a link and communication tool between the vehicle and provided services such as Cortana Intelligence. We have already mentioned previously that the Microsoft connected platform offers an improved navigation, advanced predictive maintenance, remote condition monitoring of vehicle features, enhanced in-car productivity, customer insights, intelligent assistance for drivers and helps eventually building autonomous driving abilities. Microsoft's cloud will do the heavy lifting when it comes to mobilizing vast quantities of sensor and usage data from connected vehicles to ultimately aid the company apply the information in the adequate powerful ways. The following table shows therefore the various benefits of the Microsoft connected vehicle platform adoption by Nissan.

Technical enhancements	Financial enhancements	Organizational & Strategic enhancements
• Enhancing the driver's experience; • Providing sophisticated machine learning and artificial	• Generate new and sustainable revenue streams; • Benefiting from the billions of dollars	• Benefiting from the robust measures of the platform; • Benefiting from the privacy regulations

intelligence capabilities; • Offering advanced mapping services; • Reducing potential disruptions; • Securing data connections; • Improving predictive maintenance capabilities; • Enhancing in-car productivity; • Offering better customer insights; • Improving autonomous driving capabilities; • Ensuring security and confidentiality through its features; • Providing a better monitoring of the vehicle in terms of service and providing service alerts to the user when needed; • Reducing the risks of accidents.	Microsoft has already invested into the cloud without having to do the same.	and the compliance offered by the platform; • Offering the company the flexibility it needs to build customized solutions for its client; • Providing enhanced digital services for a better driving experience; • Not requiring any additional training since the features are very simple to use.

Table 6: The technical, financial, strategic and organizational enhancements of Microsoft Connected Vehicle Platform on Nissan. (Ravi, 2017)

4.8.3 Innovation’s improvements on a selected study case from the Oil & Gas Sector: BP

We have selected BP, the British oil & gas Company, as a study case for this subsection so as to assess the various benefits and improvements in all related segments that the firm has gained through its implementation of the innovative systems and approaches that we have already discussed on subsection 4.7.3.

Among these innovative systems, we can name the Beyond Limit’s software that we previously defined as a software that focuses mainly on how to automate adequately decision making processes or approaches and how to fill the missing parts in data sets; providing by that the required operational insights and enabling the improvement of PdM and CM techniques and systems. It is a lot faster than any other AI technology in the market and has been already tested in deep space where usually there is a zero margin error. According to Beyond Limit's CEO Abdallat, this cognitive computing concentrates therefore on human thinking and the automation of decision processes unlike other cognitive computing applications which rely more on deep machine learning applied to sensor fusion and computer vision. This would make this technological solution quite unique in its nature and also because it not trained in any datacenter and following so crashed 10.000 times in simulation for further training. Moreover, it can actually operate with lacking or unknown information and create or develop some matching hypothetical scenarios and fill in the missing pieces pretty much like what human with expertise would do. *(Bindi,2017).* Table 7 summarizes the enhancements of this software on the named organization.

Technical enhancements	**Financial enhancements**	**Organizational & Strategic enhancements**
• Bringing higher levels of operational insight, business optimization and process automation; • Locating and developing reservoirs and improving how it produces and refines crude oil; • Enhancing processes' automation and operational effectiveness; • Managing in the best way the complex operations; • Improving decision velocity, decision quality; • Detecting the unknown failures ; • Delivering better cognitive reasoning	• Reducing operational, monitoring and maintenance costs; • Reducing the costs related to the development and location of reservoirs.	• Optimizing business tasks; • Managing better the marketing of the relevant products; • Upgrading the decision-making approaches; • Digitally assisting with knowledge transfer from experts to other personnel; • Ameliorating the management of the imposed operational risks.

and intelligence; • Reducing the amount of data needed; • Choosing more easily and rapidly the relevant valuable data; • Solving problems that conventional machine learning, neural net and deep learning procedures cannot solve; • Reducing operational risks and identifying opportunities; • Providing a better understanding of conditions on different sites.		

Table 7: The technical, financial, strategic and organizational enhancements of Beyond Limit's software on BP. (Ravi, 2017)

BP has also been using digital twins into its operations as an approach for checking critical engineering work through digital or virtual concepts prior performing so on actual industrial facilities or sites. Digital twins provide the perfect testing ground for advanced and innovative novel approaches and procedures of operating. It enables therefore to closely connect physical and digital assets and moreover to connect the relevant information with personnel and make it much easier for them to absorb it and use it for constructing better informed decisions. This technological solution offers a deeper comprehension of what is occurring on the production lines and in the wider manufacturing processes by monitoring the related components, assets, systems or processes in real time. It procures furthermore several advantages that we will attempt to underline in the following table.

Technical enhancements	**Financial enhancements**	**Organizational & Strategic enhancements**
• Providing valuable predictions and early	• Lowering the maintenance and	• Enabling the professional teams to

detections of faults and failures; • Enhancing reliability of the exploration and production facilities; • Providing data integrity which reduces risks, errors and delays; • Increasing the understanding of complex asset information; • Detecting accurately patterns and sending immediately the necessary alerts to the operators/engineers; • Detecting early signs of equipment failure or degradation to move from a reactive position to a proactive one; • Constructing accurate drilling and extractions models to indicate if the virtual equipment designs are feasible; • Gathering real-time data feeds to know the exact state and condition of the asset no matter its location; • Optimizing the relevant assets over their lifetimes; • Testing continuously the potential safety hazards and the logistics challenges; • Enhancing	operational costs; • Testing continuously the pricing levels; • Improved profits on a sustaining basis; • Reducing the costs of unexpected interruptions; • Increasing the total profits and revenues; • Reducing the economic risks.	take the necessary time into making the right decisions; • Allowing users to identify various plausible futures for an asset and consider their potential impact; • Ensuring more effective delivery and supply chains; • Enhancing customer services; • Enhancing situational awareness.

productivity and operational efficiencies; • Minimizing downtime and upgrading the Overall equipment effectiveness; • Extending the life of equipment and assets; • Uncovering rapidly and easily the potential operational inefficiencies; • Providing quick and effective responses to episodes of downtime; • Improving prognostics and health management practices; • Providing real-time visibility of the equipment condition and performance; • Extending error-free operations; • Refining continuously the designs and models.		

Table 8: The technical, financial, strategic and organizational enhancements of Digital twins on BP. (Prakash, 2018)(Shilova, 2017)

Another innovative system that BP has been using is the GE Intelligent Platforms Software which enables connecting all of BP's oil wells globally to the industrial internet and acquiring real time access to all the relevant machinery and operations data sets. Indeed, GE's software is helping BP to get the maximum of its existing assets and score higher levels of profitability. BP has been therefore working much closely with GE since 2008 leading information analysis and instrumentation to upgrade operational reliability and efficiency at sites including Prudhoe Bay, Alaska, the UK and Norwegian sectors of the North Sea, the Gulf of Mexico, the Caspian Sea and Angola. According to GE officials, all of the basins where the related software will be employed are offshore and would acquire subsea applications with the exception of Prudhoe Bay. They confirm that the software for BP isn't regarded as an IT or technology project but instead BP sees it as business change project. *(Boman, 2015).* Some of the key benefits of the implementation of GE's Software will be concluded on the following table.

Technical enhancements	**Financial enhancements**	**Organizational & Strategic enhancements**
• Preventing failures; • Eliminating unplanned downtime; • Creating new efficiencies in their oil fields; • Raising oil production; • Reducing the complexity of operations; • Increasing uptime ; • Making data constantly available to the right people at the right time; • Improving the overall effectiveness of maintenance and monitoring tasks; • Improving the safety of production operations; • Enhancing facilities reliability; • Helping the personnel respond quickly and adequately to emerging issues as they occur in real-time.	• Reducing costly repairs; • Increasing economic profitability, • Increasing the revenues engendered by the higher productivity of the wells.	• Taking the right informed decisions; • Acquiring better insights; • Increasing standardization and oversight; • Improving the strategies adopted and the way the company works with.

Table 9: The technical, financial, strategic and organizational enhancements of GE Intelligent platforms software on BP. (Automation.com website, 2015)

BP is also using Big data technologies among its innovative tools so as to perform more efficiently the information management operations through the enhancement of data streaming, storing and processing capabilities optimizing by that in a better way the assets and scheduling ultimately the maintenance tasks and related inspections only when needed. BP is therefore placing big data at the center of its attention to decrease the costs, as it attempts to mobilize digital and technological advancements to upgrade performance in an era of low oil prices. The UK oil group has been planning to extend its data storage capacities over the next years through the effective integration of machine learning and artificial intelligence into its activities. The huge amount of relevant and real time data collected from the implemented sensors in the corporation's wells and which inform the company about the facilities performance, productivity level and the condition of infrastructure, are eventually fed into a cloud based storage system enables the engineers from any given location to access to all types of gathered data. Table 10 illustrates the advantages of Big data usage by the British oil company.

Technical enhancements	**Financial enhancements**	**Organizational & Strategic enhancements**
• Saving time through the immediate analysis of data; • Optimizing and understanding better the processes; • Identifying accurately in real-time the root causes of problems and failures of equipment; • Identifying the most relevant information that can enhance the quality of decision making; • Providing accurate and real time predicting and monitoring of occasions that could impact the performance or operations of the	• Scoring significant cost savings; • Helping the company to be on the top of financial performance; • Uncovering new revenue streams.	• Making quick and efficient decisions based on the learnings; • Creating new growth opportunities; • Providing new ideas, new insights that would be helpful to the organization; • Reevaluating the risk portofolio rapidly and effectively; • Providing the ability to mitigate risks by optimizing complex decisions about unplanned events more rapidly, • Optimizing business innovation; • Preventing safety and environmental concerns;

business; • Boosting the operational efficiency up to 20%; • Enabling the easy and quick adoption of user-friendly predictive modeling tools; • Improving the exploration and drilling efforts and enabling new opportunities in oil exploration; • Creating more precise oil and gas field maps and easily identifying additional deposits of oil and gas; • Improving the security of oil and gas production; • Providing much faster response time to failures or problems.		• Boosting the company's competitive advantage; • Eliminating human errors.

Table 10: The technical, financial, strategic and organizational enhancements of Big Data on BP. (Oza, 2018)

PART 5: Development of a conceptual model and a recommended approach on implementing technological innovation

Introduction

The part will present the common mistakes that ought to be avoided and subsequently the necessary steps to be followed while implementing and introducing technological innovative systems properly. Indeed, it would be vital to show exactly what are the does and don’ts for the industrial companies when it comes to introducing innovation into their CM and PdM structures in order to have a better integration of the novel programs into the existing or old ones. Following so, we will present a conceptual model that demonstrates the process, strategy and overall environment of innovation establishment into the industrial context in question.

Section 9: Mistakes in innovation processes that should be avoided

We have previously mentioned some study cases of industrial companies belonging to various sectors that have made the huge step of implementing innovative tools and procedures into their structures and operations and have succeeded in doing so making by that, significant technical, financial, strategic and organizational profits. However, this isn’t always the case for a great number of companies. This can be mainly explained by the fact that these firms have made some mistakes in introducing innovation to their organisms or haven’t adopted the right strategies or procedures to overcome the challenges hindering the success of innovation’s implementation. Indeed, one of the main challenges facing innovative technologies is the security challenge. As industrial corporations are deploying a diversity of industrial IoT applications, they are more exposed to security concerns including lack of visibility, hack vulnerability, threats connected to IT/OT convergence and other insider hazards such as the absence of comprehensive cybersecurity solutions and solid security features. Another critical challenge of IIoT establishment is the lack of connectivity. Typically, it is obviously essential for organizations to control and monitor equipment in real-time and make sure that they are functioning at an optimal scale to upgrade the overall productivity. Therefore, increased visibility and enhanced insights on the health state of the machinery is also a key element in detecting abnormalities and solving problems prior their occurrence. IIoT machines are connected to various components and there’s a high probability that it could be a trouble in synchronizing as an outcome of Internet disconnections, power interruptions and manual or technical mistakes. If the company cannot respond adequately to these issues, then the result would be the removal of connected instruments from the network affecting negatively the whole production lines and process and costing ultimately the firm millions of dollars in damages. Additionally, companies could encounter another obstacle in the innovative IIoT tools installation which is the integration of the information technology an operational technology. In case companies cannot securely integrate both of them without information loss or introduction of vulnerability, their adoption and implementation would be financially impossible and logistically not feasible. *(Ven, 2018).* Moreover, the companies could also face some serious challenges related to innovation management. These obstacles could lead to the failure of innovation introduction in case the organization doesn't respond adequately to them or doesn't acquire the necessary properties to succeed. For instance, if the firm adopts a very top-down, micro-managerial approach, innovation initiatives would be suppressed and workers would feel less involved as they won't be in the position to surpass the expectations or limitations required for innovation. Also, if the firm doesn't acquire the needed resources and opportunities or doesn't have a rich infrastructure, innovation managers would find an extreme difficulty in solving the implementation issues facing them. This situation would get even worse if the company doesn't support enough a growth and innovation mindset or in other terms doesn't encourage its employees to get hold of new skills and learning competencies; innovation can't adapt to a sterile environment. Furthermore, management would find it even harder to deal with innovation if it doesn't adopt a crystal clear and a compelling vision for creating cutting edge concepts and becomes subsequently capable of communicating this vision to everyone involved in the organization as the usage of highly advanced tools isn't enough for scoring the desired objectives; people should get on board and be well prepared for the upcoming changes and above all the related facilities should be apt to welcome these enhancements otherwise there could be a high chance for innovation to fail ultimately. *(Nieminen, 2018).* Naturally, there are many other technical, managerial and organizational challenges standing in front of innovation's success in the industrial contexts. Consequently, the objective of this subsection is to demonstrate what common mistakes should be avoided and what recommendations ought to be followed in order to accomplish optimal outcomes following innovation introduction.

As we have already explained, innovation processes and approaches can be quite demanding and developing or inserting novel systems and procedures can be tricky. This is why companies ought to be careful when dealing with the expected and unexpected transformations in their related structures and operations and try as hard as they can to avoid some common mistakes.

- **Believing that innovative mindset is restricted to specific people:** firms make the common error to consider that some people are born innovative while the reality is quite the opposite. Indeed, the abilities to determine customer-driven opportunities, produce creative and innovative solutions, experiment novel concepts are all skills that can actually be learned if the company decides to invest in formal training and coaching as a way for improving the personnel capabilities.

- **Focusing on ideas instead of the customer needs and existing challenges:** industrial companies that are supposed to come up with or create innovative concepts make sometimes the mistake on focusing on ideas and their creativity level instead of what the market and their customer base need and what could actually help them overcome the existing obstacles in their related industries. By doing so, they end up developing novel products or services that no one wants, values or needs.

- **Overlooking the experimentation phase:** some companies go directly from the creation phase to the implementation phase making by that a very costly mistake. Innovation concepts must be tested without investing a lot of money and with involving the clients; otherwise the installation phase risks to be a total fiasco.

- **Pulling resources off innovation while the company is a crisis in its core business:** directing all the company's financial resources at defending the existing business can be the right decision on the short term but definitely not on the long one. Indeed, organizations that have succeeded to overcome trouble times are the ones who stayed in touch with their customers' needs and the long term perspectives.

- **Waiting to get bigger:** believing that the business has to reach a precise size in order for it to become innovative is a common mistake that many companies make. Actually, small companies have a tendency to create and innovate better and faster than larger firms.

- **Talking about innovation instead of investing in it:** a lot of CEOs and their leadership teams discuss the importance of innovation and how it can eventually improve their operations, still they don't do much about it. They continue on allocating resources such as money, time and people into their existing businesses instead of putting them into use in riskier, still, much more rewarding innovative projects.

- **Failing to involve everyone in the organization:** Companies can make the mistake to limit innovation to some teams such as product developers or founders creating serious issues of integration and communication. If the companies fail in involving everyone in the innovative projects, many workers would find severe difficulties in adjusting to the expected changes and wouldn't know how to react properly to them or to manage the resulting consequences.

- **Failing to define the appropriate innovation scope:** It might seem illogical or counter-intuitive to put in place constraints on an innovation initiative, but it is essential to determine the scope of work and the constraints otherwise the innovative activity will be a total struggle and a simple exercise of frustration. Also, beginning with no boundary conditions signifies that every single alternative or revenue must be studied making the project so broad that also every outcome is possible; this isn't simply how things should be done.

- **Using the wrong evaluation criteria:** choosing the right criteria on which we could evaluate the innovative tools and concepts is a must. Unfortunately, several companies employ the return on investment metric as a criterion for innovation evaluation. As much this metric can be a good one for projects with known costs and easily estimated revenues and return, it can be inadequate for innovative activities.

- **Failing to convert ideas into physical prototypes or simulations:** one of the most common failings of innovation teams is to make innovation a pure scientific project rather than a creative interesting process. Nothing would show that more than the absence of physical prototypes. In this case, the innovation process would lack the needed insights that would ultimately lead to the creation of better products and services.

- **Failing to link the front-end and the execution teams:** A lot of innovators make the huge mistake of constructing a supercharged front end process able of producing a large number of ideas without truly understanding the potential throughput of the development or execution team.

- **Implementing new tools and approaches but failing to trust the process:** when the company is establishing new innovative systems and procedures and these processes or tools encounter resistance, innovation fails. The resistance can be internal; it can come from executives who would feel threatened by the novel processes or from team members who would be uncomfortable with the resulted changes. The resistance can be also external; coming from customers or the channel partners who don't comprehend the new found-interest in their needs. If the company doesn't respond effectively and adequately to these types of resistance and above all doesn't encourage its personnel to trust innovation processes and demonstrate confidence in the approach, then again innovation goes downhill. *(Buisness Insider Australia, 2017) (B&T magazine, 2019) (Sponseller, 2015) (Phillips, 2013).*

Section 10: Recommendations to follow to have a successful innovation introduction and implementation

After indicating the various mistakes that should be avoided while implementing innovation in industrial contexts, it appears essential to nominate the steps that ought to be followed for a successful introduction. Innovation is a big idea with a big potential, but is it recommended to approach it with small steps preparing carefully the initial ground and trying to implement the relevant novel concepts without any rush and build the rest of the process from there. For the majority of firms, the first phases are the most critical on this long value-creating journey. At the end, the success of innovation relies above all on how your build “the innovation culture” within your organization to support and sustain the development of your ideas. Obviously, the first step in creating the maintained culture for innovation is to lay the groundwork toward constructing the organizational ability for innovation. In other terms, the climate of innovation can only blossom when every single segment of the company endorses creativity, open visions along with the commitment and acceptance of the required and expected transformations. Therefore, when introducing innovation, the company has to take into account some essential aspects including the initial groundwork, the people and the process of innovation itself.

Concerning the initial groundwork, the company has to first of all spread the word about the intent to innovate and create by developing innovation mantras. This shows everyone that the company is walking on the journey of innovation. As we have previously mentioned, the start has to be managed carefully and slowly. The company must build and reinforce the concept of innovation stone by stone while highlighting the need for accountability. More importantly, the company has to know exactly how to respond to the internal resistance manifestations against innovative initiatives. Indeed, when the personnel and professional teams feel insecure, whether this feeling of insecurity is justified or not, they tend more often to assassinate the efforts towards creativity. No matter what the form of resistance is, whether it is an open disapproval or undercover objection, it remains a threat to innovation implementation. A lot of companies make the enormous mistake of dismissing these resistance forms while they are supposed to acknowledge its existence firstly and comprehend why it exists secondly and then find out how to fight it. It appears therefore that the best way to achieve so is by accepting and encouraging disruption and risk. This might sound illogical, but the optimal approach to deal with risk is by pushing people to stop being afraid of it. In other quarters, risk as a failure should be seen and experienced as a learning experience and not a danger that should be avoided at all costs. Only then, resistance towards innovation could be managed properly.

While introducing innovation, another aspect to be taken into account is the people. Indeed, a central element in implementing innovation is finding and keeping the right people and knowing how to deal exactly with people-related problems. Going in the past, the organization’s culture would shape the workers and their behaviors. Oppositely, today, it is the value system of the employees that all together determine and define the organization’s culture and style. The workplace has also become quite complicated today and companies have to figure out how to handle the changes resulting from the introduction of technology in their structures. They must be careful in the treatment and care of employees to develop a unified culture of innovation thinking about co-working spaces, new desk layouts and floor plans. The companies ought to ensure that their personnel are committed, engaged and ready to accept and contribute eventually to innovation. Barry Salzberg, global CEO of Deloitte expresses in a company statement on this matter: *"Real opportunity exists for organizations to step up and create the conditions and commitment needed to encourage innovation in their work environments…if we get this right, we can better retain talent, remain more competitive into the future, and more positively impact society."*.

Furthermore, the process of innovation itself is an element to be looked at with infinite consideration. Indeed, companies have come to the conclusion nowadays that what they are innovating is important but how they are innovating is even more crucial. While working on developing new products or services, the responsible teams must make sure that they have the right mix of required ingredients for the implementation process that will make eventually the overall marketability occur faster and will upgrade productivity across the board. These key ingredients include mainly; generating ideas, screening, testing, analysis, beta tests, product development technicalities, commercialization and post launch review. Naturally, in order to acquire favorable innovation results, a structured and repeatable process is primary from the beginning to the end. *(Brands, 2015).*

After taking into consideration all the necessary elements in the innovation implementation and introduction processes, and if the company truly intends to be successful in the long run, it needs to establish an innovation management system so nothing is left to chance. When discussing innovation, we usually talk about terms such as creativity, open visions, new perspectives, freedom of ideas' expression; still innovation needs also concepts that involve planning, calculation, scheduling and future visualization. This is where innovation management concept interferes shaping the structures and framework conditions so that innovation potentials can be automatically detected, ideas produced and then successfully executed. If the relevant company decides to establish an innovation management system, the following steps are recommended:

- **Mission of management and objectives:** the success of innovation management depends above all on the management engagement of the firm's management. This commitment cannot occur without a clear authorization from the top management in which the objectives, purpose and expectations of innovation management are defined. The budgets, responsibilities and framework conditions are also to be determined.
- **Strategic orientation of innovation tasks:** Based on the company's management to work on innovation management system, it has to construct following that some eligible and well defined rules and guidelines that would be capable of defining the innovation vision that the company chooses to adopt.
- **Definition of the search domains:** The relevant company must define the search fields where it chooses to innovate. These domains are described as strategic subject areas that are identified on the basis of strategic tools including trend, technology and market analyses.

- **The beginning of brainstorming:** the search of ideas from the most diverse sources and with the most innovative approaches would be searched to be eventually developed within the search domains.
- **The design of the innovation process:** the process of innovation is the heart of the innovation management. It defines the management of the relevant idea from its first creation going through its successful market launching till its release to the operative management teams. *(Eschberger, 2018).*

These defined steps constitute more or less the start of the innovation management. Innovation management is a continuous process that concentrates on several segments including corporate trends, innovation strategies, brainstorming and scouting, innovation portofolio, innovation process, innovation culture and supporting processes such as open innovation and intellectual property. The company would seek continuously to develop and optimize these aspects building up them into innovation management so as to upgrade the innovation capacity and innovation performance.

Within these first steps of innovation management introduction, it is normal for the company to expect challenges, and if major mistakes are made or essential decisions are dismissed, the company must expect some significant issues through the process. This is why the firm has to take into account some key success factors that could fit in multiple cases.

- **Management commitment to innovation:** is one of the most essential success factors of innovation management. The commitment and constant engagement of all managers from top to bottom is the foundation of innovation process since it ensures and secures the support and the means to achieve innovations at all areas. Resources, time, support and budgets are the fuels for innovation success, without them we cannot talk about innovation and we can definitely not achieve the desired goals. For these elements to be provided, the company must demonstrate its full commitment to innovation otherwise innovation founders and leaders would be only wasting their time.

- **Strategic orientation:** is vital to acquire a specific knowledge on the goals, path and the general orientation of the company. In case the strategic orientation is absent, it would be more difficult for those in charge of innovation to assess what and where to look at and to choose what kind of innovation topics should be on their top priority making it eventually more complicated for them to take the right decisions. This signifies that the strategic orientation must be defined carefully on the basis of future trends, opportunities, risks and challenges as well as the corporate strategy. What is purpose of innovation and what do we want to achieve in the future? What is the contribution of innovation to corporate strategy? What are the future topics and the search domains? Answering these question will allow to establish the strategy of innovation and its vision and the base for the entire development process.

- **Clear responsibilities:** the innovation process is a huge process that involves a wide variety of disciplines and functional areas and a large number of employees in order to ultimately implement successfully the relevant novel product or service. In other terms, in order for the company to have a successful innovation introduction, all employees must be aware of their exact responsibilities and roles within the innovation process to know how they are supposed to contribute to these changes and what is expected of them at different stages of the process in question.

- **Innovation culture:** companies must comprehend once for all that innovation management is completely distinct from operative management or work. In fact, operational business is based on routine and efficiency while innovation is all about creativity demanding various values and attitudes including being open to making new steps, taking risks, thinking differently, admitting mistakes etc. Consequently, corporations must work on developing a positive innovation culture where everyone is encouraged to innovate and contribute to the innovation process. Innovation culture is therefore promoted through different levels: raising employee awareness about innovation, motivating workers and empowering them via training sessions or other, actively involving them and creating sustainable spaces and structures for their innovative tasks.

- **Change management:** it is expected that introducing and implementing innovation within the organization will result into significant changes. These transformations would only be efficient and positive if they are supported by everyone involved and by all employees. It is therefore easy to conclude that change management is vital and must be taken into account by any innovation manager.

- **Integration of all employees**: the central success factor of innovation introduction and implementation is definitely the "human being". It would be accurate to say that without the full engagement and commitment of all employees, the innovation introduction and implementation are doomed to failure. Moreover, innovation isn't a concept that would succeed within a restricted circle or group of workers. In other words, innovation requires the active support and initiation by everyone working in the company; all employees must be involved. Their involvement must include awareness-raising measures to inspire and motivate all workers for innovation, as well as structural measures for active engagement like pitching contest for instance, innovation competitions or classic idea management. The point of these initiatives is to make innovation an accepted and supported concept by all workers from bottom to top.

- **Collaboration:** as mentioned before the involvement of all employees is vital but isn't enough. Collaboration and corporation is another key success factor in innovation projects. Naturally, innovation combines between teams from various departments and disciplines. Still, it remains crucial that everyone keeps in mind a unified greater goal. Otherwise, distinct demands can lead to a lack of cooperation and support or issues at the interfaces which would eventually result in slowing down the innovation process or even its failure if the imposed problems aren't fixed rapidly and properly. This is why the company must work extremely hard to be aware all of its employees to gather their efforts and energies in pursuing a single objective whether it is related to the innovation visions or during their individual projects. *(Eschberger, 2018).*

- **Communication:** Clear and consistent innovation is the key to the success of innovation implementation. In order to achieve so, the company must put in place a large number of solid communication channels going across the entire organization and plan accordingly an eligible communication strategy that defines the company's innovation orientation and overall vision. Moreover, many companies have a mismatch between the internal and external communications making the employees feel confused and sometimes insecure as the internal messages transmitted within the company are different from the ones sent to the public. For this reason, the company ought to make sure that there's a consistency between the two communications. Communication and workers are two elements that must always go hand in hand. For the communication channels to work best, the employees must continuously and accurately be informed of the firm's decisions, strategies, goals, opportunities, milestones, failures and future expectations. *(Brands, 2016).*

- **Information access:** Everyone involved in the innovation projects must have access to all of the information needed to help make the necessary decisions about the allocation of human and financial resources. The offered information must determine if the novel introduced concepts are sufficient to meet the desired objectives and if they are meeting the imposed expectations. Having the open access to the relevant information will allow the workers to remain involved and updated on the progression of the projects in question and know exactly when and how to interfere. Also, this will enable them to draw effective and continuous learning experiences for a better implementation.

Section 11: The conceptual model of innovation introduction and implementation

Today, innovation is without a single doubt the key to economic growth and a strong competitive advantage that increases production and procures sustainable job opportunities adding by that strong business value through the new products, services and technologies. We have attempted previously to explain the various recommendations to be taken into account while introducing and implementing innovation projects and the mistakes that should be avoided. Nevertheless, knowing the does and don'ts when it comes to introducing innovation isn't enough to acquire a clear vision on innovation's interactions with the industrial environment. Building on this, it appears essential to have an overall idea on the industrial innovation model that will establish a clear pathway towards the company's objectives. For that, we will try to represent the various segments that build up the innovation concept through a conceptual model demonstrating mainly the process, strategy and overall environment of an industrial innovation project.

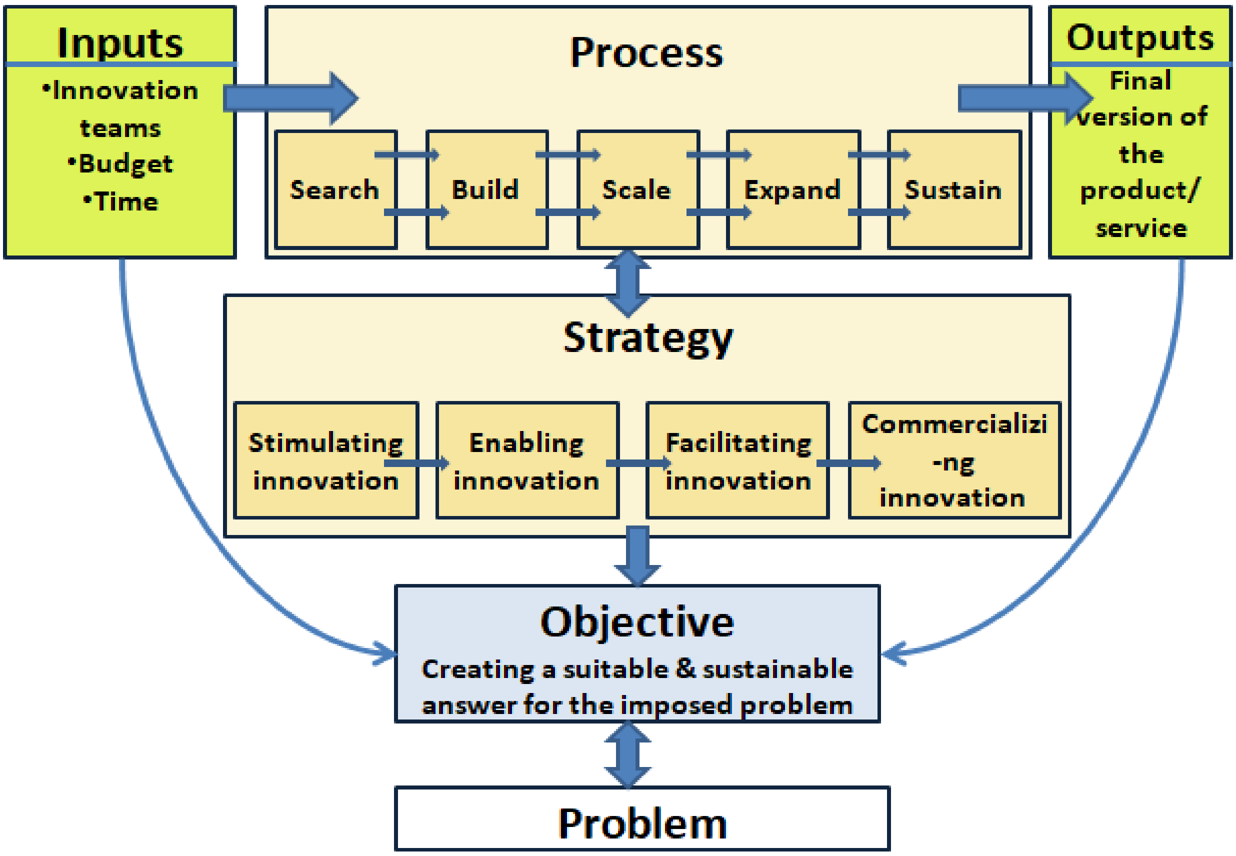


Figure 28: Conceptual model of innovation introduction and implementation.

- **<u>Inputs</u>**

The input, in the case of the conceptual model described above, would be composed of essential elements that include mainly the human resources that are the innovation developers or founders, the financial resources that would be the budget provided by the top management to the innovation project and also the time to undertake the various steps of the relevant process to be able eventually to deliver the desired outcome.

- **<u>Process</u>**

The process of innovation development starts with a searching phase that is primarily about looking for and finding innovation potentials and the derivation of ideas that would be ultimately evaluated. The innovation potential that is a newly discovered opportunity can be a total novel concept or an updated version of an existing one. Also, it could aim to conquer or create a new market or simply develop a novel technical solution, and there are countless ways to establish the search according to the choice of the innovation managers and how they choose to deploy the process's inputs. Secondly, comes the phase of building up the chosen innovative concept. This involves several segments including the study of the customer requirements, the market size and potential, the imposed challenges and various risks and the thorough analysis of the trends, patents, standards and regulations etc. Building up a concept from scratch is far from being easy and this phase constitutes the foundation for the rest of the process. Therefore, if it contains any mistakes or unsolved problems, the entire process would slow down or even fail. Following so, it would be vital to scale the results of the first two steps. Once the solutions are developed and the prototypes are built accordingly, the outcomes should be measured and tests should be carried out. In this case testing doesn't only involve lab testing but also market testing under real circumstances and conditions so as to acquire a comprehensive and full feedback. After the concept or innovative idea has been tested and has reached maturity, it would subsequently be moved towards the implementation and marketing so it can eventually be released for production. The following step that we talked about is the expansion step. It is about bringing the product or service to the market. Indeed, bringing it to the potential customers requires the marketing, logistics and sales channels to be all activated and aligned to answer the same objective that it ensuring the success of the innovative project. Finally, the company must work on the sustainability of its product or service. To achieve so, it must evaluate how the customers are responding to the product/service in question through the customer feedback and satisfaction level, the sales or any other quantitative market metrics. This will enable the company eventually to determine if the innovative product is successful the way it has been commercialized or needs improvements.

- **<u>Strategy</u>**

The strategy mentioned on the figure above concentrates on four major stages of the innovation chain that are required to transform the innovative ideas into commercial value for the company generating ultimately economic and social profits. It all starts with stimulating innovation through spreading awareness and information sharing through the various areas and disciplines of the organization. As we have already explained, for people to feel motivated they must be involved and they must comprehend what is the goal behind the innovative projects and what is exactly expected from them. Following so, innovation ought to be enabled through building supplier networks in order to make it easier for the organization to create and develop innovative projects and also support or assist the networking between support entities. In the same direction, the company must develop knowledge about innovation management through its structures, push its employees to improve the innovation strategies and determine the root causes for the company's potential innovation weaknesses. The third stage that we have mentioned on the figure was about facilitating innovation. Innovation is easily introduced and implemented if the company chooses to follow the multiple recommendations that we have detailed on the previous subsection such as the communication, collaboration, integration of all employees, the clear responsibilities and others. Such initiatives would enable the company to easily introduce innovation as a beneficial concept for the organization and boost the employees to upgrade their capabilities and adopt a more acceptable attitude towards the related implementation. At last, comes the stage of commercializing innovation through the identification of new value chains and/or business partners that would increase the quality of commercialization of the existing prototypes or products/services. *(German cooperation, n.d).*

- **Objective**

Innovation introduction and implementation have multiple goals and objectives to achieve such as the creation of an added value to the firm and increasing the economic growth and market share, still the main and initial one would be to present a sustainable and profitable creative solution to the market as a response to a certain industrial problem or dilemma.

- **Output**

The output presented on the above figure would be as described the last version of the final product or service that would be commercialized to the market after the establishment of all the phases of the innovation process and its strategy stages.

Finally, this part has allowed us to acquire a broader perspective on technological innovation in industrial contexts. After assessing its importance, impact theoretically and concretely through some chosen examples, it appeared vital to take the discussion into the next level by talking about its implementation in terms of mistakes, recommendations, strategy and process via the presented conceptual model above. Obviously, what we have presented on this last part is only a way of perceiving things as other steps could be recommended or another model can be suggested. However, the point behind this analysis was to highlight the importance of considering the adequate policies and strategies when it comes to introducing innovation to the organization and its employees. In other terms, a successful innovation implementation or introduction doesn't revolve only on focusing on the desired targets but depends mainly on the selected path and how all the company's variables are reacting to it.

PART 6: Discussion, recommendations for further studies and conclusion

Through this last part of the thesis, a discussion of the project will be elaborated. This discussion is undertaken so as to determine if the scope of work and the described objectives at the beginning of the thesis were actually met. Subsequently, a presentation of the major findings, learning areas and at last a discussion of the obstacles and challenges that have been faced during this work is executed. Following that, some recommendations for further studies are demonstrated in section 13. A brief conclusion will be presented on the next section; section 14, seeking to summarize the work that has been done in a thorough and far-reaching manner. Finally, the bibliography would be presented.

Section 12: Discussion of the thesis

6.12.1 Scope of work and objectives

The scope of the thesis includes various and distinct objectives related primarily to three main concepts; innovation, condition monitoring and predictive maintenance. Any given observer can actually conclude that these three subjects are strongly related especially when speaking about industrial contexts. Still, we have attempted through the relational diagram established on the third part to elucidate and better clarify the existing connections between innovation, CM and PdM. The relevant relationships present our proper point of view regarded from a perspective of innovation being deployed as a beneficial and profitable tool from PdM and CM mechanisms under given industrial conditions.

By firstly indicating the various obstacles facing the CM and PdM systems and mechanisms and demonstrating following so how the introduction of innovation and its implementation throughout the monitoring and the maintenance processes and activities, it was easier to identify the necessity of innovation and its importance in today’s multiple industrial markets. Furthermore, indicating the various advantages of technological innovations that we have already detailed will accentuate the established picture concerning the need for innovation nowadays.

Moreover, the explanation of how innovation is being considered as a business concept and how it has evolved throughout the various generations and industrial revolutions will enable us eventually to reach another objective that is setting up a comprehensive framework about innovation progression as well as the development of its interaction with the CM and PdM tools and systems.

As for demonstrating study cases from numerous industries that have been deploying and developing innovative tools into their CM and PdM approaches and processes, it allows to fulfill the objective of analyzing in a concrete manner how these innovations can enhance the operations' performance of the firms in question in multiple aspects, technically, economically, organizationally and strategically.

Lastly, the study of the common mistakes made in innovation introduction and implementation and the analysis of the various recommendations that ought to be followed to reach the highest level of quality and performance of these innovative procedures will ultimately make it possible to open the discussion of another aspect of innovation that is its optimal establishment for any given industrial corporation.

6.12.2 Major findings

During the last decade, it has become clear that the novel technological solutions appearing in every single industrial segment are shaping the future of industries and pushing companies to invest heavily and work much harder on developing and implementing highly advanced tools into their maintenance and monitoring operations and structures. Indeed, technological innovation isn't just an improvement tool for the industrial processes' performance or a facilitator that enables conducting CM and PdM activities at the speed of thought but constitutes mostly a novel way of thinking and a strategic policy that revolutionizes the entire industrial environment. Consequently, comprehending the level of importance of innovation and the significant profits it brings to various organizations belonging to different fields would allow perceiving in a more concrete manner how innovation transforms today's markets.

However, understanding the need for innovation in relation to PdM and CM or believing in its power is far from being enough to be capable of adopting it as a central strategy. It seems therefore essential to understand how innovation can be demonstrated as a business concept and the ways innovation has evolved through these years going from an industrial generation to the next. Only throughout an exhaustive look at the historical changes of technological innovations in industrial contexts can companies determine where innovation stands today and what would be the possible approaches to introduce it into their environments.

We can therefore agree that when the innovation initiatives end up being successful, the relevant corporation gains a huge competitive advantage and accomplishes considerable economic profits. This brings the light to a crucial question on the matter which is how to best introduce and apply innovation in an industrial organization. Responding to this interrogation is done through detecting what are the most common errors that could firms make when approaching innovation and what are on the other hand the suitable and recommended means to achieving a full rewarding innovation implementation.

6.12.3 Obtained learning

The work on this thesis has provided us with a wider comprehension and an overall learning on innovation, condition monitoring and predictive maintenance as well as on their connections. An exhaustive study of these concepts and their interactions with a main focus on innovation as a central element has been established throughout this project.

Analyzing the main obstacles and challenges facing the CM and PdM processes and systems has allowed us to observe in a better way what the operators in various industrial sites and facilities have to deal with on a daily basis especially when using traditional and old fashioned tools and approaches. Simultaneously, taking this discussion to innovation and its broad benefits and diversified ways of bringing the best out of complex or problematic situations and ending up solving them and improving their outcomes eventually, would only lead us to the obvious conclusion: innovation when used properly and implemented how it should is the ultimate key for maintenance and monitoring issues.

Going through the diverse industrial revolutions and the different innovation generation models has enabled us to track the evolution and progression of innovation and put in a broader context not only in relation to predictive maintenance and condition monitoring. This has moreover allowed us to construct the image of innovation as a business concept.

Throughout this project, we have learned that multiple companies from numerous sectors are entering a large competition to provide the most advanced and beneficial innovative tools that will enhance their operational and maintenance activities and processes. We have more importantly come to the conclusion that these same tools are the ones that aid the firms in question to score considerable profits in different segments of their structures whether they are technical, financial, organizational or strategic. Obviously, not every establishment of these tools leads to a success, this is why it has appeared vital to get a closer look on what would be the best ways to approach innovation and transform it into a profitable strategy for any industrial corporation no matter its size, sector or market share.

6.12.4 Encountered challenges

Innovation, condition monitoring and predictive maintenance are three interesting subjects that we could easily find all the necessary information about which is not really the case about their connections and interactions. Therefore one of the main challenges of this thesis was to find relevant data about all of these concepts combined and their relations. Most of the gathered information was website based since the main goal was to choose the most recent news about innovation, CM and PdM and as it is known the Internet can be sometimes a misleading tool as much as it can be useful. Consequently, the point was to select suitable information that responds to our scope of work and handling the large amount of data was a time consuming task requiring intensive efforts. This was another challenge in itself.

Section 13: Recommendations for further studies

We have focused mainly through this thesis on technological innovation and the fourth industrial revolution with its major segments including artificial intelligence, Internet of Things, machine learning and others. Therefore, a useful subject for further analysis would be organizational innovation and how its resulting changes can reshape and influence the company's operations and strategies.

Moreover, we have discussed during this project study cases of companies from certain fields that are the aerospace, automotive and oil and gas sectors. We can consequently extend the study to other industries such as the health and agriculture sectors or others and attempt to look for more detailed studies on the subject including numbers that could back up the financial analysis of the innovation enhancements and solve by that one of the delimitations of this thesis which was the non access to economic figures of corporations in question. It is also possible to further detail these studies by taking a specific case and tracking its progression for the start of the innovation introduction and implementation until today to perceive in a better manner the resulting transformations and improvements.

We have thought that the best way to finish up this work is by detailing the best approaches and give some advice for installing innovative tools and approaches so as to give an opening section for broader perspective. This can actually lead to perform additional studies on the subject by analyzing some concrete cases on how some companies that acquire fruitful innovative projects and strategies have reached their success.

Throughout this project, we have constantly considered innovation as the actor in charge, the concept that establishes changes and transforms the company. What if we inverse roles and lead an entirely different study in which innovation is the one that is being influenced by monitoring and maintenance? This is again another topic for further assessments that could be quite interesting.

Section 14: Conclusion

During the last decades, there’s has been a significant uptake in innovation talk. This is quite obvious, everyone likes creativity, invention; the idea of coming up with something new has always been fascinating. But is talking about innovation enough? The answer is simply no. Companies have therefore begun to grasp that over the last few years by taking serious initiatives towards innovation and especially the technological one. They have started investing millions and billions of dollars into this rewarding yet risky road mobilizing their time, human resources, money and energy into shifting not only the way industrial markets operate today but mostly the way they think. This thesis aimed therefore to illustrate this picture in the most possibly comprehensive and organized approach. To achieve so, we have determined what technological innovations we are exactly interested in and have analyzed their multiple advantages and how they have can help organizations overcome the challenges as well as the technical and managerial obstacles facing them. Subsequently, we have discussed the innovation progression through the various phases and generations of industrial revolution so as to conclude its current state and how it is considered today as a business concept and a solid factor in the economic growth of industrial firms. An exhaustive study of concrete examples concerning companies belonging to multiple industrial fields that are adopting innovation in their PdM and CM systems and tasks has been performed so as to perceive closely how organizations are starting nowadays to follow the technological trends and establish them as a core part of their strategies. These examples enabled us as well to analyze the closer impact of innovation on the organization’s financial, technical and organizational states linking by that the second and fourth part of this thesis. We have also attempted to clarify as much as possible the recommended ways in which we can implement successfully innovation in a general perspective not essentially related to CM or PdM mechanisms and that’s because even if firms decide to introduce and establish innovative and technological systems into their structures, they won’t succeed in doing so unless they work extremely hard in taking care of every single aspect of innovation and make sure that this notion isn’t just regarded as a business concept or a source of profits but a way of thinking and a whole culture in itself.

Bibliography

Airbus.com, (2019). *About us.* [online]. Available at: https://www.airbus.com/ [Accessed 12.04.2019].

Airbus.com, (2017). *Airbus launches Skywise – aviation's open data platform.* [online]. Available at: https://www.airbus.com/newsroom/press-releases/en/2017/06/airbus-launches-new-open-aviation-data-platform--skywise--to-sup.html [Accessed 10.05.2019].

Airbus.com, (2018). *Airbus' open aviation data platform Skywise continues to gain market traction.* [online]. Available at: https://www.airbus.com/newsroom/press-releases/en/2018/02/airbus--open-aviation-data-platform-skywise-continues-to-gain-ma.html [Accessed 10.05.2019].

Airbus.com, (2019). *Skywise.* [online]. Available at: https://www.airbus.com/aircraft/support-services/skywise.html [Accessed 08.05.2019].

Akselos.com, (2018). *Innogy Ventures and Shell Ventures back predictive digital twin pioneer with $10 million investment*. [online]. Available at: https://akselos.com/dddp2018-3/ [Accessed 01.05.2019].

Analytics-magazine.org, (2018). *Shell drills into big data analytics*. [online]. Available at: http://analytics-magazine.org/shell-drills-into-big-data-analytics-2/ [Accessed 29.04.2019].

Automation.com, (2015). *GE software to connect 4,000 global oil wells for BP*. [online]. Available at: https://www.automation.com/automation-news/industry/ge-software-to-connect-4000-global-oil-wells-for-bp [Accessed 13.05.2019].

BANDT.com, (2018). *The Six Innovation Mistakes Almost Every Organisation Makes*. [online]. Available at: https://www.bandt.com.au/opinion/six-innovation-mistakes-almost-every-organisation-makes [Accessed 15.05.2019].

Barsh, J., Capozzi, M. and Davidson, J., (2008). *Leadership and innovation*. [online] McKinsey & Company Website. Available at: https://www.mckinsey.com/business-functions/strategy-and-corporate-finance/our-insights/leadership-and-innovation [Accessed 08.03.2019].

Basu, A., (2018). *5 Ways Aircraft Health Monitoring Systems Are Revolutionizing Aircraft Maintenance.* [online] ISG Website. Available at: https://isg-one.com/industries/aerospace-and-defense/articles/5-ways-aircraft-health-monitoring-systems-are-revolutionizing-aircraft-maintenance [Accessed 11.04.2019].

Bean, W.C. and Hashemian, H.M, (2011). *State-of-the-Art Predictive Maintenance Techniques* [pdf] IEEE. Available at: www.indiana.edu/~t581pm/Week_13/Articles/PreventiveMaintenance.pdf [Accessed 13.03.2019].

Bell, P., (2017). *Creating a Culture of Innovation in Copenhagen.* [image]. Available at: https://www.citiesdigest.com/2017/08/15/creating-culture-innovation-copenhagen/ [Accessed 07.03.2019].

Bellias, M., (2017). *The evolution of maintenance.* [blog] IBM. Available at: https://www.ibm.com/blogs/internet-of-things/maintenance-evolution-prescriptive/ [Accessed 13.03.2019].

Berberian, P., (2019). *Cloud Technology Condition-Based Monitoring.* [online] ReliabilityWeb.com. Available at: https://reliabilityweb.com/articles/entry/cloud-technology_condition_based_monitoring/ [Accessed 18.03.2019].

Berkhout, A.J., Hartmann, D., Van der Duin, P. and Ortt, R. (2006), Innovating the innovation process, Int. J. Technology Management, Vol. 34, Nos. 3/4, pp.390–404.

Berman, N., (2018). *20 Things You Didn't Know About Chevron*. [online] MoneyInc.com. Available at: https://moneyinc.com/chevron// [Accessed 07.05.2019].

Berman, N., (2018). *20 Things You Didn't Know About Chevron*. [online] MoneyInc.com. Available at: https://moneyinc.com/chevron// [Accessed 07.05.2019].

Bhrugubanda, M., (2015). *A Review on Applications of Cyber Physical Systems*. [pdf] IJISET. Available at:https://pdfs.semanticscholar.org/275d/2d701b930a7f165082678b1feac284a5e7ba.pdf [Accessed 19.03.2019].

Bindi, T., (2017). *BP invests $20m into AI startup Beyond Limits to transform oil and gas exploration.* [online] ZDNet website. Available at: https://www.zdnet.com/article/bp-invests-20m-into-ai-startup-beyond-limits-born-in-nasas-caltech-labs/ [Accessed 12.05.2019].

Bjorlin, C., (2018). *Volvo Trucks' IoT-Enabled Fleet Uses SAS to Boost Uptime*. [online] IoT World Today website. Available at: https://www.iotworldtoday.com/2018/11/09/volvo-trucks-iot-enabled-fleet-uses-sas-to-boost-uptime/ [Accessed 25.04.2019].

Bloomberg.com, (2019). *Company Overview of OSIsoft, LLC*. [online]. Available at: https://www.bloomberg.com/research/stocks/private/snapshot.asp?privcapId=2443931 [Accessed 01.05.2019].

BMWgroup.com, (2019). *About the company*. [online]. Available at: https://www.bmwgroup.com/en/company.html [Accessed 23.04.2019].

Boeing.com, (2019). *Investing in the future of innovation.* [online]. https://www.boeing.com/innovation/ [Accessed 04.04.2019].

Boeing.com, (2019). *Our Company*. [online]. Available at: https://www.boeing.com/company/ [Accessed 04.04.2019].

Boman, K., (2015). *GE Software to Connect BP Wells to Industrial Internet*. [online] Rigzone website. Available at: https://www.rigzone.com/news/oil_gas/a/139570/ge_software_to_connect_bp_wells_to_industrial_internet/ [Accessed 13.05.2019].

Bombardier.com, (2019). *About us.* [online]. Available at: https://www.bombardier.com/en/about-us.html/ [Accessed 09.04.2019].

Bombardier.com, (2015). *Pratt & Whitney Signs Agreement to Provide Data Management Service for Bombardier CSeries Aircraft's Health Management System*. [online]. Available at: https://www.bombardier.com/en/media/newsList/details.bombardier-commercialaircraftt20150512prattwhitneysignsagreement.bombardiercom.html [Accessed 10.04.2019].

Bouley, D., (2016). *7 predictive maintenance techniques for boosting power equipment reliability* . [blog] The Schneider Electric blog. Available at: https://blog.se.com/power-management-metering-monitoring-power-quality/2016/08/31/7-predictive-maintenance-techniques/ [Accessed 14.03.2019].

BP.com, (2019). *Digital innovation*. [online]. Available at: https://www.bp.com/en/global/corporate/what-we-do/technology-at-bp/digital-innovation.html [Accessed 02.05.2019].

Brands, R.F., (2016). *Communication is Key for Innovation Implementation and Business Success.* [blog] InnovationCoach. Available at: https://chiefexecutive.net/the-key-to-successful-innovation-is-proper-implementation/ [Accessed 16.05.2019].

Brands, R.F., (2015). *The Key to Successful Innovation Is Proper Implementation*. [online] ChiefExecutive website. Available at: http://www.innovationcoach.com/2016/10/innovation-process-communication/ [Accessed 16.05.2019].

Broderick, S., (2018). *Airlines Deriving Benefits From Maintenance Data-Crunching*. [online] MRO-Network.com. Available at: https://www.mro-network.com/big-data/airlines-deriving-benefits-maintenance-data-crunching [Accessed 09.05.2019].

Bruland, K. and Mowery, D., (2018). *Innovation through time*. [pdf] University of Oslo and University of California at Berkeley. Available at: www.globelicsacademy.org/pdf/DavidMowery_2.pdf
[Accessed 25.05.2019].

Buragohain, S. and Fontaine, R., (2018). *Announcing HDP 3.0 – Faster, Smarter, Hybrid Data*. [online] HortonWorks website. Available at: https://fr.hortonworks.com/blog/announcing-hdp-3-0-faster-smarter-hybrid-data/ [Accessed 11.05.2019].

BusinessDictionary.com, (n.d). *Business Concept* [online]. Available at: http://www.businessdictionary.com/definition/business-concept.html [Accessed 29.05.2019].

BusinessDictionary.com, (n.d). *INNOVATION* [online]. Available at: http://www.businessdictionary.com/definition/innovation.html [Accessed 07.03.2019].

Business.gov.au, (2018). *Innovation.* [online]. Available at: https://www.business.gov.au/change-and-growth/innovationhtml [Accessed 27.05.2019].

Business Insider Australia, (2017). *The two biggest mistakes companies make when trying to innovate.* [online] Business Insider France Website.. Available at: https://www.businessinsider.fr/us/the-two-biggest-mistakes-companies-make-when-trying-to-innovate-2017-5 [Accessed 15.05.2019].

Buyse, K., (2012). *Five generations of innovation models*. [online] Stratagem website. Available at: https://stratagemgr.wordpress.com/2012/09/29/rothwells-generations-innovation-models/ [Accessed 27.05.2019].

Canaday, H., (2018). *Continued Progress Under Boeing's Predictive Maintenance Umbrella*. [online] MRO-network.com. Available at: https://www.mro-network.com/technology/continued-progress-under-boeing-s-predictive-maintenance-umbrella [Accessed 06.04.2019].

Canaday, H., (2019). *There Are Twins In The Future Of Predictive Maintenance*. [online] MRO-network.com. Available at: https://www.mro-network.com/technology/there-are-twins-future-predictive-maintenance [Accessed 15.04.2019].

Cao, Q., De Bertrand de Beuvron, F., Giustozzi, F., Reich, C. and Zanni-Merk, C., (2019). *Smart Condition Monitoring for Industry 4.0 Manufacturing Processes: An Ontology-Based Approach.* [online] Researchgate website. Available at: https://www.researchgate.net/publication/331238903_Smart_Condition_Monitoring_for_Industry_40_Manufacturing_Processes_An_Ontology-Based_Approach [Accessed 15.03.2019].

Carr, A., (2017). *The Big Data technologies that saved BP $7bn.* [online] Scott Logic website. Available at: https://blog.scottlogic.com/2017/07/18/bp-big-data.html [Accessed 03.05.2019].

CbcCanada.com, (2016). [image]. Available at: https://www.cbc.ca/news/canada/montreal/liberals-invest-bombardier-1.3800954%20figure%2010 [Accessed 17.04.2019].

CIO Journal Website, (n.d). *The benefits of M2M – a clever connectivity.* [online]. Available at: https://www.challenger-mobile.co.uk/the-benefits-of-m2m-a-clever-connectivity-management-platform/2 [Accessed 18.03.2019].

Challenger-mobile.com, (2017). *Chevron Launching Predictive Maintenance to Oil Fields, Refineries.* [blog]. Available at: https://blogs.wsj.com/cio/2018/09/05/chevron-launching-predictive-maintenance-to-oil-fields-refineries/ [Accessed 08.05.2019].

Chan, B., (2017). *Future-proofing your IoT Infrastructure*. [online] Strategy of things website. Available at: https://strategyofthings.io/future-proofing-iot [Accessed 18.03.2019].

Claveria, K., (2019). *The origins of predictive maintenance*. [online] Mariner insight to achieve website. Available at: https://www.mariner-usa.com/blog/the-origins-of-predictive-maintenance/ [Accessed 13.03.2019].

Cleverism.com, (2019). *Careers at Hortonworks.* [online]. Available at: https://www.cleverism.com/company/hortonworks/ [Accessed 11.05.2019].

Cousineau, M., (2018). *Implementing predictive maintenance with the help of preventive maintenance*. [blog] Fiixsoftware blog. Available at: https://www.fiixsoftware.com/blog/implementing-predictive-maintenance-and-preventive-maintenance/ [Accessed 14.03.2019].

Darragh, P., (2015). *13 stunning stats about product innovation.* [online] VisionCritical official website. Available at: https://www.visioncritical.com/blog/stats-product-innovation [Accessed 05.05.2019].

Datastax.com, (n.d). *What is Apache Cassandra™?* [online]. Available at: https://academy.datastax.com/planet-cassandra/what-is-apache-cassandra [Accessed 05.05.2019].

Datsunnews.com, (2019). *About Nissan Motor Co., Ltd.* [online]. Available at: https://datsunnews.com/pages/about-nissan-motor-co-ltd [Accessed 22.04.2019].

De Jesus, A., (2018). *Predictive Analytics in the Oil and Gas Industry – Current Applications.* [online] Emerj website. Available at: https://emerj.com/ai-sector-overviews/predictive-analytics-oil-gas-industry-current-applications/ [Accessed 05.05.2019].

DELL and INTEL, (2017). *Unlock the benefits of predictive maintenance with edge computing.* [pdf]. Available at: https://www.intel.com/.../benefits-predictive-maintenance-edge-computing-white-paper/ [Accessed 20. 03.2019].

Derber, A., (2018). *Aircraft OEMs Racing To Catch Up With Health-Monitoring Solutions.* [online] MRO-Network.com. Available at: https://www.mro-network.com/engineering-design/aircraft-oems-racing-catch-health-monitoring-solutions [Accessed 08.04.2019].

Desjardins, J., (2018). *The Future of Automotive Innovation.* [online] Visual Capitalist website. Available at: https://www.visualcapitalist.com/future-automobile-innovation/ [Accessed 17.04.2019].

Dhingra, P., (2018). *A strategy for implementing industrial predictive maintenance: Part I.* [blog] Google Cloud. Available at: https://cloud.google.com/blog/products/data-analytics/strategy-implementing-industrial-predictive-maintenance-part-i [Accessed 17. 03.2019].

Digitalistmag.com, (2017). *Artificial Intelligence: The Future Of Oil And Gas*. [website]. Available at: https://www.digitalistmag.com/digital-supply-networks/2017/08/07/artificial-intelligence-future-of-oil-gas-05259467 [Accessed 08. 04.2019].

Durmus, M., (2019). *Smart Predictive Maintenance: The Key to Industry 4.0*. [online] AISOMA website. Available at: https://www.aisoma.de/smart-predictive-maintenance-the-key-to-industry-4-0/ [Accessed 16.03.2019].

EdWordle.net, (2017). [image]. Available at: http://www.edwordle.net/create.html# [Accessed 06.03.2019].

Efficient Plant Editorial Staff, (2013). *Condition-Monitoring: 10 Common Management Mistakes.* [online] Efficient Plant official website. Available at: https://www.efficientplantmag.com/2013/11/condition-monitoring-10-common-management-mistakes/ [Accessed 12.03.2019].

Enkel, O. Gassmann and H. Chesbrough, "Open R&D and Open Innovation: exploring the phenomenon," R&D Management, vol. 39, no. 4, pp. 311-316, 2009.

Eschberger, T., (2018). *7 important success factors for the introduction of innovation management.* [online] Lead Innovation Management website. Available at: https://www.lead-innovation.com/english-blog/success-factors-for-the-introduction-of-innovation-management [Accessed 16.05.2019].

eTurboNews.com, (2018). *Airbus invites next generation of talent to make their innovative ideas fly*.[image]. Available at: https://www.eturbonews.com/231091/airbus-invites-next-generation-of-talent-to-make-their-innovative-ideas-fly/ [Accessed 12.04.2019].

Euronews.com, (2019). *Airbus Skywise: A revolution in the clouds*. [online]. Available at: https://www.euronews.com/2018/07/19/airbus-skywise-a-revolution-in-the-clouds [Accessed 10.05.2019].

Faulisi, A., Janousek, V., Neumann, W. and Tomarchio, G., (2018*). Jumping into Industry 4.0 with Predictive Maintenance Solutions.* [online] EEtimes Europe Website. Available at: https://www.eetimes.eu/2018/11/13/%EF%BB%BFjumping-into-industry-4-0-with-predictive-maintenance-solutions/ [Accessed 23.05.2019].

Fernandez, S., Ferreiro, S., Konde, E. and Prado, A., (2016*). INDUSTRY 4.0: Predictive Intelligent Maintenance for Production Equipment*. [pdf] EUROPEAN CONFERENCE OF THE PROGNOSTICS AND HEALTH MANAGEMENT SOCIETY. Available at: *https://pdfs.semanticscholar.org/638c/2b72a747ea4b82e098572be820083dca9c7a.pdf* [Accessed 16.03.2019].

FiixSoftware.com, (n.d). *Predictive maintenance: Everything you need to know about maintenance software*. [online]. Available at: https://www.fiixsoftware.com/maintenance-strategies/predictive-maintenance/ [Accessed 12.03.2019].

Fuchs, K., (2017). *How M2M enables predictive maintenance.* [online] Teralink solutions website. Available at: https://www.teralinksolutions.com/how-m2m-enables-predictive-maintenance/ [Accessed 19.03.2019].

Gall,R., (2018). *Energy sources and power management in IoT sensors and edge devices*. [online] Jaxenter website. Available at: https://jaxenter.com/energy-sources-power-management-iot-sensors-edge-devices-145006.htmlidUSKCN1R11JU [Accessed 17. 03.2019].

Garber, L., (2017). *What are the biggest challenges facing innovation managers in enterprises?* [online] Quora website. Available at: https://www.quora.com/What-are-the-biggest-challenges-facing-innovation-managers-in-enterprises [Accessed 14.05.2019].

GE.com, (2019). *Digital Twin.* [online] GE digital. Available at: https://www.ge.com/digital/applications/digital-twin [Accessed 14.04.2019].

GE.com, (2019). *GE Aviation.* [online] GE news. Available at: https://www.ge.com/news/company-information/ge-aviation [Accessed 14.04.2019].

German Cooperation (n.d). *THE INDUSTRIAL INNOVATION STRATEGY*. [pdf] Giz and Ministry of trade and industry. Available at: https://www.psmeegypt.org/media/1052/iap-booklet-english.pd [Accessed 17.05.2019].

Gouillard, F., (2018). *The unbalanced race towards innovation dominance.* [online] Leyton official website. Available at: https://www.leyton.com/blog/?p=2738-unbalanced-race-towards-innovation-dominance [Accessed 05.05.2019].

Green, E., (2013). *Innovation: The history of a buzzword.* [online] The Atlantic official website. Available at: https://www.theatlantic.com/business/archive/2013/06/innovation-the-history-of-a-buzzword/277067/ [Accessed 07.03.2019].

Gunther McGrath, R., (2012). *A brief history of inventing innovation.* [online] Harvard business Review. Available at: https://hbr.org/2012/10/a-brief-history-of-inventing-innovation [Accessed 07.03.2019].

Hackerearth.com, (n.d). *Schlumberger.* [online]. Available at: https://www.hackerearth.com/fr/companies/schlumberger/ [Accessed 07.04.2019].

Hanke, T., (2019). *Airbus evolving into digital company as it develops Skywise data platform.* [online] Handelsblatt.com. Available at: https://www.handelsblatt.com/today/companies/google-of-the-skies-airbus-evolving-into-digital-company-as-it-develops-skywise-data-platform-/23879778.html?ticket=ST-1708115-AEF0dmE9dbxFOKZpOT6b-ap1 [Accessed 13.04.2019].

Hasan, D., (2013). *Innovation generations.* [blog] INNOVATION Blog. Available at: https://dalalhasan.weebly.com/innovation-generations.html [Accessed 26.05.2019].

Hölzle, U., (2017). *Schlumberger chooses GCP to deliver new oil and gas technology platform.* [blog] Google Cloud. Available at: https://www.blog.google/products/google-cloud/schlumberger-chooses-gcp-to-deliver-new-oil-and-gas-technology-platform/ [Accessed 07.05.2019].

Ijaz, R., (2018). *The security benefits of using IoT as a small business; IoT is bringing numerous security benefits to small businesses*. [online] Innovation Entreprise website. Available at: https://channels.theinnovationenterprise.com/articles/iot-security-benefits-for-small-businesses [Accessed 18.03.2019].

Imaginovation.com, (2017). *IoT Security Risks and Benefits.* [online] Medium website. Available at: https://medium.com/@Imaginovation/iot-security-risks-and-benefits-18428819e735 [Accessed 18.03.2019].

Infoentrepreneurs.org, (2009). *Use innovation to grow your business*. [online]. Available at: https://www.infoentrepreneurs.org/en/guides/use-innovation-to-grow-your-business/ [Accessed 30.05.2019].

Ipacso.eu, (n.d). *The evolution of innovation framework models.* [online]. Available at: https://ipacso.eu/innovation-modelling/innovation-model-analysis/187-the-evolution-of-innovation-framework-models.html [Accessed 27.05.2019].

ISO 2011. ISO 17359:2011 Condition monitoring and diagnostics of machines –General guidelines. International Organization for Standardization

Ismail, N., (2018). *What are the advantages of industrial IoT and how do companies make it secure?* [online] Information Age website. Available at: https://www.information-age.com/advantages-industrial-iot-secure-123470377/ [Accessed 18.03.2019].

Jalan, A., (2018). *The Future of IIoT Predictive Maintenance.* [online] PRESENSO website. Available at: https://www.presenso.com/blog/emory-research [Accessed 16.03.2019].

Johnson, J., (2018). *Capturing Value Through Machine Learning, Shell Adapts The Era of Low Oil Prices.* [online] DigitalInitiative website. Available at: https://rctom.hbs.org/submission/capturing-value-through-machine-learning-shell-adapts-the-era-of-low-oil-prices/#_edn3 [Accessed 29.04.2019].

Khurana, A., (1999). *Managing complex production processes.* [online] MITSloan Mangement review official website. Available at: https://sloanreview.mit.edu/article/managing-complex-production-processes/ [Accessed 07. 03.2019].

Krasadakis, G., (2017). *Data quality in the era of Artificial Intelligence*. [online] FreeCodeCamp website. Available at: https://medium.freecodecamp.org/data-quality-in-the-era-of-a-i-d8e398a91bef [Accessed 18.03.2019].

Lacob, R., Parpala, R.C., (2017). *Application of IoT concept on predictive maintenance of industrial equipment.* [online] ResearchGate website. Available at: https://www.researchgate.net/publication/319014395_Application_of_IoT_concept_on_predictive_maintenance_of_industrial_equipment [Accessed 17.03.2019].

Lavi, Y., (2018). *The rewards and challenges of predictive maintenance.* [online] InfoQ website. Available at: https://www.infoq.com/articles/predictive-maintenance-industrial-iot [Accessed 15.03.2019].

LinkedIn.Com, (2019). *Baker Hughes, a GE company.* [online]. Available at: https://www.linkedin.com/company/bhge [Accessed 05.04.2019]

Maggiore, J.B., (2009). *Monitoring real time environmental performance*. [online] Boeing.com. Available at: https://www.boeing.com/commercial/aeromagazine/articles/qtr_03_09/article_07_1.html [Accessed 06.04.2019].

Mapr.com, (2019). *Apache Hadoop : Open Source Framework for the Distributed Storage and Processing of Very Large Datasets*. [online]. Available at: https://mapr.com/products/apache-hadoop/ [Accessed 18.04.2019].

Mapr.com, (2019). *Apache Hive: Open Source Data Warehouse on Top of Hadoop*. [online]. Available at: https://mapr.com/products/apache-hive/ [Accessed 04.05.2019].

Marr, B., (2017). *How BMW Uses Artificial Intelligence And Big Data To Design And Build Cars Of Tomorrow.*[online] Forbes official website. Available at: https://www.forbes.com/sites/bernardmarr/2017/08/01/how-bmw-uses-artificial-intelligence-and-big-data-to-design-and-build-cars-of-tomorrow/#5d8343902b91 [Accessed 24.04.2019].
Marr, B., (2019). *How BP Uses Big Data And AI To Transform The Oil And Gas Sector.*[online] Bernard Marr & Co website. Available at: https://www.bernardmarr.com/default.asp?contentID=1378 [Accessed 03.05.2019].

Marr, B., (2017). *The Amazing Ways Volvo Uses Big Data, Machine Learning and Predictive Analytics.*[online] StraightTalk website. Available at: https://straighttalk.hcltech.com/amazing-ways-volvo-uses-big-data-machine-learning-and-predictive-analytics [Accessed 26.04.2019].

Marr, B., (2018). *What is Industry 4.0? Here's A Super Easy Explanation For Anyone.*[online] Forbes official website. Available at: https://www.forbes.com/sites/bernardmarr/2018/09/02/what-is-industry-4-0-heres-a-super-easy-explanation-for-anyone/#549508209788 [Accessed 15.03.2019].

Matthews, D., (2018). *Data Is Key To Autonomous Vehicle Technology, And Tesla Says It's Winning.* [online] SmartCollectiveData website. Available at: https: https://www.smartdatacollective.com/data-key-autonomous-vehicle-technology-tesla-says-winning/ [Accessed 21.04.2019].

Matthews, K., (2018). *Predictive Maintenance With IoT: What It Means for Manufacturing.* [online] Manufacturing.net. Available at: https://www.manufacturing.net/article/2018/06/predictive-maintenance-iot-what-it-means-manufacturing [Accessed 19.03.2019].

Mehta, Y., (2018). *Condition monitoring crucial to industry 4.0.* [online] Readwrite webstite. Available at: https://readwrite.com/2018/06/08/condition-monitoring-crucial-to-industry-4-0/ [Accessed 14.03.2019].

Merriam-Webster.com, (n.d). *Preparation* [online]. Available at: https://www.merriam-webster.com/dictionary/preparationhtml [Accessed 07.03.2019].

Messer, A., (2018). *How ultrasonic sensors and artificial intelligence improve condition monitoring.* [online] MaintWorld website. Available at: https://www.maintworld.com/Asset-Management/How-ultrasonic-sensors-and-artificial-intelligence-improve-condition-monitoring [Accessed 18.03.2019].

Michaels, M., (2016). *5 reasons why this technology should appeal to a diverse workforce.* [online] Construction Business Owner website. Available at: https://www.constructionbusinessowner.com/equipment/equipment-management/november-2016-benefits-remote-controlled-equipment [Accessed 18.03.2019].

MicrosoftIoT.com, (2017). *Helping automakers drive innovation through connected cars.* [online]. Available at: https://blogs.microsoft.com/iot/2017/01/05/helping-automakers-drive-innovation-through-connected-cars/ [Accessed 23.04.2019].

Mitchell, E., (1999). *The history of a condition monitoring and condition based maintenance.* [online] ResearchGate website. Available at: https://www.researchgate.net/publication/297391398_The_history_of_condition_monitoring_and_condition_based_maintenance [Accessed 10.03.2019].

Modi, P., (2018). *How AI Is Providing Digital Twins For Predictive Maintenance In Oil And Gas.* [online] Forbes website. Available at: https://www.forbes.com/sites/nvidia/2018/06/21/how-ai-is-providing-digital-twins-for-predictive-maintenance-in-oil-and-gas/#5fb191c4780b [Accessed 06.05.2019].

Myllylä, J., (2018). *Innovation Strategy – What is it and how to develop one?* [online] VIIMA website. Available at: https://www.viima.com/blog/innovation-strategy [Accessed 25.05.2019].

Neale, M.J. and Woodley, B.J, (1975). *Condition Monitoring Methods and Economics.* [pdf] Bruel & Kjaer. Available at: https://www.bksv.com/doc/16-054.pdf [Accessed 11.03.2019].

Nguyen, H., (2018). *What is Predictive maintenance (PdM)? Its Pros and Cons.* [blog] Trg solutions. Available at: https://blog.trginternational.com/introduction-to-predictive-maintenance-techniques [Accessed 14.03.2019].

Nieminen, J., (2018). *50+ statistics on innovation – What do the numbers tell us?* [online] Viima official website. Available at: https://www.viima.com/blog/innovation-stats [Accessed 05.03.2019].

NissanOfrr.com, (2018). *Get excited about the 2019 nissan pathfinder*. [online]. Available at: https://www.nissanofrr.com/get-excited-2019-nissan-pathfinder/ [Accessed 22.04.2019].

NOAA.gov, (2018). *What is LIDAR?*. [online]. Available at: https://oceanservice.noaa.gov/facts/lidar.html [Accessed 21.04.2019].

NorthEastAutomotiveAlliance.com, (n.d). *Predictive Maintenance Scheme – Senseye.* [online]. Available at: https://www.northeastautomotivealliance.com/neaa-membership-services/predictive-maintenance-scheme/ [Accessed 24.04.2019].

OSIsoft.com, (2016). *2016 - Users Conference - Berlin - Oil & Gas Shell: The Journey from Reactive to Predictive Operations*. [video]. Available at: https://www.osisoft.com/Presentations/Shell--The-Journey-from-Reactive-to-Predictive-Operations/ [Accessed 01.05.2019].

Oza, H., (2018). *Many Benefits of Big Data Analytics for Your Company*. [online] Dataversity Website. Available at: https://www.dataversity.net/many-benefits-big-data-company/ [Accessed 14.05.2019].

Palem, G., (2013). *M2M Telematics & Predictive Analytics*. [online] ResearchGate website. Available at: https://www.researchgate.net/publication/236336259_M2M_Telematics_Predictive_Analytics [Accessed 17.03.2019].

Paraskova, T., (2019). *Big Oil Has Finally Joined The Digital Revolution*. [online] Oil Price website. Available at: https://oilprice.com/Energy/Energy-General/Big-Oil-Has-Finally-Joined-The-Digital-Revolution.html [Accessed 07.05.2019].

Parker, J., (2018). *Overview: All You Need to Know about Toyota Motor Corporation.* [online] MarketRealist website. Available at: https://marketrealist.com/2016/05/overview-need-know-toyota-motor-corporation/ [Accessed 26.04.2019].

Peycheva, R., (2017). *IoT and CMMS: The New Competitive Advantage*. [online] Mobility Work website. Available at: https://www.mobility-work.com/blog/oil-and-gas-is-reaping-the-benefits-of-predictive-maintenance [Accessed 29.04.2019].

Peycheva, R., (2017). *Predictive Maintenance: Benefits in The Oil and Gas Industry*. [online] Mobility Work website. Available at: https://www.mobility-work.com/blog/iot-and-cmms-new-competitive-advantage [Accessed 19.03.2019].

Phillips, J., (2013). *20 Mistakes Innovators Make*. [pdf] OVO innovation. Available at: https://ovoinnovation.files.wordpress.com/2013/06/20-mistakes-innovators-make.pdf [Accessed 17.05.2019].

Phukan, R., (2018). *Predictive maintenance can make vehicle recalls a thing of the past*. [online] IoTagenda website. Available at: https://internetofthingsagenda.techtarget.com/blog/IoT-Agenda/Predictive-maintenance-can-make-vehicle-recalls-a-thing-of-the-past [Accessed 17.04.2019].

Plackett, B., (n.d). *A new record in renewable investment.* [online] eniday website. Available at: https://www.eniday.com/en/sparks_en/2015-record-renewable-investment/ [Accessed 28.04.2019].

Prakash, J., (2018). *Digital Twins Define Oil & Gas 4.0*. [online] ARC advisory group website. Available at: https://www.arcweb.com/blog/digital-twins-define-oil-gas-40 [Accessed 13.05.2019].

Predictiveanalyticstoday.com, (n.d). *BP Global oil wells to be connected to the industrial internet.* [online] Pat Research website. Available at: https://www.predictiveanalyticstoday.com/bp-global-oil-wells-to-be-connected-to-the-industrial-internet/ [Accessed 03.05.2019].

Proaxsion.io, (n.d). *Condition monitoring: Understanding the options*. [online]. Available at: https://www.proaxion.io/condition-monitoring-options [Accessed 08.03.2019].

Proaxsion.io, (n.d). *Predictive maintenance.* [online]. Available at: https://www.proaxion.io/predictive-maintenance/ [Accessed 12.03.2019].

Putre, L., (2016). *IoT at M&T: An Inside Look at Toyota Operations Technology*. [online] IndustryWeek website. Available at: https://www.industryweek.com/industryweek-manufacturing-technology-conference-expo/iot-mt-inside-look-toyota-operations-technolog [Accessed 27.04.2019].

Ravi, S., (2017). *Empowering car makers with new Microsoft Connected Vehicle Platform*. [blog] Microsoft Industry blogs. Available at: https://cloudblogs.microsoft.com/industry-blog/manufacturing/2017/01/05/microsoft-empowers-car-makers-with-new-connected-vehicle-platform/ [Accessed 12.05.2019].

Reifer, A., (2015). *How SAS Enterprise Miner simplifies the data mining process*. [online] SearchBusinessAnalytics Website. Available at: https://searchbusinessanalytics.techtarget.com/feature/How-SAS-Enterprise-Miner-simplifies-the-data-mining-process [Accessed 19.03.2019].

Reliabilityweb.com, (2018). *Senseye announces predictive maintenance software upgrades*. [online]. Available at: https://reliabilityweb.com/news/article/senseye-announces-predictive-maintenance-software-upgrades [Accessed 10.05.2019].

Richter, I., (2018). *Quantifying the Benefits of Predictive Maintenance: 8 Benefits*. [Blog] SEEBO Blog. Available at: https://blog.seebo.com/benefits-predictive-maintenance/ [Accessed 13.03.2019].

RMIT University Website, (n.d). *Business concept innovation*. [online]. Available at: https://www.dlsweb.rmit.edu.au/adc/mdes/contribute/coursesA/GRAP2280/content/mod03/m3_topic02.htm [Accessed 29.05.2019].

Rothwell, R. (1994), Towards the Fifth-generation Innovation Process, International Marketing Review, Vol. 11 No. 1, 1994, pp. 7-31

Roubaud, J., (2017). *How Predictive Maintenance Fits into Industry 4.0*. [online] Engineering.com. Available at: https://www.engineering.com/AdvancedManufacturing/ArticleID/15798/How-Predictive-Maintenance-Fits-into-Industry-40.aspx [Accessed 16.03.2019].

Rouse, M., (2017). *Business Innovation.* [online] TechTarget Website. Available at: https://searchcio.techtarget.com/definition/business-innovation [Accessed 30.05.2019].

Scanimetrics.com, (n.d). *Equipment condition monitoring: A history.* [online]. Available at: https://www.scanimetrics.com/index.php/scanimetrics-news-menu-item/10-equipment-monitoring/98-equipment-condition-monitoring-a-history [Accessed 10.03.2019].

Schroeder, T., (2017). *The benefits of predictive maintenance.* [Blog] Excellence Blog. Available at: https://blog.softexpert.com/en/the-benefits-of-predictive-maintenance/ [Accessed 13.03.2019].

Seidenman, P. and Spanovich,D., (2016). *Southwest Installing Advanced Airplane Health Monitoring Sensors.* [online] MRO-network.com. Available at: https://www.mro-network.com/maintenance-repair-overhaul/southwest-installing-advanced-airplane-health-monitoring-sensors [Accessed 16.04.2019].

Sensor-works.com, (2018). *A short story of predictive maintenance* [online]. Available at: http://sensor-works.com/a-short-history-of-predictive-maintenance/ [Accessed 13. 03.2019].

Sensor-works.com, (2018). *Top five benefits of condition monitoring* [online]. Available at: http://sensor-works.com/top-5-benefits-of-condition-monitoring/ [Accessed 10.03.2019].

Sentryo.net, (2017). *The 4 industrial revolutions.* [online]. Available at: https://www.sentryo.net/the-4-industrial-revolutions/ [Accessed 25. 05.2019].

ServivesbyAirbus.Com, (2019). *AIRMAN-web.* [online]. Available at: https://services.airbus.com/maintenance/e-solutions/airman-web/airman-web [Accessed 12.04.2019].

ServivesbyAirbus.Com, (2019). *Skywise.* [online]. Available at: https://services.airbus.com/maintenance/expertise-and-other-services/skywise/skywise [Accessed 09.05.2019].

Sewell, H., (2019). *AI manufacturing firm brings tech to North East.* [online] BusinessCloud website. Available at: https://www.businesscloud.co.uk/news/ai-manufacturing-firm-brings-tech-to-north-east [Accessed 22.04.2019].

Sheep, E., (2018). *Redefining the oil and gas industry through machine learning* .[online] DigitalInitiative website. Available at: https://rctom.hbs.org/submission/redefining-the-oil-and-gas-industry-through-machine-learning/ [Accessed 07.05.2019].

Shell.com, (2019). *Artificial Intelligence* [online]. Available at: https://www.shell.com/energy-and-innovation/overcoming-technology-challenges/digital-innovation/artificial-intelligence.html [Accessed 28. 04.2019].

Shell.com, (2019). *Who we are* [online]. Available at: https://www.shell.com/about-us/who-we-are.html [Accessed 28. 04.2019].

Shenfeld, A., (2019). *Pushing IIoT predictive maintenance forward; two challenges to overcome.* [online] Reliabilityweb.com. Available at: https://reliabilityweb.com/articles/entry/pushing-iiot-predictive-maintenance-forward-two-challenges-to-overcome [Accessed 14.03.2019].

Shiklo, B., (2018). *How IIoT transforms condition monitoring*. [blog] Science Soft website. Available at: https://www.scnsoft.com/blog/iot-for-condition-monitoring [Accessed 17. 03.2019].

Shilova, M., (2017). *Digital Twin as a strategic technology trend*. [online] ApiumHub website. Available at: https://apiumhub.com/tech-blog-barcelona/digital-twin-technology/ [Accessed 13.05.2019].

Simon, K., (2018). *How AI Can Fill Maintenance Skills Gaps & Boost Productivity*. [online] Manufacturing.net website. Available at: https://www.manufacturing.net/article/2018/08/how-ai-can-fill-maintenance-skills-gaps-boost-productivity [Accessed 22.04.2019].

Singh, H., (2018). *Benefits of Industrial IoT in Condition Monitoring.* [online] DZone website. Available at: https://dzone.com/articles/benefits-of-industrial-iot-in-condition-monitoring [Accessed 15.03.2019].

Skillicorn, N., (2016). *What is innovation? 15 experts share their innovation definition.* [Blog] Idea to value. Available at:

https://www.ideatovalue.com/inno/nickskillicorn/2016/03/innovation-15-experts-share-innovation-definition/ [Accessed 07.03.2019].

Skyscanner.net., (2019). *Southwest Airlines flights*. [online]. Available at: https://www.skyscanner.net/airline/airline-southwest-airlines-wn.html?previousCultureSource=GEO_LOCATION&redirectedFrom=www.skyscanner.com [Accessed 17.04.2019].

Slb.com, (2019). *About Schlumberger*. [online]. Available at: https://www.slb.com/about.aspx [Accessed 06.04.2019].

Spacey, J., (2018).*7 Types of Business Concept*. [online] Simplicable Website. Available at: https://simplicable.com/new/business-concept [Accessed 29.05.2019].

Spillar, M., (2017). *How Nissan is Harnessing Big Data to Provide Value to Customers*. [blog] HortonWorks blog. Available at: https://fr.hortonworks.com/blog/nissan-harnessing-big-data-provide-value-customers/ [Accessed 22.04.2019].

Statista.com, (n.d). *BP - Statistics & Facts*. [online]. Available at: https://www.statista.com/topics/1967/bp-plc/ [Accessed 02.05.2019].

Stevens, L., (2018). *Buying Boeing After Its Recent Death Cross*. [image]. Available at: https://seekingalpha.com/article/4230888-buying-boeing-recent-death-cross [Accessed 05.04.2019].

Streich, K., (2018). *Smart sensors for condition monitoring*. [online] Infsoft website. Available at: https://www.infsoft.com/blog-en/articleid/293/smart-sensors-for-condition-monitoring [Accessed 18.03.2019].

TechMahindra.com, (2015). *Bombardier Selects Tech Mahindra as a Supplier for the C Series Aircraft's Health Management System* [online]. Available at: https://www.techmahindra.com/media/press_releases/Bombardier-Selects-Tech-Mahindra-as-Supplier.aspx [Accessed 11.04.2019].

TelecomsBusiness.com, (2018). *Shell Selects C3 IoT as Strategic AI Software Platform*. [online]. Available at: https://telecomsbusiness.com/industries/retail/shell-selects-c3-iot-as-strategic-ai-software-platform/ [Accessed 29.04.2019].

Teradata.com, (2019).*About Teradata*. [online]. Available at: https://www.teradata.fr/ [Accessed 26.04.2019].

Tesla.com, (2019).*Model S/Tesla*. [online]. Available at: https://www.tesla.com/models [Accessed 18.04.2019].

The Agility Effect.com, (2019). *Is innovation the enemy of maintenance?* [online]. Available at: https://www.theagilityeffect.com/en/about/innovation-enemy-maintenance/ [Accessed 05. 05.2019].

Torres, C.E., (2018). *Digitalization of Predictive Maintenance*. [blog] Power-MI blog. Available at: https://power-mi.com/content/digitalization-predictive-maintenance [Accessed 16.03.2019].

Trader, T., (2014). *BMW Preempts Problems with Predictive Analytics.* [online] Datanami website. Available at: https://www.datanami.com/2014/03/12/bmw_preempts_problems_with_predictive_analytics/ [Accessed 24.04.2019].

Trejo, L., (2017). *Toyota, Hitachi collaborate for enhanced efficiency*. [online] Autonomous Vehicle Tecchnology website. Available at: https://www.autonomousvehicletech.com/articles/345-toyota-hitachi-collaborate-for-enhanced-efficiency [Accessed 27.04.2019].

Tuckwell, M., (2015). *Condition Monitoring: why now?*. [pdf] Sagentia. Available at: https://www.sagentia.com/files/2015/12/FINAL_CM_why-now_2015.pdf [Accessed 11. 03.2019].

Uptake.com, (2018). *How AI is Making Predictive Maintenance a Reality for the Industrial IoT* [blog]. Available at: https://www.uptake.com/blog/how-ai-is-making-predictive-maintenance-a-reality-for-the-industrial-iot [Accessed 19.03.2019].

Vanderpool, C., (2017). *Sensors in the IoT: Manufacturers Benefit from Condition Monitoring, Remote Data Capture, and Product Performance Improvements*. [online] ApplianceDesign website. Available at: https://www.appliancedesign.com/articles/95511-sensors-in-the-iot-manufacturers-benefit-from-condition-monitoring-remote-data-capture-and-product-performance-improvements [Accessed 18.03.2019].

Vault.com, (2018). *Chevron Corporation*. [online]. Available at: https://www.vault.com/company-profiles/oil-gas/chevron-corporation [Accessed 07.05.2019].

Ven, R., (2018). *Top Three Industrial IoT Implementation Challenges.* [online] DZone website. Available at: https://dzone.com/articles/3-iiot-industrial-internet-of-things-implementatio [Accessed 14.05.2019].

Venugopal, A., (2019). *Starbucks sets up $100 million fund to invest in food and retail startup*. [online] Reuters official website. Available at: https://www.uptake.com/blog/how-ai-is-making-predictive-maintenance-a-reality-for-the-industrial-iot [Accessed 05.05.2019].

Visiativ-industry.fr, (2019). *Four industrial revolutions*. [image]. Available at: https://www.visiativ-industry.fr/industrie-4-0/ [Accessed 25.05.2019].

Volvogroup.com, (2019). *About us* [online]. Available at: https://www.volvogroup.com/en-en/about-us.html [Accessed 25.04.2019].

VolvoTrucksGlobal.com, (2018). *Volvo Trucks introduces new monitoring services to maximize uptime.* [online]. Available at: https://www.volvotrucks.com/en-en/news/press-releases/2018/sep/pressrelease-180906.html [Accessed 26.04.2019].

Ward, S., (2018). *Business Innovation Definition*. [online] the balance small bsuiness Website. Available at: https://www.thebalancesmb.com/business-innovation-definition-2948310 [Accessed 29.05.2019].

Wells, J., (2018). *Shell drives industry transformation and innovation with Microsoft.* [online] KMworld Website. Available at: http://www.kmworld.com/Articles/News/KM-In-Practice/Shell-drives-industry-transformation-and-innovation-with-Microsoft-128332.aspx [Accessed 29.04.2019].

Wienstroth, F., (2018). *BMW Improves Quality With Data Analysis Data analysis allows for predictive maintenance and quality control*. [online] Assemblymag website. Available at: https://www.assemblymag.com/articles/94293-bmw-improves-quality-with-data-analysis [Accessed 25.04.2019].

Wilber, L., (2018). *B2B digital marketplaces bring agility and innovation to industrial markets.* [blog] Manufacturing Transformation Blog. Available at: http://www.apriso.com/blog/2018/09/b2b-digital-marketplaces-bring-agility-and-innovation-to-industrial-markets/ [Accessed 21.03.2019].

Wilkins, J., (2019). *Maintenance in the Cloud: The Benefits of Cloud Computing*. [online] RELIABLEPLANT website. Available at: https: https://www.reliableplant.com/Read/31247/maintenance-in-cloud [Accessed 19.03.2019].

Wirawanrizkika.com, (2016). *BIG DATA & DATA ANALYSIS (TESLA STUDY CASE).* [online]. Available at: https://wirawanrizkika.wordpress.com/2016/09/12/big-data-data-analysis-tesla-study-case/ [Accessed 20.04.2019].

WiseGuyReports.Com, (2019). *Aircraft Health Monitoring Systems 2019 Global Market Net Worth US$ 7.55 billion Forecast By 2026.* . [online] MarketWatch website. Available at: https://www.marketwatch.com/press-release/aircraft-health-monitoring-systems-2019-global-market-net-worth-us-755-billion-forecast-by-2026-2019-01-29 [Accessed 22.03.2019].

Zoho.com, (2019). *Business Intelligence*, *Reporting and Analytics Software*. [online]. Available at: https://www.zoho.com/analytics/ [Accessed 19.04.2019].