Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

Mohamad Al-Shami

Smart Maintenance

Master's thesis in Subsea Technology
Supervisor: Per Schjølberg
Co-supervisor: Jon Martin Fordal

June 2021

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Preface

This is a master thesis in smart maintenance at NTNU during spring semester 2021. I am pleased to collaborate with my supervisor Per Schjølberg and co-supervisor Jon Martin Fordal. It has been worked to develop a new concept about smart maintenance for master students. It aims to provide knowledge about smart maintenance and challenges it may face.

Acknowledgment

I would lovely thank all who supported and helped me to successfully complete this paper. Firstly, I am grateful to my supervisor Per Schjølberg for his unforgettable supports and guidance. As well, I would like to thank co-supervisor Jon Martin Fordal for his valuable contribution and assistance. I appreciate their collaboration, time, and efforts. Moreover, I would lovely extend my pleasure to my wife who constantly stands with and support me to work hard. Her contribution is priceless. I would thank everyone in NTNU who helped me and guide me to write this paper.

Executive Summary/ Abstract

The rapid growth in industry 4.0 globally made smart maintenance an exciting topic in recent years. Moreover, there is a need in the industry for a new concept for smart maintenance that leads to optimal outcomes. This paper provides a unique perspective of how the smart maintenance process may look like in the future and its implementation challenges. Moreover, it demonstrates tools, technologies, and solutions in which could be deployed currently in smart maintenance. As well, the work illustrates the role of artificial intelligence and machine learning in smart maintenance. It has been presented the critical role of augmented reality in smart maintenance. The paper aims to provide the readers with some insights about smart maintenance definitions, development, and its challenges and impacts.
It has been searched in and read previous and latest works regarding smart maintenance. Moreover, it has been developed a new smart maintenance concept. Furthermore, it has demonstrated two scenarios about how smart maintenance may be implemented on an actual physical asset.

It was found that smart maintenance is still in the development phase. And smart maintenance has many different definitions and challenges. It is found that the primary keys in smart maintenance are AR, IoT, CPS, and machine learning. The newly developed concept consists of four essential elements are smart fault detection system, smart prognostic system, smart inspection tools, and smart communication, and planning tools. This new concept may lead to promising outcomes and impacts on safety and costs.

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Acronym

AI	**Artificial Intelligent**
CPS	**Cyber Physical System**
AR	**Augmented Reality**
CMMS	**Computerized Maintenance Management Software**
IEEE	**“The institute of electrical and electronic engineering**
IoT	**Internet of Things**
KPI	**Kye Performance Indicator**
ML	**Machine Learning**
PM	**Predictive Maintenance**
RUL	**Remaining Useful Life**

Chapter 1

1. Introduction

Smart maintenance is an advanced solution for the maintenance industry. Since the world of industry move to fourth industry via digitalization, the smart maintenance represents the maintenance domain in this move. Smart maintenance adapts digital transmission to provide a smart and digital solution for maintenance. Smart maintenance in currently under development phase. Therefore, there are considerably interests to discover how it may lead to eco friend safer and cost-efficient operation.

There are a lot of papers and work about smart maintenance and digitalization of maintenance.

This paper aims to develop a new perspective for smart maintenance. It presents the challenges that may smart maintenance implementation may face and the proposed solution to overcome these challenges. The work demonstrates the two scenarios two illustrate how smart maintenance could be implemented on real asset. Moreover, it has been presented the drivers of smart maintenance and the impact of smart maintenance on safety and costs.

2. Objective

- Introduce smart maintenance as new maintenance concept.
- Review tools and technologies used in smart maintenance.
- Develop new perception about smart maintenance.
- Introduces smart maintenance challenges and the proposed solutions.
- Presents impact of smart maintenance on safety.
- Review the impact of smart maintenance on profit indicator.

3. Research Questions

- What is smart maintenance?
- What are smart maintenance challenges?
- How can smart maintenance affect the safety ?
- Does smart maintenance lead to big savings and broader uptime?
- What is the role of artificial intelligent in smart maintenance?

4. Approach

This study provides theoretical overview about smart maintenance. Due COVID-19 the was no direct contact with industry or companies. For that reason, there are no experiments. The approach is by reviewing and reading latest works, papers and articles and research related to maintenance.

5. Contribution

It has been developed a new perspective for smart maintenance. The new concept is associated with two scenarios to give more insights about the implementations of smart maintenance. Moreover, it has been contribute toward presenting the potential challenges and the proposed solutions.

6. Limitations

There is a large set of limitations due to COVID-19 restrictions. There is a limited access to university libraries. There are some restrictions to campus and reading room. There are restrictions to meet physically with peers, supervisors, and experts due to national recommendations. In addition, for me as father for children in kindergarten, there are extra limitations according to kindergarten availability.

7. Outline

- **Preface** : this section presents the work which was done in this project and when it has been performed.
- **Acknowledgment :** this part shows the gratitude to supervisor Per Schjølberg and co-supervisor and my family who have been supporting this work.
- **Executive summary** : This section describes the main findings of the project.
- **Table of content** : it contains list of sections and subsections titles.
- **Table of figure** : it contains list of names of figures used in this project.
- **Table of table** : it contains list of names of tables used in this work.
- **Acronym :** it contains the abbreviations.
- **Chapter 1 :** it provides objectives and contribution.
- **Chapter 2** : it provides theoretical background about maintenance. It presents definitions and explanations about maintenance in general and its types.
- **Chapter 3** : it demonstrates new technologies could be used recently in smart maintenance such as industry 4.0, IoT, CPS and big data.
- **Chapter 4** : it demonstrates the new concept of smart maintenance. Moreover, it describes challenges that it may face.
- **Chapter 5** : it presents the impact of smart maintenance on safety and cost.
- **Chapter 6 :** it presents conclusion and further work.
- **Bibliography** : it contains list of references.
- **Pre-study report :** It presents limitations of the projects and schedules of time of work. It demonstrates initial risk register and brief information about the project.

Chapter 2

2.1 Maintenance

Maintenance has vital role in our life. It intervenes in every detail in our daily life activity. We can start from our body health to organization and community we belong to. In general, maintenance can be defined as an act or process to keep things working at top and quality level. For more academic and specific definition, as given in NS-EN 13306 standard, " *The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore to, a state in which it can perform a required function*". The maintenance organizations seek to reach best maintenance solutions to meet the operational challenges. Maintenance may include, minor repairing, replacement of equipment or a part, lubricating, servicing, adjusting and modification.

Currently we globally experience a race for the technologies in most parts of our life from renewable energy, oil and gas, medical industry and so on. This technological race needs to have a development in maintenance domain as well. Despite that the companies call the maintenance "*necessary evil*", there still is a large investment in developing a new maintenance solutions and tools.

The main objectives of maintenance are:

- *Prevent deterioration of item.*
- *Reduce or avoid the downtime of operation.*
- *Increase the safety and quality of system.*
- *Reduce the costs.*

- *Increase the availability and visibility.*
- *Improve the performance of system.*
- *Inventory optimization.*
- *Extend life cycle of item.*
- *Accelerate service request process.*

The maintenance can be mainly divided into two types, corrective maintenance, and preventive maintenance according to the standard NS-EN 13306.

2.2 Corrective maintenance

Corrective maintenance is obviously a traditional form of maintenance that requires to perform maintenance once the item is failed (Wang, Deng, Wu, Wang, & Xiong, 2014). The ordinary actions in corrective maintenance are repairing or replacement. This type of maintenance mainly is used for not critical component with small consequence effects. The principle is to utilize the asset until it fails.

2.3 Preventive maintenance

Preventive maintenance means to perform maintenance actions before that fault occurrence (Mobley, 2002). There are several types of illustration of equipment behaviors, the most known one with three domains which are infant maturity , useful life and wear out (Mobley, 2002). Based on this curve, the preventive maintenance can be used as tool to plan for maintenance actions before the failure occurs. The main idea is to schedule a maintenance program based on time or age of item. The time-based maintenance and age-based maintenance are considered as traditional forms of preventive maintenance. However, the predictive maintenance is considered as developed and advanced version of preventive maintenance.

2.4 Age-based maintenance

It is a form of preventive maintenance. The idea is simply to act before failure occurrence by selecting a criterion based on the operational parameter of item. That means there is a need to execute a maintenance action i.e., oil shift each 10 km for car.

2.5 Clock-based maintenance

It is simply to perform maintenance each fixed interval of time. For instance, to oil shift for the car each 1 year, even the car and motor in good state.

2.6 Predictive maintenance (PM)

It is quite advanced maintenance method. It aims to detect the fault and predict the remaining useful life for the item based on gathered data (Mobley, 2002). It has been highly worked in this domain to develop tools and codes that may help to obtain the goal. Predictive maintenance relies on the new technologies such as internet of things, cyber physical system, big data, and data mining (Selcuk, 2017). These technologies support to connect to the machine and collect data, then process these data and gain valuable insight about the health of the machine. There is a huge focus recently on this type of maintenance in many different areas of industry (Hashemian, 2011). The predictive maintenance leads to promising outcomes (Mainnovation, 2018).

2.7 Definitions

This list of important terms is used in this project.

Asset : is a resource with economic value that an individual, corporation, or country owns or controls with the expectation that it will provide a future benefit (BARONE, 2021) (Rausand, Barros, & Hoyland, 2020).

Item: A term is used to denote any component, subsystem, or system can be considered as an entity (Rausand et al., 2020).

Quality : the totality of features and characteristics of product or service that bear on its ability to satisfy stated or implied need (ISO 8402) (Rausand et al., 2020).

Reliability : The ability of item to perform a required function, under given environmental and operational conditions and for a stated period of time (ISO 8402) (Rausand et al., 2020).

Availability : The ability of an item (under combined aspects of its reliability, maintainability, and maintenance support) to perform its required function at a stated instant of time or over a stated period of time (BS 4778) (Rausand et al., 2020).

Maintainability : the ability of an item, under stated conditions of use, to be retained in, or restored to a state in which it can perform its required function, when maintenance is performed under stated conditions and using prescribed procedures and resources (BS 4778) (Rausand et al., 2020).

Safety : freedom from conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property (MIL-STD-882D) (Rausand et al., 2020).

Chapter 3

3.1 Technologies related to smart maintenance

This chapter presents the latest and most advanced solutions, technologies, and devices in which they are key elements in smart maintenance.

3.2 Internet of things

Internet of things (IoT) is a new term refers to connect things to each other via network. The objects are mainly embedded by sensors, software and technologies that allows it to be connected to each other. IoT has direct significant impact in our daily life. It highly involves in smart manufacturing, smart cities, smart home (Wortmann & Flüchter, 2015). IoT is creating large numbers of opportunities and possibilities for a big set of novel and valuable applications that promise to improve the quality of our lives (Xia, Yang, Wang, & Vinel, 2012). Regarding maintenance field, the smart maintenance relies highly on use of IoT applications. This technology provides the maintenance developers to use these possibilities and capabilities to establish low-cost, advanced, and smart maintenance program in which leads to promising results.

3.3 Augmented Reality

There is a long work and large amount of studies to seamlessly combine real and virtual worlds (Billinghurst, Clark, & Lee, 2015). Augmented Reality (AR) is defined as a real-time direct or indirect view of a physical real-world environment that has been augmented by adding virtual computer-generated information to it (Carmigniani & Furht, 2011). It aims to help the users to see the objects or things in which cannot be seen by his eyes. Augmented Reality aims to make our life easier by supplying virtual information about surroundings and hidden objects to any indirect view of the real-world environment, such as a live video stream (Carmigniani et al., 2011). That strongly supports the user to highly interacting with the real environment. AR has a wide range of applications, starts from entertainment to education, medical and marketing (Mekni & Lemieux, 2014). AR is widely used in maintenance domain to simplify the maintenance and assembly work by visualizing the instructions and information that the technicians need to perform their job well. The main reason to utilize AR in maintenance is to save the time during performing a task. Because once the technicians use the paper documents and manuals to conduct the work, they can be fully focusing in the actual job, but they need to lose some attention to read, understand and translate the information from these manuals and paper, that leads inevitably to more time to finish the missions (Henderson & Feiner, 2007). Moreover, AR can be used as training platform in maintenance, the study shows that the team with AR solutions 25% faster than team without AR solution to perform the same maintenance task (Graziano Terenzi, 2016). Moreover, AR technology is used in smart inspection tools that helps to detect and diagnose the dysfunction in equipment (Aransyah, Rosa, & Colombo, 2020). See figure 1.

Figure 1 augmented reality for maintenance (Google)

How AR support smart maintenance

As mentioned, that smart maintenance refers to act smart during performing maintenance task. There is a strong link between smart maintenance and AR. Smart maintenance use the hardware and software from AR for instance, smart inspection tools, and smart glasses to perform maintenance task seamlessly, effectively, and accurately. These AR tools display virtually the real-time environment and objects to the maintenance crews to clearly see the parts and excellently act based on the displayed information. That causes to large time savings, enhance safety, and high-quality services. So, the augmented reality is considered as significant driver in smart maintenance. Moreover, AR support the safety of smart maintenance. Using AR leads to reduce the risk caused by human errors or human intervention in maintenance work in which may causes injures (Tatić & Tešić, 2017). In addition, when the maintainers watch stream video about how to perform maintenance, installation or assembling create a significant safe work environment, “near zero accident”. AR helps maintainers to recognize the critical information during maintenance task. Moreover, it lead to carrying out the proper procedures and making the right decision (Aransyah et al., 2020).

3.4 Computerized Maintenance Management Software (CMMS)

CMMS aims to store the information and data about all maintenance details for instance, maintenance work, spare part, historical data about the equipment (Aransyah et al., 2020). This data and information are critical elements in making decision in maintenance industry (Labib, 2004). The benefits from using CMMS can be summarized by (Labib, 2004) :

- Provide insights about the item which essential for condition-based monitoring.
- Provide important information about the spare parts and track it.
- Communication tool between the operator to report the failure and the maintainers to perform maintenance quickly.
- Store historical data that assists the planners to schedule for preventive maintenance.
- Support accountants by providing information on machines for better capital expenditure decisions.

The CMMS is not often used as a tool for data analysis and coordination. It more to be deployed as a tool for equipment data store and planning for maintenance tasks (Swanson, 1997).

3.5 Robotics

There is a long experience with the robotics inside the maintenance domain. Robotics application varies from performing assembly, pre-planned maintenance task, inspections and emergency breakdowns repairing (Parker & Draper, 1998). Robots can increase the safety of the maintenance operation, by eliminating the human being exposed to dangerous operations and materials (Paula, 1989). In addition, the robots can reduce the downtime (Paula, 1989). The main idea is to deploy the robot to perform maintenance action in very challenging and risky work environments (Hamel, 2000). That means to avoid the human to be under hazardous situations. The robots are able to support the maintenance team through physical work and cognitive work (Bragança, Costa, Castellucci, & Arezes, 2019). However, there are two options, there is Cobot or called people-focused robot and robots. The cobot can collaborate with human and assist to perform repetitive job and heavy job (Bragança et al., 2019). That what is called human-robot interaction, that became undeniable fact (Xing & Marwala, 2018). The robot can provide service by itself without human intervention, it mostly is used for critical and risky situations. Why the robotics are important in smart maintenance? Well, the role of robot in cognitive work is critical and can help in (Bragança et al., 2019):

- Support the decision-making process via visualization of potential decisions.
- Observe work process to give proposes that may improve the process.
- Offer learnings and trainings to enhance the professionals experience.
- Store data and information, that helps the crew to review once there is a need.
- Enhance the safety of maintenance operations.

3.6 Big data

"Big data is larger, more complex data sets, from various data sources. These data sets are so huge that traditional data processing software is not able to treat them. But these massive amount of data are useful to solve challenges and problems organizations wouldn't have been able to deal with before " (Oracle, 2021). The data sources can be feedback from the costumers, data from sensors, images, videos, design data, staff behavior, environmental and operational conditions and so on (Yan, Meng, Lu, & Li, 2017). It is worth to mention that big data is referred as "5V" characteristics that are velocity, volume, value, veracity, variety (Sagiroglu, Terzi, Canbay, & Colak, 2016). It is critical player in fault detection tool and fault prognostics (Yan et al., 2017). This data collected about the operational and environmental conditions, plus design data, data about equipment, data about the users can be processed and analyzed to obtain essential insights and information that are crucial for maintenance organization to professionally deal with this equipment.

3.7 Cyber Physical System

Cyber Physical Systems (CPS) are automated systems that enable connection of the operations of the physical reality with computing and communication infrastructure , for instance smart phones, smart cars (Jazdi, 2014). While (Lee, Bagheri, & Kao, 2015) defined as transformative technologies for managing interconnected systems between its physical assets and computational capabilities. The main purpose of CPS is to exchange data via what is called internet of things (Jazdi, 2014). It is worth to mention that CPS is considered as key factor in what is currently called industry 4.0(Lee et al., 2015). (Lee et al., 2015) presents the CPS architecture 5C, is smart conductivity, data-to-information conversion ,cyber level, cognition level configuration level as shown in figure 2.

The CPS is the tool that allow to maintainer remotely access to process data about required item that need maintenance. It is one of the most essential elements in advanced maintenance domain.

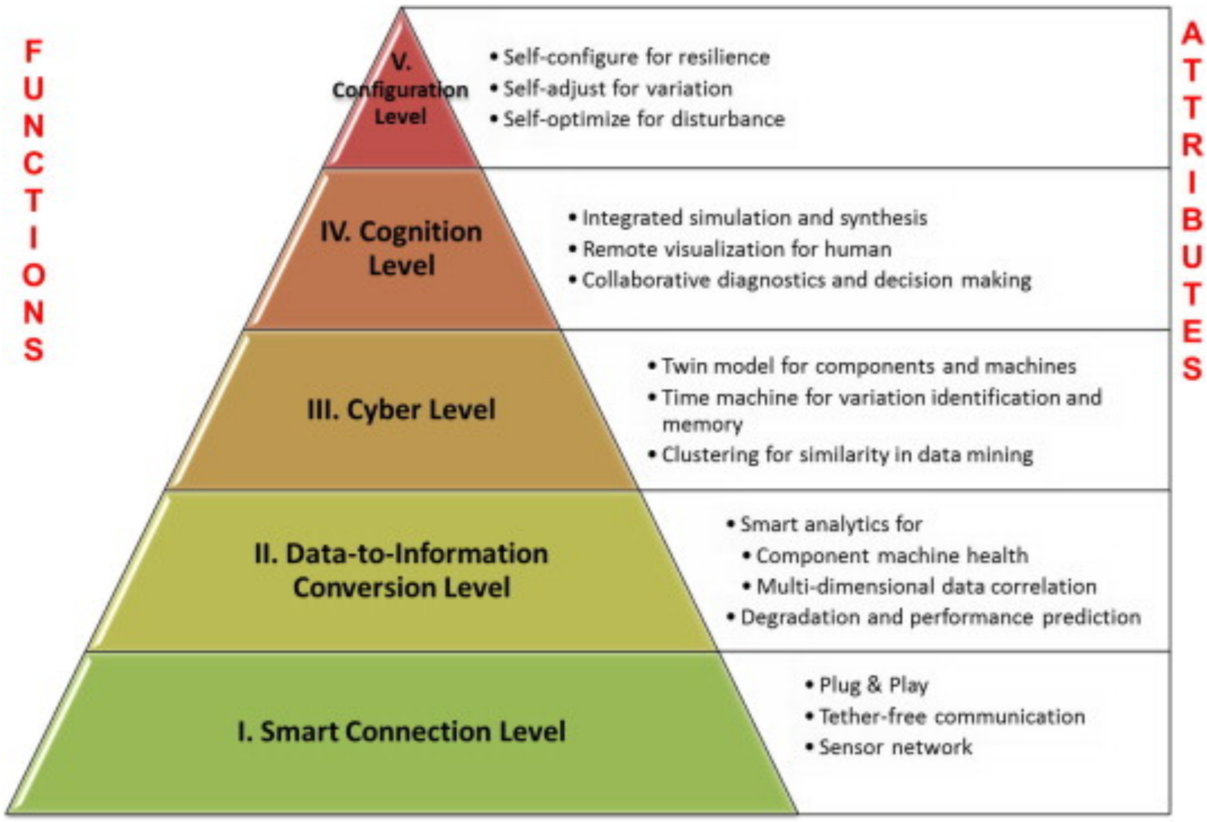

Figure 2 5C architecture of CPS (Lee et al., 2015)

3.8 Industry 4.0

Currently, there is a large number of works in what called industry 4.0. The term refers to the fourth industrial revolution. Hannover trade fair in 2011 in Germany was the start for this new term (Pfeiffer, 2017). Industry 4.0 refers smart manufacturing, smart production, digital transformation, and smart factory. There are six crucial elements in smart manufacturing. These elements are manufacturing technology and processes, materials, data, predictive engineering, sustainability and resource sharing and networking (Kusiak, 2018). In industry 4.0, the machines become fully equipped by smart sensors. They are connected to each other and to computers via internet. They are trained and learned to perform safely their functions, to detect anomalies and warn the operators. In other words, they started to manage themselves and production process without human intervention. (Kang et al., 2016) explains Industry 4.0 could be realized through cloud computing, big data, 3D printing, smart sensors, as well as CPS. (Vogel-Heuser & Hess, 2016) Presents that Cyber-Physical Systems (CPS) have major role in industry 4.0 as shown in figure 3 .

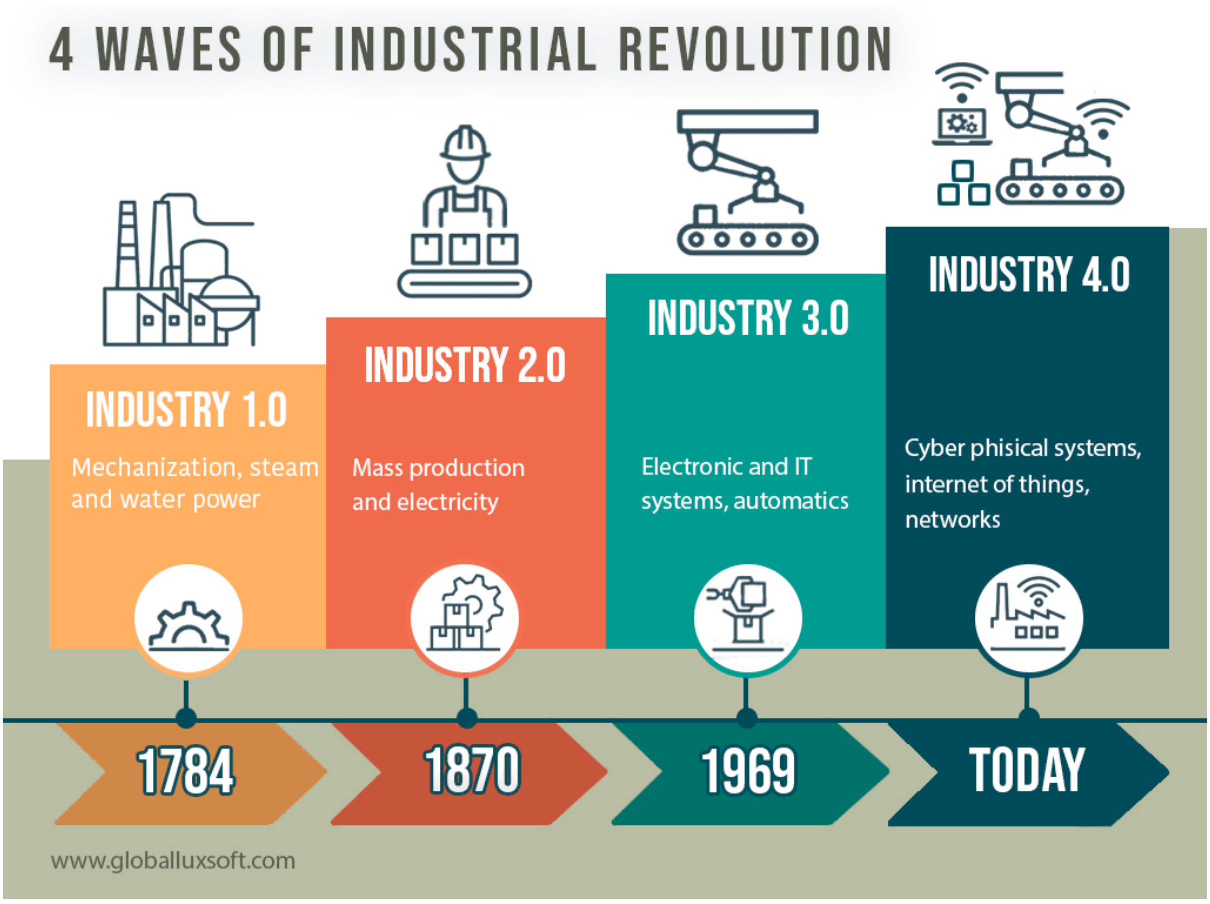

Figure 3 Industry 4.0 (Google)

3.9 Smart Sensors

“The institute of electrical and electronic engineering (IEEE) defines smart sensor as sensor that provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity. This function typically simplifies the integration of the transducer into applications in a networked environment” (Frank, 2013). Currently sensors entire our daily life for instance in smart phones, cars, doors, and kitchen. There are a large set of measurements can be sensed by sensory devices such as temperature, humidity, and pressure. Presents the development phases vary from sensor 1.0 where it was pure mechanical transducer, then moved to sensor 2.0 phase where was used electrical sensing system after that it came sensor 3.0 where the electronic sensing system became the most developed solution, finally today the sensor 4.0 or called smart sensor the most advanced technology (Schütze, Helwig, & Schneider, 2018) . Figure 4 shows more details. Smart sensing system is one of the most actuators of smart maintenance. Smart sensors provide the organizations the capabilities to monitor their asset’s health and performance continuously and remotely. The main functions of the sensory devices are monitor continuously and remotely, to timely gather data and to send this data to required destination. The accuracy, robustness, and privacy (not to be easily hacked) of the sensory devices and system can be one of the major challenges that smart maintenance may experience.

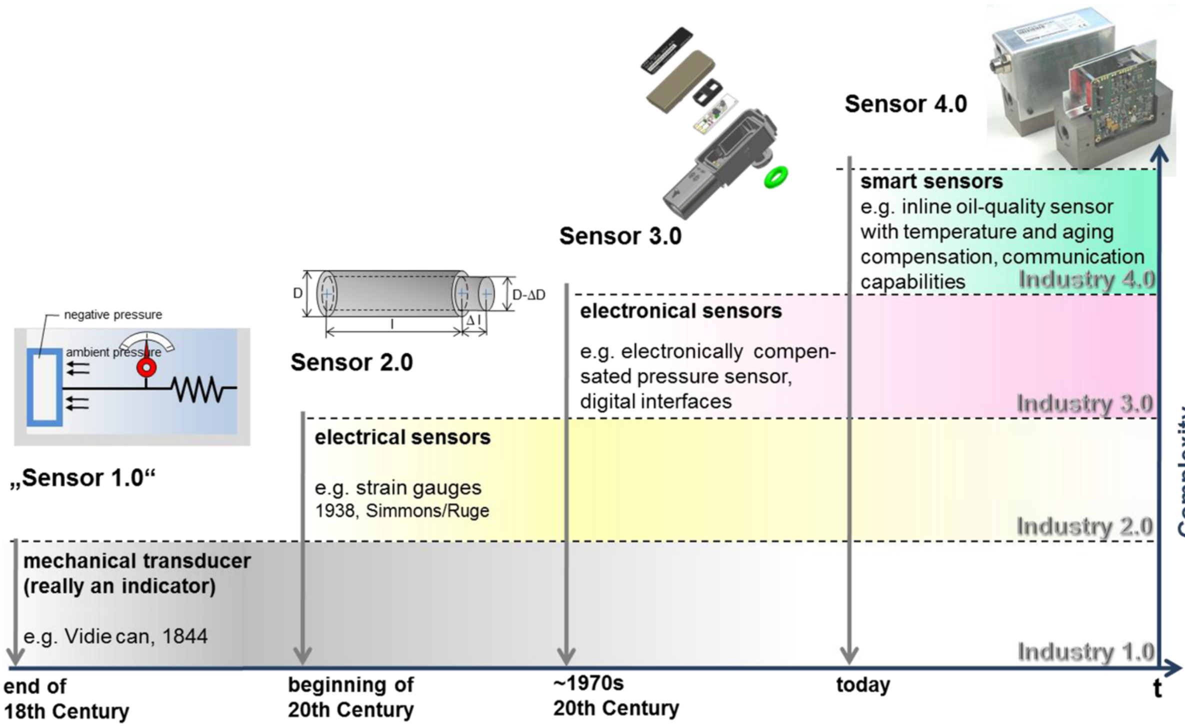

Figure 4 Sensing technology development (Schütze et al., 2018)

3.10 Artificial intelligent

Today, however, most researchers want to design automated systems that perform well in complex problem domains by any means, rather than by human-like means (Dick, 2019). The idea is to create artificial senses such as listening (auditory), feeling warm and cold, smelling, or detecting smoke, tasting- detecting abnormal concentrations, visualizing (eyesight) by using artificial intelligent AI (Russell & Norvig, 2002). AI has a wide range of applications. It has a crucial impact on generally maintenance, particularly smart maintenance (Foresti, Rossi, Magnani, Guarino Lo Bianco, & Delmonte, 2020). By input the historical data of system and data from sensors, these artificial senses can be used to simulate human senses interpretations in which help to detect anomalies and recognize the pattern of lifetime and degradation. AI simulates human intelligence to act smartly like human to provide best solutions for predictive maintenance.

3.11 Machine Learning

Machine learning is a set of algorithms that used to make predictions or decisions. It is simply to train and learn algorithms about a case then, these algorithms can support user's decision or give the user a prediction. There is a very large focus and work on machine learning development in the recent decade (Jordan & Mitchell, 2015). Machine learning can be divided to several type of learning such as supervised, unsupervised and reinforcement learning (Zhang, 2020) as demonstrates in figure 5. Machine learning is the essential tool in smart fault detection system and smart fault diagnostics system. The idea beyond ML is once user has preprocessed data set. Data can be split it into training set and validation set. Following steps are to perform machine learning process:

1. Divide the data set into training data set and learning data set
2. Train algorithm by using the training data set.
3. Then, verify model by using the validation data set.
4. Finally, test by using a test data set.
5. The previous steps should be repeated on all machine learning models.
6. Then, we select the optimal model in which provided highest accuracy and the least error.

In the maintenance domain, this selected machine learning model can represent the lifetime and degradation models for the intended asset/item. That supports operators and organizations to detect early faults and to predict the future pattern of item. For complex systems with a very large amount of information, ML provides interesting results because it works regardless physical-conceptional understanding.

- Machine Learning
  - Euclidean data learning
    - Supervised learning
    - Unsupervised learning
    - Semi-supervised learning
      - Self-training
      - Co-traing
      - Active laerning
    - Reinforcement learning → Q-learning
    - Transfer learning
      - inductive transfer learning
      - transductive transfer learning
      - Unsupervised transfer learning
      - Multitask learning
      - Self-taught transfer learning
      - domain adaptation
      - EigenTransfer
  - Non-Euclidean data learning → Graph machine learning

Figure 5 Machine learning tree (Zhang, 2020)

Chapter 4

4.1 Smart maintenance

There are several various definitions for smart maintenance. “Smart maintenance is to achieve a harmonized human robot relationship, the intelligent robotic systems should be able to mimic any naturally occurring system” (Xing & Marwala, 2018). “Smart maintenance is an organizational design for managing maintenance of manufacturing plants in environments with pervasive digital technologies” (Bokrantz, Skoogh, Berlin, Wuest, & Stahre, 2020) as shown in figure 6. It has four dimensions, data driven decision, human capital resource, internal integration, external integration. It can be defined as a tool to identify the faults and reveal the asset health status and inform the operator what it needs to be done to avoid any downtime or costly breakdowns (Fumagalli, Macchi, Colace, Rondi, & Alfieri, 2016). The aim of smart maintenance is to create a system or protocol to remotely monitor the system, equipment, or component to collect data and support the maintenance decision. Smart maintenance strongly related new technologies. It aims to connect the machine with human and technology to obtain optimal, eco-friendly, safe, and cost-effective maintenance decision. For maintenance organization, the major goal is to keep the system on top performance with the least cost and highest quality and safety. That implicitly means, to initiate maintenance action when it is only necessary with most economic and safe measures. However, there is set of challenges that meet establishing comprehensive smart maintenance program. It is not that easy to have robust smart maintenance program.

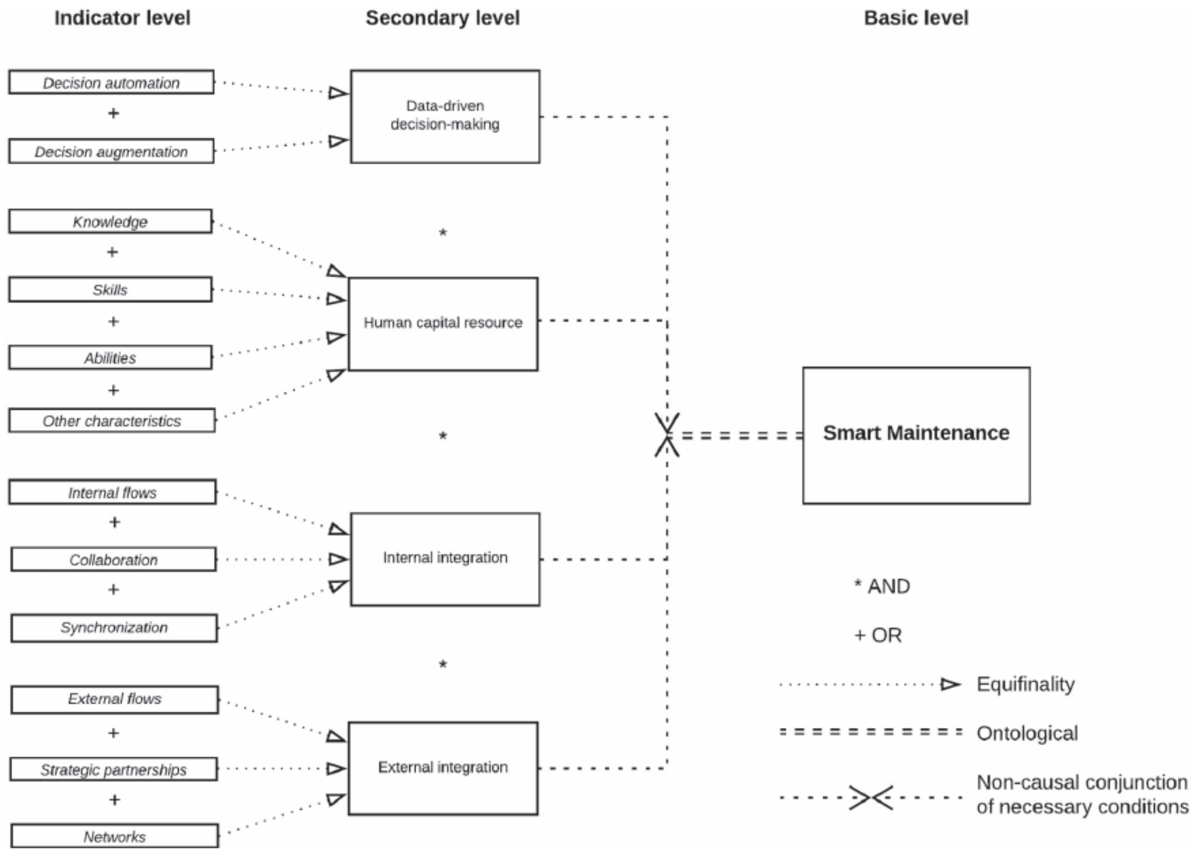

Figure 6 Smart Maintenance Structure (Bokrantz et al., 2020)

4.2 New perspective to smart maintenance

It is to perform all maintenance actions in a smart way, regardless how simple and small action is. That means we need smart fault detection system, smart prognostic system, smart inspection tools, smart communication, and planning tools. As shown in figure 7.

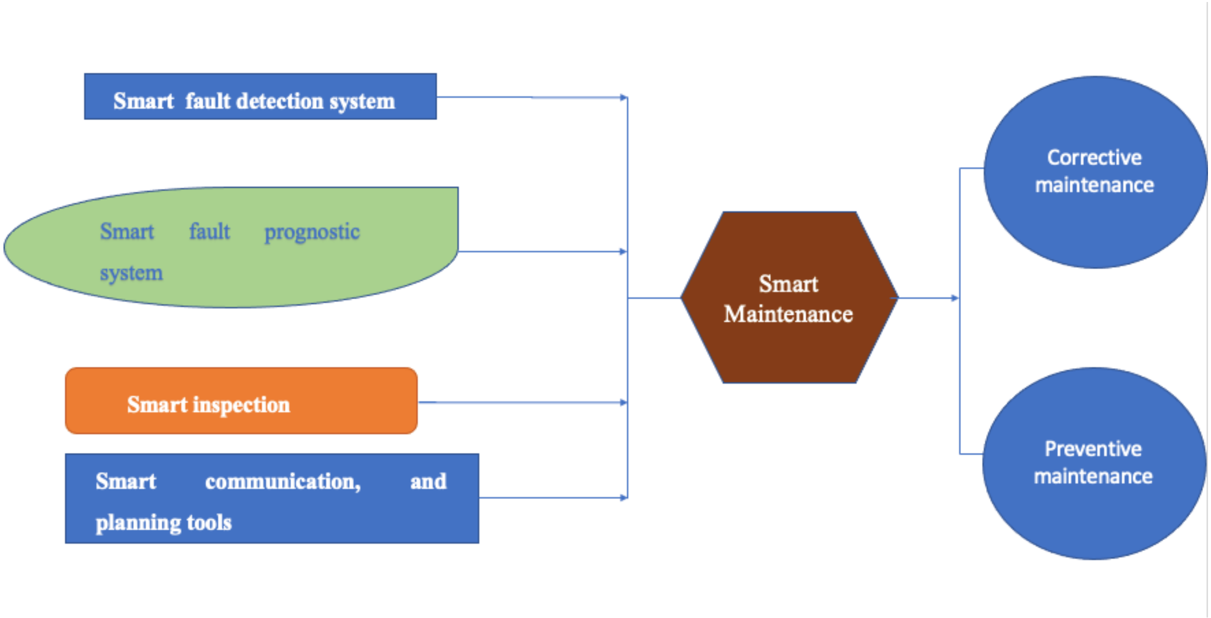

Figure 7 New Structure to smart maintenance (Author)

4.2.1 Smart fault detection system

It is simply any abnormal symptom or signal that informs the user that there is something work strangely, and it need to be closely investigated.

Since the fault is considered as the start for a large problem in machine. So, it is quite interesting to work hardly to detect or diagnose the faults in which may entail big damage in and impacts on equipment (Isermann, 2005). Smart faults detection system or called smart diagnostic system is intended to detect the faults in the item in a smart way by not only deploying set of smart devices that timely monitor the health and status of the required item, but the smart inspection tools. These smart devices collect data about the required item. This data can be sent to a unite to process it and converted to valuable and visualized insights. These insights are critical keys to the operators and technicians where these insights teach them whether there is something is going wrong, or everything is normally going as required. The rapid increase in new technologies and solutions, makes them easy and cheap to adapt in our daily life. The company quickly moves to utilize these technologies to serve the maintenance domain. Besides the smart devices that timely monitor item, the most advanced technology is used in faults detections is artificial intelligent i.e., machine learning, data analytics. To build a smart faults system, we need to smart devices or equipment equipped by set of smart sensory system plus data process system and data analytics to process the gathered data and presented as visualized insights. Fault's detection system helps the maintenance organization to plan beforehand for maintenance actions, this leads to more safety, cost effective and improved performance maintenance operation (Li & Gu, 2020).

There are several methods and techniques that helps to detect the fault (Venkatasubramanian, Rengaswamy, Kavuri, & Yin, 2003). These methods and techniques vary according to type of required item. For instance, monitor the corrosion, thickness of wall, temperature, vibration, rare voices, particles in oil and wearing out.

4.2.2 Smart fault prognostic system

There is a large set of fault prognosis definitions (Sikorska, Hodkiewicz, & Ma, 2011). (ISO 13381–1, 2004) "*simply defined the prognosis as the estimation of the Remaining Useful Life (RUL), and the estimation of the risk of subsequent development or existence of one or more faulty modes*". In other words, fault prognosis is obviously to estimate when the item will die based on data and analytics. The fault prognostic is advanced solution in maintenance domain. It is vital in maintenance industry to learn when most probably the equipment may die or be out of service. That provides the user a capability to schedule beforehand for next maintenance action, reserve spare part beforehand, save time in maintenance task performing, enhance the production and increase the safety of the operations. The most important question is how to predict or estimate when probably the item may die?

Well, simply based on data gathered about the item's health, operational condition, and status, it is applicable to process this data by using artificial intelligent tools such as machine learning and artificial neural networks to make a prediction. Based on gathered data, these computing systems can highly help to give a prediction about the remaining useful life for required item. However, there is still some challenges regarding the complexity of mathematical models and the uncertainty about the results. But recently there is an enormous numbers of research regarding developing this model to obtain best models that lead to more accurate and better quality results (Hassoun, 1995).

4.2.3 Smart inspection

Inspection is periodic maintenance action. Planning for inspections is a critical key in maintenance industry. The frequent inspection program, leads to more production stops and downtime, entails to unnecessary costs. While, the low number of inspections may lead to very bad and undesired consequences such large accidents, fatalities, huge economic loss due to prolong production stop. But, how to plan an optimal inspection program with effective and cost-efficient outcomes? Well, by utilizing data collected from the item, and analyzing this data, we are able successfully scheduling an optimal and smart inspection program.

During inspection session, the inspector observes the health and status of the required item. These observations are used to analyze the condition of item. Preforming inspection, the inspector uses tools to observe the item condition. These tools start from the eyes of the inspector and ends to smart wearable devices. The traditional and old tool is the human senses, sight, hearing, touch, smell, and taste. However, over the time these tools developed and were converted to digital and smart devices. These devices have the same function of the human's ones but, it more advanced. It can observe and detect more accurately and can store data. Examples on smart devices used in smart inspection can be camera, smart glass, and tablet. There are new technologies such as Augmented Reality used in these devices. It provides capabilities to display the instruction and standards about how to perform inspections. It creates an interesting communication channel between inspector and item. And lead to better inspector understanding about the item.

The smart inspection is important player in smart maintenance. Because deploying these smart devices leads to less-time to perform the inspection, more accurate data, and information about item. And there is possibility to having a remote inspection by using such smart devices. And this leads to safer and more cost-efficient inspection operation.

4.2.4 Smart communication, and planning tools

Since smart manufacturing requires deploying new technologies and complex systems, that generated persistent need for having a fully trained and skillful workers to perform maintenance work on these complex machines and systems. In addition, it requires a clear and direct communication between the onsite worker and remote specialist to carry out the task quickly, safely and cost efficiently. Due to bad communication between the onsite worker and remote-specialist, Computerized Maintenance Management Software (CMMS) showed a drawback on establishing a clear procedure in rectifying the unexpected breakdown (Aransyah et al., 2020). To solve this challenge, we need to adapt new technology that can connect the onsite worker with specialist in same time with the machine. Augmented Reality (AR) technology can provide this solution. There are several AR solutions in maintenance industry such as smart glass, that allows the onsite worker to be connected with specialist and machine to perform the complex work in very simple and accurate way. These solutions additionally can stream video to onsite worker about how to perform the job and what the instructions to follow and what the tools he/she may need to complete the job successfully. This good communication capability and digital instructions demonstrations leads firstly to increase the safety to highest levels, secondly to possibility to reduce the number of onsite workers and resources (Wójcicki, 2014).

The most advanced solution is the integration between CMMS and AR. This solution provides untrained operators to diagnose and safely perform some maintenance job (Aransyah et al., 2020). In addition, this combination can lead to better and smart planning for maintenance tasks and actions. Hence, smart maintenance needs to utilize this CMMS-AR integration solution to enhance the safety and profit performance element of production operation.

4.3 Smart maintenance implementation

In this section, we are going to build initial smart maintenance system from different perspectives. We are going to establish two scenarios corresponding to real life cases.

4.3.1 Old assets scenario

In this scenario, we assume that a company has an old critical asset in their production systems. These old items have presumedly no sensors connected via internet and not able to send any data about its status. But there is a very traditional periodic inspection program performed by either visually or using old inspection tool. That is done by an inspector based on professional experience and knowledge.

The important questions are :

Is it economic to adapt smart maintenance program to maintenance this asset?

If yes. How could we establish smart maintenance program fit for this case?

The answer for the first question depends on the remaining useful life of this old asset and about the costs resulting from adaption this new solution. These calculations can be conducted within the company to take decision.

For answering the second question, that requires a full understanding on the situation. Since the asset is not equipped by sensors and not connect via internet to monitor, so we have two ways:

- **First alternative** is to use set of smart sensors and cameras in a way the company can continuously receive data and monitor the asset. And company need to establish a database and data processing system by using artificial system. This solution provides the users a capability to reduce resources to perform costly and unnecessary periodic inspections. Moreover, this solution enhances the safety of operation by reducing numbers of human exposures to the danger. In addition, this solution provides professional tool to gather real-time data about the asset in which is essential for maintenance planning and scheduling. That may lead to extend the life of asset and save time for reserving spar parts. This solution is occupied by some costs. This solution requires to buy some sensors, cameras, solutions to connect asset via internet. However, these costs are going to be lower and lower due to large availability of this solution in market.

- **Second alternative** is to adapt augmented reality based smart inspection tools plus database and data processing system. This solution provides the company possibility that specialist can remotely watch and observe during inspection session the asset. In this way, the inspector equipped with AR-tool is continuously the specialist that can provide the right and fit instructions to perform successfully and quickly the task. This alternative, create a clear communication between the asset, inspector, and specialist, that lead to save time, better maintenance performance, gather and store data about asset in which is essential factor in maintenance planning. However, this solution is occupied with some extra costs causes of AR tool, AR technology and more training for inspectors to use this technology.

4.3.2 World-class assets scenario

We can define world-class asset as an asset is fully equipped with set of sensors that give some warnings that there is something abnormally going on. In addition, the asset has virtual version. In this scenario, we assume that there a company that have a critical world-class asset is adapting artificial intelligent, AR technology and tools. Smart maintenance can be considered as perfect solution for such high-class asset. If the something goes wrong, the asset should gather and send data to a computer-powered system to process and analyze the data and provide the valuable insights. Based on this insight, the right and suit maintenance work order with clear and comprehensive instructions and information is automatically initiated. This information and instruction inform the maintenance crew what is exactly the problem and how quickly and efficiently to fix it. Then, maintenance crew can rapidly and professionally follow the instruction that can be video streamed via AR tools. In this scenario company can adapt just-in-time maintenance action and leave periodic inspection maintenance and occupied costs. Moreover, in this scenario the maintenance team has a strong understanding about the asset condition, and excellent communication with asset and the specialist in case there is something not clear.

4.4 Smart maintenance challenges

Smart maintenance is currently in development phase. It still in research and study papers. So, this solution has some challenges that hinder its progression. This section presents some of challenges that may face organization that intends to change their maintenance policy to new and advanced maintenance.

- Data collection, uncertainty, complexity, and privacy.
- Digital transformation of long and wised experiences of professionals.
- Old machines, and assets.

- Trust on human observations and data collections.

4.4.1 Data challenges

The current time and the future are depending highly on data. The idea is to understand the condition of item and circumstances around it by gathering data. The data need to be not only about the health and specifics of the item, but about the operational parameters, surrounding conditions, operators. In short words, data should include every detail about operating the item. The more data we have the better and clearer understanding we have about our asset. That gives the organizations the power to select the best decision on right time. However, to obtain such comprehensive and valuable database, is required a complicated system and software. That faces the privacy, complexity, and uncertainty challenges. For instance, if the operators share their experiences, challenges, information about item that leads to very big picture about the item from different operators that provide easier way to predict any issue it might happen in future, but it still hard to reach such collaborations due to privacies and policies of companies. Regarding uncertainty of data, human can trust completely on technologies and devices, because there is still some uncertainty which may come from mathematical modelling and error.

The proposed solution for these challenges is to build a safe data system in which the operating companies and manufactures can share their experiences and data about an item. This data system should be safe regarding to data privacy. But in same time all companies who own this item have access to all saved data and information. In this way, organization can share safely their data, and benefit from shared data from the other's experiences without risk to breach privacy and security of companies. Regarding the complexity of data and uncertainty, there is a need for more reliable and accurate mathematical models that simulate the real time conditions.

4.4.2 Digital transformation challenges

Digitalization refers to the structuring of many and diverse domains of social life around digital communication and media infrastructures (Brennen & Kreiss, 2016). It is about adapting changes to create a value by utilizing new technologies. In maintenance the digitalization means to obtain a model that help to predict remaining useful life for a system and to calculate and estimate profit loss indicator (Rødseth, Schjølberg, & Marhaug, 2017). In addition, it means how to convert experiences and solutions of old smart professionals to digital solutions in a way the organizations can easily and safely utilize these experiences to solve the challenges they meet. The idea is converting the way the operator, or the technician think and consider once the machine starts to deviate from the top performance to mathematical model in which can simulate the real time case and gives the best results and solutions. For instance, artificial intelligent learns machine to build it understanding based on purely mathematical model without any physic understanding or considerations to predict what may happen in future. The challenge is to how extend organizations can trust these models and these results.

The proposed solution is building a reliable dynamic and physics-based models that simulate the human thinking ways. That helps to keep trucking every deviation or abnormality during the operation. In this way, the organizations can be updated continuously. *Imagine that there is constantly a specialist monitoring the system*. The ***specialist*** could be a software or model that is available and updated continuously, while ***monitoring*** could be set of devices and technologies that collect precisely and continuously data.

4.4.3 Trust on human observations and data collections

Inspection is a large part of maintenance domain. This part depends strongly on human visual observations and smart measuring devices. The inspection is a maintenance action to verify that item conform the requirements, standards and rules (Kurniati, Yeh, & Lin, 2015). The inspections vary depending on type of item and system i.e. typical measures are thickness, corrosion, and wear (Ghobadi, 2017). There are two challenges related human intervention in inspections. The first is the skills of operators to use the new technologies. The second is to estimate human error regarding to visually measuring and recording information. Studies and researches show that human error responsible for 80% of industrial accidents, 20-50% of all equipment failures, 50% of pilot accidents and 20-70% of all system failures at nuclear power plants (Lindblad, 2015).

The proposed solution is to provide the crew and professionals the latest leaning about the devices. It needs to offer the crews periodic updated courses and training to enhance their competencies and skills (Senders & Moray, 2020).

4.4.4 Old machines and assets

There is currently a remarkable move to automation and smart manufacturing. However, there still a tremendous number of old assets, machines, and systems that have not many technologies and sensors in many various industries. At the same time, these assets still available and run in a well and accepted way. As well, it needs periodic maintenance to stay at top performance. These old assets need to be included in the smart maintenance program. That create a challenge to perfectly monitor it. The proposed solution could be for instance, to modify this asset by a set of sensors to help to provide required data. It could be by using the historical recorded data to by supplied to a software.

Chapter 5

5.1 Smart maintenance and safety

The Merriam-Webster Dictionary describes safety as "the condition of being safe from undergoing or causing hurt, injury, or loss". In industry field, safety is a result of interactions between management, worker, and equipment (Raouf, 2004). It is an essential element to keep the staff, assets, and environment in a safe stat during any work or operation. Safety must be achieved by applying the technical actions. Maintenance and modification is significant element in safety management (Hale, 2003).

There are several papers and research show that the maintenance plays an important role in safety of the operation. In old time, the safety and maintenance were not considered as related highly aspects to each other (Duffuaa, Raouf, & Campbell, 1999). However, there is a big awareness of the relationship between the safety and maintenance currently. The integration between maintenance and safety activities outlets to promising results and value addition (Raouf, 2004).

Smart maintenance as new concept provides an interesting information about the item's health status that leads to avoid huge problems (Fumagalli et al., 2016). These could cause a severe consequence on people. If maintenance is performed incorrectly or not on right time or there was a bad communication between maintenance team and operation team, that must have direct significant effects on safety. Statistics shows that over 40 % of serious accidents were maintenance linked (Pintelon & Muchiri, 2009).

How can smart maintenance enhance the safety?

By detecting the faults and revealing the health status of item and providing the most suitable and precise maintenance actions cause a significant reduction for exposing the item to dangers. That leads to support the safety of the item and the operation.

Smart maintenance can create advanced platform for establish communication channel between all staffs working on items and systems. It additionally can create communication between machine and staff.
These smart communication leads to improve the safety in the operation and safety of the item. The better and comprehensive information the operators and maintenance team receive from the machine, the safer and higher quality production can be obtained. Adaption smart maintenance results in precise and clear instructions, easy access to information, better communications in which entails to higher safety and quality of item and operations. In addition, smart maintenance displays simply and professionally standards and rules in a way it easy and simple to review and to follow. This inevitably will reduce human error, mistakes and risk comes from them. And it absolutely guides to improve safe work environment, operation, and equipment.

5.2 Smart maintenance and profit loss indicator

Profit loss indicator (PLI) includes performance loss, availability loss and quality loss (Rødseth, Skarlo, & Schjølberg, 2015). It measures the performance of operation and item. PLI presents an important element in maintenance management. Maintenance managers work hardly to improve the PLI for their operations and system. PLI consider all type of losses, (Tsarouhas, 2019):

- Machine failure/stop/break down.
- Waiting for performing an action.
- Loss due to adjustments and modifications.
- Rework or called re do same action.
- Loss due to reducing the speed of work.
- Loss performance due to minor stoppage

These allow the maintenance managers to measure the performance of operations and item. Where the performance can be defined by four dimensions (De Toni & Tonchia, 2001)

- Cost/productivity
- Time
- Flexibility

- Quality

(Lundgren, Bokrantz, & Skoogh, 2020) summed up that the effect of smart maintenance can be measured by profit indicators. It is anticipated that smart maintenance will leads to promising results and outcomes regarding saving costs, enhancing safety, and protecting the environment. The use of smart maintenance techniques and tools such as smart glasses in maintenance work, will obviously entail to improved performance in maintenance crew. That consequences to higher profit indicator. The smart solutions that display the instructions, rules, standards, and 3D drawings helps the maintainers to obtain cost-effective maintenance actions and experience in which will leads to less down-time , improved productivity, better and high-quality performance.

5.3 Self-maintenance techniques

There is a huge work on what is called the promising future maintenance as self-maintenance. It is simply that machine make some maintenance work by itself or by ordering maintenance work order to a close maintenance robotic. The main idea to move to pure machine phase without any human intervention. This type of maintenance is still as thoughts, ideas and papers. The purpose behinds that are to reach zero human injuries and less costs operations and better environmental conditions. There is a good example on this type of maintenance in unmanned offshore platform. The main idea to reduce the human visits to platform to reduce costs and increase the safety. Smart maintenance could be the basis for self-maintenance concept.

Chapter 6

6.1 Conclusion

Smart maintenance is still under development stage. There are much work and research go into this field. Smart maintenance has many different definitions. However, this paper presented a new concept and view for smart maintenance with four dimensions. It has been found that smart maintenance consists of a smart fault detection system, smart prognostic system, smart inspection tools, smart communication, and planning tools. Moreover, it has been found that there are several challenges that face the implementation of smart maintenance. It is concluded that AR, IoT, CPS, sensors, and new technologies are the essential keys for smart maintenance.

It has been presented two scenarios to explain how the new smart maintenance could be implemented. The scenarios give explanations and demonstrations.

Finally, it is found that promising smart maintenance has a direct impact on safety and cost for safe operations. It is found there is a significant effect on profit indicator. It has been presented shortly the latest topic in future maintenance which called self-maintenance as a good solution for reducing human intervention to enhance safety and reduce the costs.

6.2 Further work

- Investigate the challenges that meet smart maintenance implementation.
- Investigate the link between smart maintenance and self-maintenance.
- Implement new concept of smart maintenance on real asset.
- Introduce new smart maintenance strategy.

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Pre-study Report

Master Thesis

Smart Maintenance

Mohamad Alshami

10.02.2021

Supervisor Per Schjølberg

Department of Mechanical and Industrial Engineering

Preface

This pre study report aims to give a project overview. The master thesis mainly will be an opportunity to highlight or solve a challenge face the industry. This pre study provide the tool to manage and control the time during the semester work. It should be followed to submit a best solution in collaboration with department of mechanical and industrial engineering.

I would lovely to extend my pleasure to everyone contribute toward this work. Particularly to the supervisor Per Schjølberg and the assistant Jøn Martin Fordal for their support and help to perform a best work. Moreover, I would thank my family for their unforgettable support to complete this work.

Mohamad Al-Shami

Trondheim- 12.02.2021

Introduction

Smart maintenance is an exciting topic to develop. There is a huge attention in the last decade toward smart maintenance. This paper presents the role of smart maintenance in safety and environment. In addition, the paper demonstrates how may smart maintenance lead to large savings in the operations and more uptime.

Project description

As a subsea technology master student at Norwegian University for Science and Technology (NTNU), it is needed to perform a master thesis which counts 30 study point. During this semester, the student has no need to take any course, but it should use the whole time to write the master thesis. The student should be fully dedicated in collaborating and discussing to solve the challenge and produce best solutions. Following to discussion with supervisor, I found that smart maintenance is a quite interesting topic. So, the project may introduce the various aspects may smart maintenance lead to. These aspects vary from safety to costs to environment. The project shall highlight the role of artificial intelligent for predictive analytics as an advanced tool in smart maintenance.

The project for the most part is conducted by Mohamad Al-Shami as a student in subsea technology- maintenance and operation major.

Project aim

This work aims essentially to find out how may smart maintenance can impact the safety and environment to provide reasonable solutions for challenges by reading set of articles and previous works. By collaboration with supervisor the project will be provided by practical data and information.

Actors

There are several main players support and provides the tools and data to perform this project.

Norwegian University for Science and Technology

The NTNU is a large university with an international focus. It supports over 40000 students, and 397 doctoral degree. It professionally provides an exciting and helpful assist and supervision to the student and professionals to guide them to professional life with best methods and technologies.

Project management

The work will follow a pre-stated schedule of time. This schedule will be divided generally according to the workload. Mostly, there is 40 work hours each week. These will be distributed among reading articles, previous papers, and discussing with the supervisor. Appendix 1 demonstrates time scheduling of the project.

Project arrangement

During the project time, there will be several meetings and discussion sessions with supervisor and experts. We will discuss about the progress in the project and the guidance. The meetings most probably will be held online to obtain the guidance and data.

Risk management

There is no risk to conduct the task. However, there some factors may affect the project progress. This will be introduced in the ***Table 1***.

Index	Description	Cause	Consequence	Initial risk	Recommendations	Residual risk
1	Limited access to obtain the resources	COVID-19 Restrictions	Low quality	Medium	Following the NTNU procedures	Low
2	Lack of discussion	Bad	Low quality	Low/ Medium	Building a good time schedule	Low

Table 1 Initial Risk Register

Limitation

There may have some limitation during the project work due to COVID-19 restrictions. These is regarding time, available data, resources and connection with the company.

Time

The spring semester starts in 15.01.2021 and ends in 10.06.2021. In the submission time there will be exam time, so it may require more space to deliver a good work. Due to corona crisis may lead to need to extend the deadline.

Resources

It is quite known that NTNU has an extensive access for a significant libraries, books, papers and researches. But, due to tough time we experience du to COVID 19, there may be a limited access to the physical library and sources.

Communication

It could be a limited communication due to strict measurements according to public health rules. Thus, there may be a limited access to the companies, university, library and industry.

Reference

There will be several references depending on the project requirements. There are a huge amount of previous works, paper and research. The articles in internet is references as well.

Appendix 1

Project Overview Statement		
Project title : Smart Maintenance		
Responsible : Mohamad Al-Shami	Strat date : 15.01.2021	Submission : 10.06.2021
Supervisor : Per Schjølberg	NTNU	Company :

Objectives :	Duration
Writing abstract, litterateur and introduction	5 weeks / 200 hrs
Data collection, communication, search	5 weeks /200 hrs
Writing methodology, descriptions, and solutions	5 weeks /200 hrs
Conclusion, results, further works, submission	5 weeks /200 hrs

Table 2 Project Overview Statement

Writing abstract, litterateur and introduction		
Project title : Smart Maintenance		
Responsible : Mohamad Al-Shami	Strat date : 15.01.2021	Submission : 10.06.2021
Supervisor : Per Schjølberg	NTNU	Company :

Objectives :	Duration

Read and search for relevant paper	2,5 week / 100 hrs
Write review literature and introduction	2,5 week /100 hrs

Table 3 Writing abstract, litterateur and introduction

Writing project description		
Project title : Smart Maintenance		
Responsible : Mohamad Al-Shami	Strat date : 15.01.2021	Submission : 10.06.2021
Supervisor : Per Schjølberg	NTNU	Company :
Objectives :	Duration	
Work on project and discussions with experts	5 weeks / 200 hrs	
Data collection and write the project	5 weeks /200 hrs	

Table 4 Writing project description

Writing results and conclusion		
Project title : Smart Maintenance		
Responsible : Mohamad Al-Shami	Strat date : 15.01.2021	Submission : 10.06.2021
Supervisor : Per Schjølberg	NTNU	Company :
Objectives :	Duration	
Writing a conclusion according to data	2 weeks / 80 hrs	
Review the work	0.5 week /20 hrs	

Table 5 Writing results and conclusion

Writing references		
Project title : Smart Maintenance		
Responsible : Mohamad Al-Shami	Strat date : 15.01.2021	Submission : 10.06.2021
Supervisor : Per Schjølberg	NTNU	Company :
Objectives :	Duration	
Inserting the used references and citations.	2.5 week / 100 hrs	

Table 6 Writing references

Thank You

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