POLITECNICO DI TORINO

Corso di Laurea Magistrale

in Mechanical Engineering

Tesi di Laurea Magistrale

Industry 4.0 and maintenance and safety

Relatore:
DEMICHELA MICAELA

Candidato:
LYU GAO

Anno Accademico: 2020/2021

Abstract

Maintenance plays a significant role in the modern manufacturing system, it is to keep and preserve machines, equipment, and facilities in a normal condition. Good maintenance work can make the company have the ability to minimize downtime, improve product quality, and reduce production costs. Meanwhile, maintenance activity is a high risk work, because maintenance work always carried out in an environment that maintenance operator will face different kinds of hazards, and compare to other areas in the industry, maintenance does not belong to high automation level work, most maintenane works can not be finished by using robots, so safety is a critical issue during maintenance work.

This thesis analyzes the safety problems and risks during maintenance work. Maintenance operations are exposed to all the hazards present in a more environment toghter with those hazards specific for their activities. And then, thanks to Industry 4.0 bring some innovation technologies, Industry Internet of things, Big Data, Cloud computing, Augmented reality, Virtual Reality, Simulation, etc. Based on the background of Industry 4.0, predictive maintenance provides a real-time condition monitoring method strongly that relies on the Internet of things and sensor technology. Predictive maintenance can help maintenance wrokers know the real condition of machine parts, according to the real condition information, maintenance workers can quickly find the broken parts, reducing the risk of can not find broken roots. Predictive maintenance can provide an estimation of failure to maintenance workers, helping them to schedule their maintenance activities.

Augmented Reality (AR) technology has the ability that can combine virtual information with the real world. It can integrate some other technologies, such as

three-dimensional modeling, real-time tracking, and sensor technology. Visualizing the information, such as text or image, and then it is used in the real world, in order to realize the "Augmentation" of the real world. An adaptive maintenance support system based on Augmented Reality is introduced, this system can provide useful information and necessary support to the maintenance worker, helping them to solve difficult problems during the maintenance process. Meanwhile, according to the knowledge and actual requirements of the maintenance workers, different combination of information will be sent to the workers, making sure that the maintenance workers can get appropriate information. The system can help the maintenance workers to check their maintenance operations finished corretly or not before performing the next maintenane steps. A remote-assisted maintenance system based on the Augmented Reality can be used to build a relationship between the maintenance workers and experts. The maintenance workers can complete the maintenance tasks safely with the knowledge from experts. Before perfoming real maintenance activities, the maintenance workers can be trained by using Virtual Reality. The maintenance workers are allowed to perfrom maintenance operations as usual in a virtual environment, helping maintenance workers more familiar their operations, reducing the risk of finishing maintenance operations incorrecrly.

In thesis i have identified in the literature several solutions pertaining to the Industry 4.0 domain and i have discussed them both in terms of enhancing maintenance operations and of enhancing safety.

【 Keywords】

Maintenance, Safety, Industry 4.0, Internet of Things, Augmented reality (AR)
Predictive maintenance, Real-time Condition Monitoring, Sensor technology,
Maintenance support system, Remote-assistance, Virtual Reality training

Table of contents

1 Introduction

From the the First Industrial Revolution to the Fourth Industrial Revolution, maintenance methods have changed a lot, experiencing from reactive maintenance to predictive maintenance. But safety and health problems are still critical nowadays during maintenance activities, by studying different types of maintenance methods, methods based on Industrial 4.0 technologies are most useful ways to increase the safety during maintenance. Some Industrial 4.0 technologies such as Industry Internet of things(IOT), Big Data, Cloud computing, Augmented reality (AR), Virtual Reality (VR), etc, these technologies can be acted as powerful tools and give support to maintenance wokers when carrying out their maintenance operations. There is an agency called Advanced Technology Services [1], presenting information about the situation of maintenance today, it is easy to find that most participants need to improve safety during maintenance, and there are a lagre number of participants believe that advanced technologies can bring benefits to their maintenance work.

Then a variety of safety problems during maintenance activities are analyzed, such as physical hazards, chemical hazards, biological hazards, psychosocial hazards. These four types of hazards are most common hazards for maintenance workers [2]. By studying hazards during maintenance process, the bad effects and disorders result from hazards can be known.

Thanks to industrial 4.0 which means the fourth industrial revolution in manufacturing industry bring some innovation technologies to decrease the bad effects on maintenance workers safety and health. Concept of maintenance reffered to Industry 4.0 is based on following technologies:

• Big Data: Data collected and analyzed means that the equipment can generate a large variety of time series at a high speed. Data come from machine need to be collected and analyzed at real time. The real time machine condition data can help maintenance workers know the work condition of machine, by using the condition data, the broken parts can be easily find, reducing the risk of maintenance workers can no find the broken parts.

• Cloud Computing: The machine condition information will be stored on the cloud, and only when the information are required the the data will be downloaded. This can make devices such as the smartphone or tablet, which will be used by the maintenance workers have no memory problems, also do not need to often clean the memory. When enough machine condition data stored in the cloud, the historical work condition of machine can be known, by studying the historical work condition of machine can help maintenance workers better understand the machine. Meanwhile, Machine Learning based on enough machine condition data can be used to predict the next failure, this can help maintenance workers to schedule their maintenance activities, reducing night work or weekend work, decreasing the risk of maintenance workers exposed in the psychosocial hazards.

• The industrial internet of things: The internet of things has the ability to interconnect the machines or equipments, a variety of devices, different kinds of sensors. This is the basic element in Industry 4.0 domain, many Industry 4.0 solutions to increase the safety of maintenance all need it, such as predictive mainteannce, remote-assisted method. Another important application for the internet of things is to connect the cloud, it is convenient for maintenance workers to find required

information quickly by using a smartphone or tablet, such as solutions for maintenance problems, helping maintenance workers to carry out maintenance operations correctly and safely.

• Augmented reality: Augmented Reality has the ability to make the real working environment can be augmented by visualizing the information. During maintenance process, augmented useful information and guides will be provided to the maintenance workers, helping them to perform operations correctly. It also can provide remote assistance from experts, helping maintenance workers solve maintenance problems with knowledge from experts.

• Virtual Reality: Virtual Reality training can provide a virtual maintenance space that similar to the real maintenance space, maintenance workers can perform maintenance operations as usual in the virtual maintenance space. So maintenance worekers will better understand and familiar their operations that they will perform and maintenance situation, decreasing the risk of maintennce workers perform a wrong operations during maintenance process.

Some Industry 4.0 solutions to increase the safety of maintenance can be develploed based on these techologies.

Based on the industrial internet of things, cloud, big data and sensor technology, real time monitoring become possible. Predictive maintenance performed on electrical motors is introduced [102]. The vibration of electrical motors is detected, the real time vibration information can be known. According to the real time vibration data, maintenance workers can know if the motors in a normal work condition or not. The vibration data will be stored in the cloud, so the historical measurement of vibration data can be achieved, some vibration peaks can be found at certain frequency, this means the motors work in a abnormal condition. Such vibration data can be labelled with the explanations, if next time have strong vibration in the similar frequency, maintenance workers can quickly locate the broken parts, decreasing the risk of can not find the broken parts. Predictive maintenance also can estimate the next failure, this can help maintenance workers schedule maintenance activities. Avoiding night work, weekend work, and emergenct work, reducing the psychosocial stress of maintenance workers, decreasing the risk of maintenance workers exposed in the psychosocial hazards. On the other hand, comparing to preventive maintenance, predictive maintenance only need to perform maintenance operations before broken, reducing the maintenance times, decreasing the risk of maintenance workers exposed in hazardous maintenance environment.

Augmented reality technology is used to offer helpful information in a lot of different industrial maintenance applications. An adaptive maintenance support system based on augmented reality by using wrist position is described [103]. During maintenance process, a combination of augmented information will be provided to maintenance workers, helping maintenance workers to solve difficult problems efficiently during maintenance process and making sure maintenance operations performed correctly and safely. The real time wrist position of maintenance workers can be tracked, and right wrist position during maintenance operations will be set, comparing the real time wrist position with the right postion and operations duration, if maintenance operations performed correctly or not can be known. This can help maintenance workers to check their maintenance operations, preventing maintenance workers continue to perform next maintenance steps after finishing a wrong operations. There are 4 augmentation level, each level can provide different augmented information, according to the knowledge and requirements of maintenance

workers, suitable augmented information can be provided to maintenance workers, decreasing the risk of maintenance workers perform incorrect operation due to inappropriate support information. When maintenance workers finish the maintenance step, the feedback will also offered to a maintenance worker before next step by using the image based detection mudule to check the maintenance operation is finished correctly or not, if maintenance workers continue to perform next maintenance steps after finishing a wrong operations, sometimes can result in fatal accidents, so using image based detection mudule can increase safety of maintenance workers during maintenance process.

A remote-assisted maintenance system can be developed based on Augmented reality technology [104]. Nowadays, maintenance problems become more and more complicated, maintenance workers need to use knowledge from experts. Remote-assisted maintenance system can develop a relationship between maintenance workers and experts. Maintenance problems can be solved by using the knowledge from the experts in the remote place, making sure that maintenance workers can finish the maintenance operations correctly and safely, decreasing the risk of performing a wrong operation. Oral and visual description can be used to describe the maintenance problems during maintenance problems, so experts can better to understand the problems and give suitable solution, preventing that experts misunderstand the problems and give incorrect solutions, this condition may cause maintenance workers perform maintenance operations incorrectly. Meanwhile, the visual feedbacks from the experts can make maintenance workers better understand the meaning of the solutions, so with guides and supports from experts, maintenance wokers can finish the maintenance operations safely.

Before carrying out maintenance tasks, providing an efficient training for maintenance workers is an effective way to make maintenance workers familiar their works. A training method based on Virtual Reality can provide a virtual maintenance space where maintenance workers can perform maintenance operations like in the real maintenance space [105]. On the one hand, maintenance workers can practise their maintenance operations in the virtual space, this can help maintenance workers more familiar their operations which they will perform in the real condition and tools or Personal Protective Equipment (PPEs) that are required to use, this can help maintenance workers to decrease the safety risk, such as forgetting to perfom one maintenance operations, performing a wrong operations, using inappropriate tools or Personal Protective Equipment (PPEs). On the other hand, this can be uesd to decide if a maintenance worker is suitable to carry out maintenance tasks or not. If a maintenance worker can not perform all maintenance operations correctly in the virtual space, then the maintenance worker can be considered that he/she can not finish the maintenance tasks safely. This can reduce the risk that a maintenance worker is not skilled to perform some maintenance operations.

2 Literature review and background

2.1 Introduction and definition of maintenance

Maintenance has been with us since the birth of human. From the regular polishing of human's earliest spears and tools to the repair work required by modern technology, our equipments and machines require maintenance and repair. Some official records about maintenance can be found even in the ancient Egypt. With development of manufacturing,maintenance also improved. Industrial maintenance describe an action that maintenance operator provide a way to keep the machines or equipments in a good condition, to reduce the downtime and cater to the need of the company. Maintenance is an nessary and important part in many different types of industries which can involve trouble shooting,deassembling,replacing,assembling,etc,.

Maintenance is a professional and corporate action, it has changed a lot in the past fifty years, from reactive maintenance to predictive maintenance. Maintenance is a job not only for the businessman, engineers and manager also involved to take part in manage maintenance practice. There are a lot of company managers make light of the important effect of a successful maintenance on the company's production activities. General speaking, a good maintenance work can only have a positive effects on the company and it is nessary and essential to improve the quality of products and guarantee the delivery of products on time. In many famous companies, maintenance management is considered as a critical part of commercial operation,since maintenance has a strong effect on the corporate performance and bring many benefits. Nowadays, companies develop maintenance in order to reduce both scheduled downtime and unscheduled downtime which all reduce the available time, improving operator's safety, reducing environmental risks, decreasing the costs.

Some maintenance definitions can be found by searching literature. Maintenance is described as "Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" [3]. Maintenance manegement include actions like inspection, adjustments, cleaning, lubrication, testing, and replacement of expendable parts, as necessary to maintain the serviceability of the equipment [4].

From Simeu-Abazi and Sassine's point of view, "the main purpose of maintenance engineering is to reduce the adverse effects of breakdown and to increae the availability at a lower cost, in order to increase performance and improve the dependability level" [5].

Bagadia presents the point that maintenance indicates actions that help the machine and equipment bring to required condition. These actions can assess and identify real and general condition of specialized establishments and then take technical actions to restore its abilities in order to have a required quality [6].

2.2 History and evolution of maintenance in the industry

2.2.1 Reactive maintenance and the First Industrial Revolution (1760-1840)

As we all know, the characteristic of the first industrial revolution was the widespread use of steam machine as power machine, which in 1765 was created by James Watt. The first industrial revolution began in the England, it was a huge revolution in the history of technological development, and it created the period of replacing manual labor with machines. The first industrial revolution also changed the way that people used energy, and it pushed a big step to form industrial society. The productivity of labor was a big increase because machine was widely used to replace the manual work.

During the first industrial revolution, the main way of maintenance was reactive maintenance, it was the oldest maintenance strategy, which also can be called corrective maintenance or breakdown maintenance. “You can repair machine only when it is broken” used to describe the reactive maintenance [7]. This is means that maintenance operation will be carried out only when the machine totally failed. Maintenance was just considered as a background work. The purpose of reactive maintenance is to save the broken machine and bring them to normal condition. Locating the broken parts, replace or repair it after machine stopped. Such maintenance has advantages and disadvantages. The advantage is that it need less time and cost, require less planning. The disadvantages is that it always introduce inevitable delay and increase downtime, sometimes may led to a big loss of time and money. Meanwhile, Unpredictable breakdown increase risk of safety, introduced some safety problems.

Reactive maintenance is an easy and natural method. It catered to the need during the first industrial revolution, because machine and equipment was not complex and their structure is simple at that time. Nowadays there also a large number of manufacturing companies decide to use reactive maintenance.

2.2.2 Preventive maintenance and the Second Industrial Revolution (later in 1870)

The Second Industrial Revolution brought people to a period of electrification. The assembly lines were wildly accepted. Henry Ford adopted the assembly line for his car factory based on division work in order to increase the production of the car. During this period, a lot of innovations were created, like Edison invented lamp in 1879 and transformer was created by Tesla. Other important creation like combustion engine, electric motor, phone and aircraft, because of these new technologies, people’s life was changed.

During the period of the Second Industrial Revolution, the machine and equipment became more and more complex. Breakdowns took place very often which led to an increase of cost. In order to reduce the expenses, preventive maintenance was created. From 1919, FORD company adopted preventive maintenance and used to check the running gear and make sure all bolts and nuts in a normal condition, if any abnormal condition was found, took actions as soon as possible. It just need a little time but can reduce the risk of accident on the road.

Preventive maintenance can be carried out by a specific timetable inspection to check the components or machine's condition, take measures to bring machine in an operating condition [8]. Preventive maintenance has two different kinds, maintenance in periodic cycles or maintenance according to the condition of machine. On the other hand, it is difficult to perform maintenance in periodic cycles for most machine because of high cost. But it is more effective to perform maintenance according to the condition of machine, only when machine or equipment show the abnormality, repairing or changing parts.

Preventive maintenance introduces less risk of breakdowns and decrease the downtimes, and compare to reactive maintenance, preventive maintenance seems more intelligent. It provides a better understanding of machine and component health. Normally, the main cost of preventive maintenance is conventional replacements, but sometimes need an extra part and led to an increase of scheduled time. A company which only adopt reactive maintenance can save more than 18 per cent of cost by using preventive maintenance, it depends on the condition of equipment or machine [8]. Even though preventive maintenance is not a perfect solution, but it still has more benefits than reactive maintenance. Preventive maintenance successfully decreases breakdowns and reduce downtime, making machines and parts have a long life time. It also can make workers more effective and ensure a safe working environment

2.2.3 Proactive maintenance and the Third Industrial Revolution (1940s-1980s)

Talking about the Third Industrial Revolution, usually relate to the electronic technology, computer engineering and information technology. In 1969, the first PLC (programmable logic controller) was created which can make the industrial process more automatic. Soon this technology was adopted to control the equipment and in order to have an automatic production process. Like from the First Industrial Revolution to the Second Industrial Revolution, people used electricity as power source to instead of steam, from the second Industrial Revolution to the Third Industrial Revolution, there was a transform from mechanics to automation.

After the Second World War, the industry system was rebuilt. Owing to this, maintenance stepped into a new period. Since market became more competitive, this situation make company to increase production. But with the growth of production, the equipment usually worked in a load condition which contributed to an increase of downtime. This means companies needed to pay a lot to repair the equipment or machine.

Between the 1960s and 1980s, companies became increasingly more focus on the safety problems. Companies intended to protect maintenance operators so they started to pay much attention to develop maintenance. Meanwhile, machine also had evolved

and integrated a variety of advanced technologies, maintenance work became more dangerous than before. Therefore, in the companies, maintenance became more significant, and this situation accelerated the birth of the first procedure of maintenance. Owing to the first maintenance procedure, the number of maintenance accidents were reduced sharply, it was convenient to follow up the function of the machine closely and can get rid of the critical failure of the whole production line. It was really a great step that companies wanted to develop maintenance for protecting employee's safety not for making profits. The first maintenance standard was introduced, in the background that increased awareness of risks related to the use of complex and advanced machine. In 1979, in France and other European Union countries, the standard of maintenance was gradually and successfully carried out [9]. Then in 1985, two new maintenance standards were introduced which are AFNOR X60 and X60 000. So the maintenance experienced a big transformation, and became a professional and necessary work in the company. In 1980s, the first Advanced Technician's Certificate training and other training course was founded. For safety and effective purpose, it is necessary to train people who would like to do the work relate to the maintenance.

During the Third Industrial Revolution, productive maintenance was created. This is an innovation data driven and analytical technology. It also can be seen as a combination of reactive maintenance and preventive maintenance, which can find the causes that led to the machine breakdown in time and increase the efficiency of production. Productive maintenance prolongs the life of components and machines, reduces the scheduled downtime and unscheduled downtime, decreases the cost, lowers the risk of breakdown, provides a safe working environment. But it is different from reactive maintenance and preventive maintenance, productive maintenance become a part of company strategy and it has been proved worth. It can collect information about machine or components, sometimes can realize real time monitoring. Productive maintenance later developed two different types during the Third Industrial Revolution, which were total productive maintenance and reliability centered maintenance [10].

2.2.3.1 Total Productive Maintenance

With the development of Japanese manufacturing technologies, new maintenance method was created by Seichi Nakajima which called Total Productive Maintenance. Then in 1971, he applied Total Productive Maintenance into Japanese manufacturing system and still used in Lean Manufacturing [11].

- T is total, means every company worker need to take part in
- P is productive, means increase the efficiency of industrial production process and maintenance
- M is maintenance, means take actions to ensure machine and equipment in a good condition

Total Productive Maintenance aims to link all company employees to participate on the activities in order to reduce the downtime and decrease the risk of accidents, provide a more safety environment. In traditional strategy, company always divided people into production worker who working on the machine and maintenance worker who focus on maintenance tasks. Different from traditional strategy, Total Productive

Maintenance require a production worker to find abnormalities during his work and predict the breakdown in the future. Briefly, "Protect your machine and take care of it with your own hands."[12]. In Total Productive Maintenance, diagnostic and maintenance tasks performed by the worker who carry out the production work. It asks production worker to do machine cleaning work, inspect the condition of machine and improve machine working environment [13]. Total Productive Maintenance help operators to better understand his equipment in order to perform the maintenance tasks more convenient.

Total Productive Maintenance change the relationship between human and machine, the operator not only carry out the production tasks but also act as an active maintenance coworker. This new maintenance method can keep the machines and equipment in a normal working condition. Total Productive Maintenance successfully decrease breakdowns and reduce downtime, making machines and equipment have a long life time. It also can use labour more effective and ensure a safe working environment. Such maintenance method lasts a long time and improve the productivity, but the main disadvantage is need an assimilation of information from trained operator and experienced engineers, machine or equipment manufactures.

2.2.3.2 Reliability Centered Maintenance

In 1997, Moubray, J. described Reliability Centered Maintenance as "a procedure to establish maintenance requirements for any physical asset in its operational context" [14]. It can ensure the system continues to perform user requirements in the current work environment. Reliability Centered Maintenance method can deal with basic problems that other maintenance programs cannot solve. Considering that all machines in a company don't have a similar structure and their operating ways are also different from each other, so there are a variety of reasons to account for a same failure. And it also takes the situation into account that a company wants to be optimized but without enough budget and personal assets.

The Reliability Centered Maintenance method can filter the performance of each component and describe the results of its failures [14]. By using failure mode and effects analysis (FMEA), Reliability Centered Maintenance method can make a decreasing order list of the results on the basis of significance of individual disorders. When determining the results, all the activities of component of monitored machine should be taken into account. Through the selected maintenance mode, if it is not possible to reduce the risk because of failure, it is essential to replace the component. The Reliability Centered Maintenance method also can be used to analyze the possible reasons that cause equipment failure.

2.2.4 Predictive maintenance and the Fourth Industrial Revolution

The Fourth Industrial Revolution is happening nowadays and we are experiencing it.

During the Fourth Industrial Revolution, predictive maintenance method was created due to the innovation Industry 4.0 technologies, which is a good method to optimize the maintenance timing. By analyzing information relate to production process, predictive maintenance method can predict the failure and prevent the machine breakdown. This method is based on a combination of Industry 4.0 technologies, such as big data and the industrial internet of things to realize real time analysis and inspect anomalies. The information link to production process not only come from the equipment but also include environment data, it's a combination of equipment information and environment data. There is a warning function for critical components or machine based on predict technologies like stress analysis, vibration analysis.

The essential elements to perform predictive maintenance method are sensor technology, Internet of Things, Cyber-Physical System, Cloud computing, Big Data, Augmented Reality, Artificial Intelligence. Meanwhile, the work related to predictive maintenance is different from other maintenance methods. Predictive maintenance method not only need experienced maintenance operators but also require data engineers, because predictive maintenance need to use a large quantity of data such as environmental data, machine real time monitoring data, maintenance history data[15].

Nowadays, with the concept of 'Industry 4.0' and 'Smart Factory', useful information about equipment can be analyzed automatically. The digitization of information means real time condition monitoring information which come from multiple sources can be collected by using sensor technology and can be stored in an easily accessible way. This make a great improvement of advanced analytics, more easily and quickly, giving a real-time assessment of condition, pointing out any abnormal situation, allowing company have time to schedule production activities. Cloud technology make information more accessible, allowing technicians to respond rapidly and have a good solution to deal with the anomalies. This technology is further developed by using Prognostics. Condition information collected from the critical part of machine used to calculate its Remaining Useful Life (RUL) and indicate when a machine will break down, reducing the loss because of unscheduled downtime.

There are some significant elements can led to perform predictive maintenance successfully such as availability of data, security of information, corporate budget, technical solutions.

According to Heinz P. Bloch, Fred K. Geitner [16], the saving results can be found by using predictive maintenance:

- Return in investment: 10 times
- Reduction of maintenance costs: 25%-30%
- Troubleshooting: 70%-75%
- Reduction of downtime: 35% -45%
- Increased production: 20%-25%

Table 1 Correlation of Industrial Revolution and Maintenance [17]

Industry revolution	Industry 1.0	Industry 2.0	Industry 3.0	Industry 4.0
Characteristics of the industrial revolution	Mechanization steam power weaving loom	Mass production, assembly lines, electrical energy	Automation computers electronics	Cyber Physical Systems,IoT, networks, cloud, BDA
Type of maintenance	Reactive maintenance	Planned maintenance	Productive mainteanance	Predictive maintenance
inspection	Visual maintenance	Instrumental inspection	Sensor monitoring	Predictive analysis
OEE	<50%	50-75%	75-90%	>90%
Maintenance team reinforcement	Trained craftsmen	Inspectors	Reliability engineers	Data scientists

2.3 The situation of maintenance today

Nowadays, there are a large number of companies present their opinions that they want to adopt data-driven maintenance strategies, in order to decrease the downtime and increase the productivity.

Advanced Technology Services (ATS) and Plant Engineering magazine in the year of 2020 conducted a survey in order to find the situation of maintenance nowdays [18]. They carried out an interview with some people who charging the whole or part of maintenance work in their companies, the content including challenges, safety condition, their schedule to reduce the downtime, safety condition, effect of advanced technologies, use of machine data, which type of maintenance strategies are used, outsourcing condition.

There were near 200 participants took part in the survey, and about 80 per cent of them have the engineering or maintenance background. The average industrial experience for them is 23 years, and there are about 30 per cent of them have industrial experience more than 30 years. Here is the figure 1 to decribe the primary business they served.

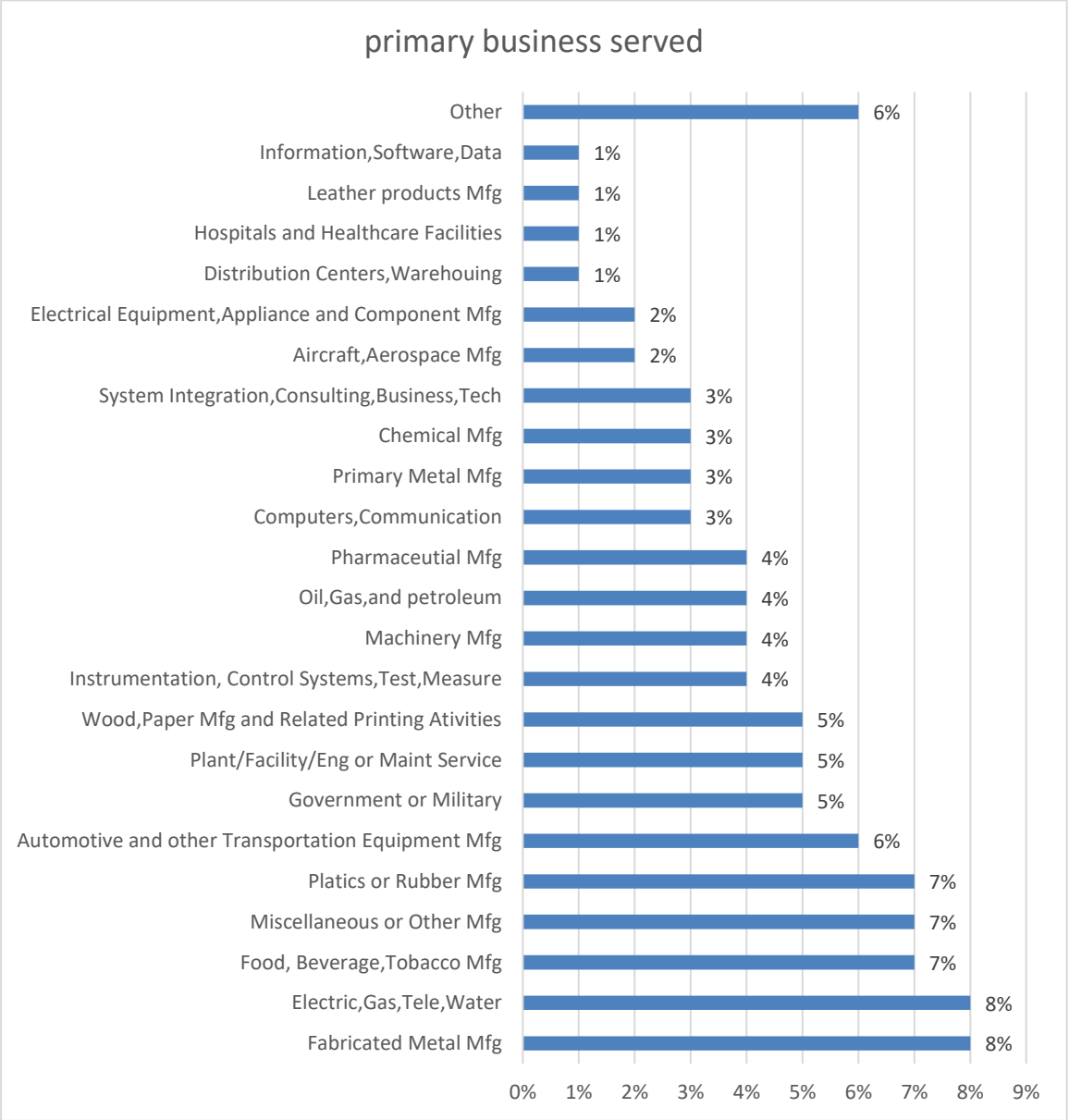

Figure 1 primary business they served[18]

There are three elements in the current maintenance challenges, people, process, and technology. The following figure 2 showing the challenges to current maintenance. There are near about half of the participants consider that the lacking of experienced maintenance workers is a critical problem, meanwhile, there are also 19 per cent of participants think it moderately challenging and the percentage of participants who consider it is least challenging is 33 per cent.

For the process, like training work, reporting work, work planning work. There are only 27 per cent of participants consider that process is a critical issue in the current maintenance challenges. Meanwhile, near half of participants (46%) think it moderately challenging, and the percentage of participants who think process is least challenging same to the percentage of most important (27%).

There are 40 per cent of participants present their opinions that technology application is least challenging, meanwhile, the percentage of participants who

consider that technology is most challenging is 25% and 35 per cent of participants think technology is moderately challenging.

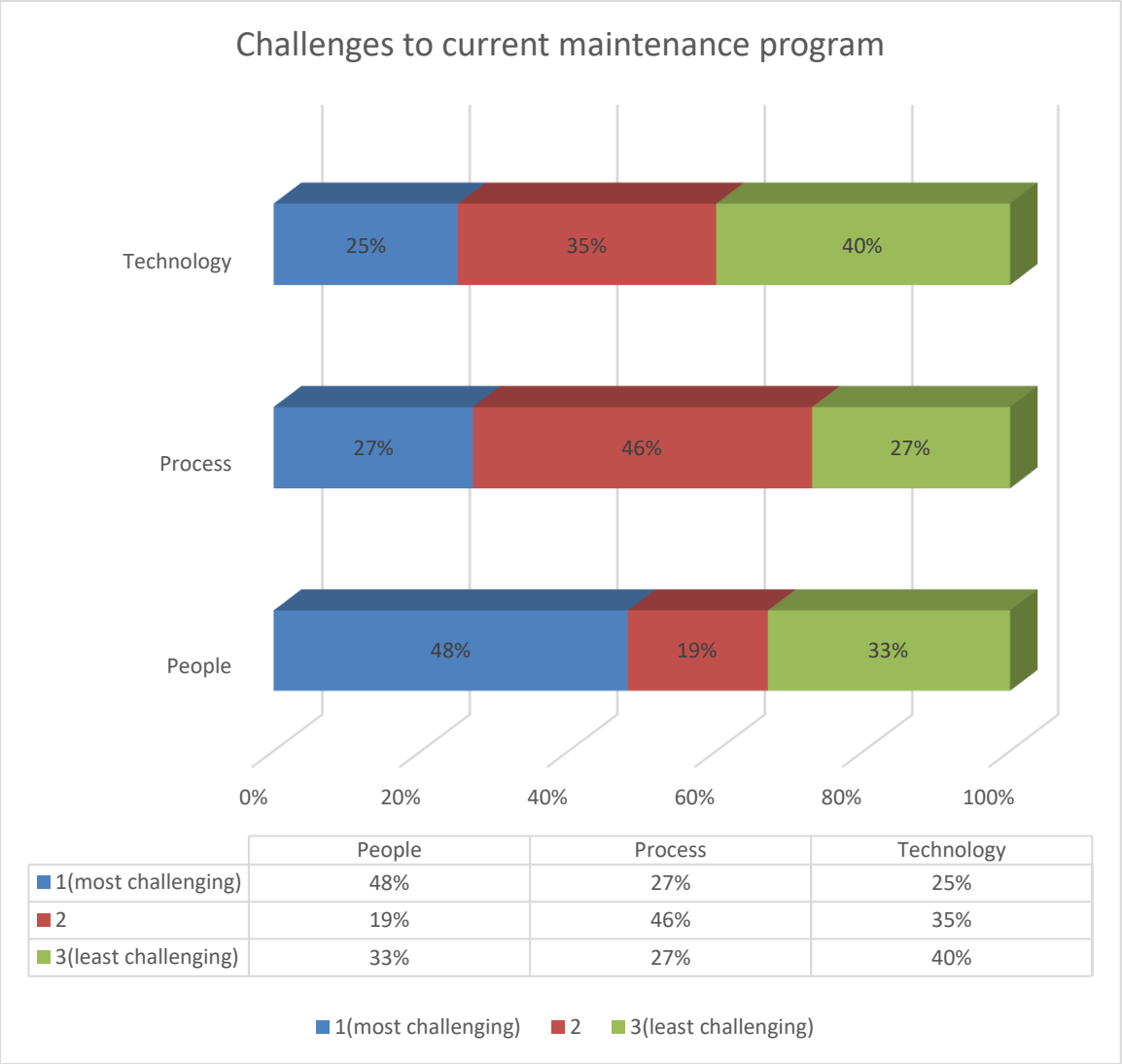

Figure 2 Challenges to current maintenance program[18]

The safety of maintenance workers is an important issue, the following figure 3 describing the current safety condition.

There are more than half of participants consider that the safety of maintenance worker need to be improved, the percentage is 68%. There are only 19 per cent of participants think that they can carry out excellent maintenance work and take very good actions to protect the safety of the maintenance worker. Meanwhile, there are 12 per cent of participants present their opinions that the safety of maintenance workers is a problem, they can not protect the safety of maintenance workers when they carrying out maintenance tasks. There are only 1 per cent of participants think that safety is not a priority.

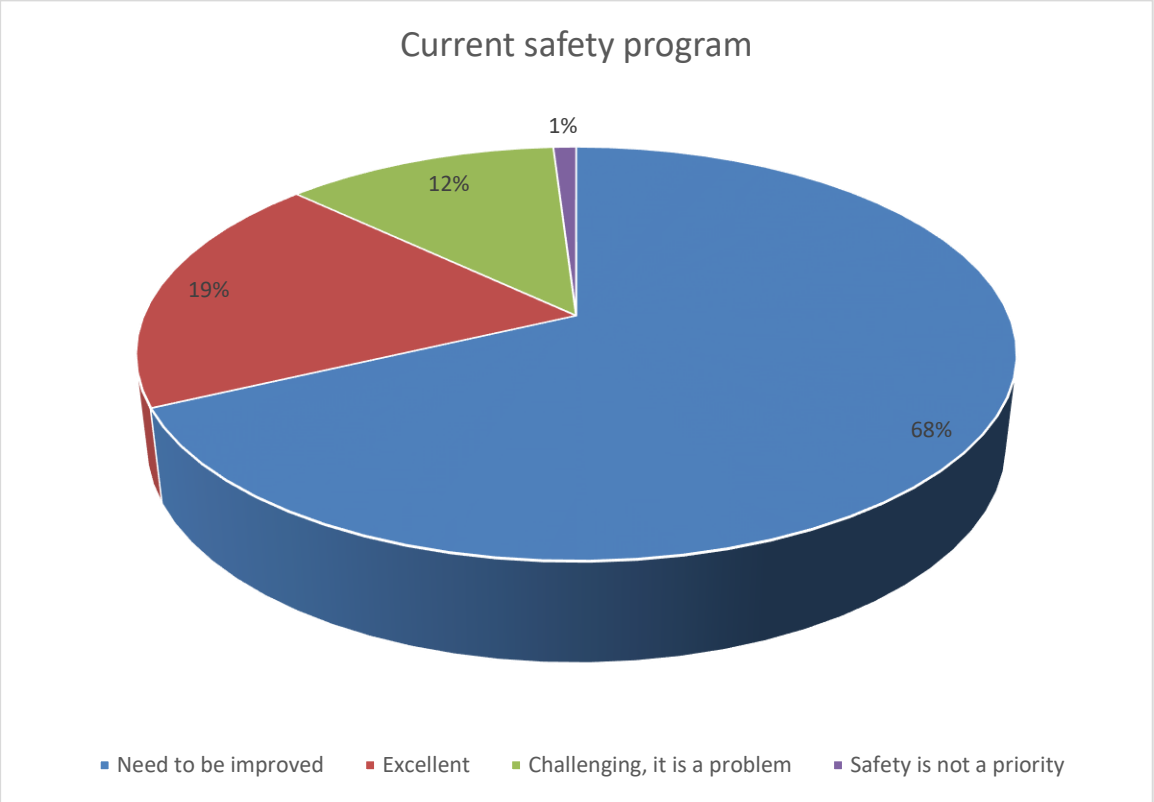

Figure 3 Current safety program[18]

The following figure 4 describing the key challenges to improve maintenance, it is obvious to see that the main challenges are related to people, such as lack of experienced staff (41%), lack understanding of technologies (31%), lack of support from management (26%), lack of training (26%). Meanwhile, there are also an important challenge to improve maintenance is outdated technology, using some modern technologies is a necessary step to improve the maintenance, including increase the maintenance efficiency and the safety of maintenance workers. Also lack of available funding is another limitation to improve the maintenance.

The following figure 5 describing the plans that participants will take to decrease the unscheduled downtime. It is easy to see that participants use a lagre amount of methods in order to reduce the downtime, the most common methods are introducing or changing the maintenance strategy and upgrade equipment, the percentage of them are same (46%). Improving training and increasing the frequency is the next, which account for 33 per cent. Meanwhile, there are 32 per cent of participants will expand their monitoring abilites and there are 16 per cent per cent want to adopt automated analytics with machine learning, these two method all based on The Industrial Internet of Things. Some participants plan to increase the scheduled downtime, which accout for 13 per cent. The percentage of using more maintenance workers and outsource their maintenance activities is the same (9%).

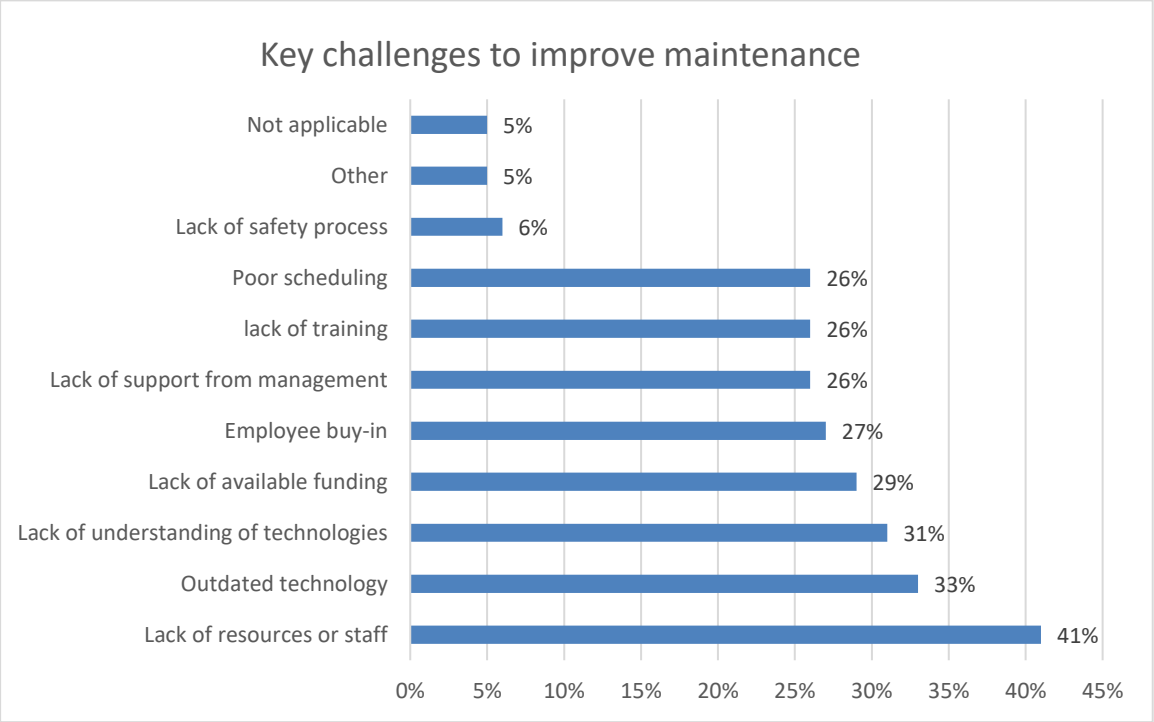

Figure 4 Key challenges to improve maintenance[18]

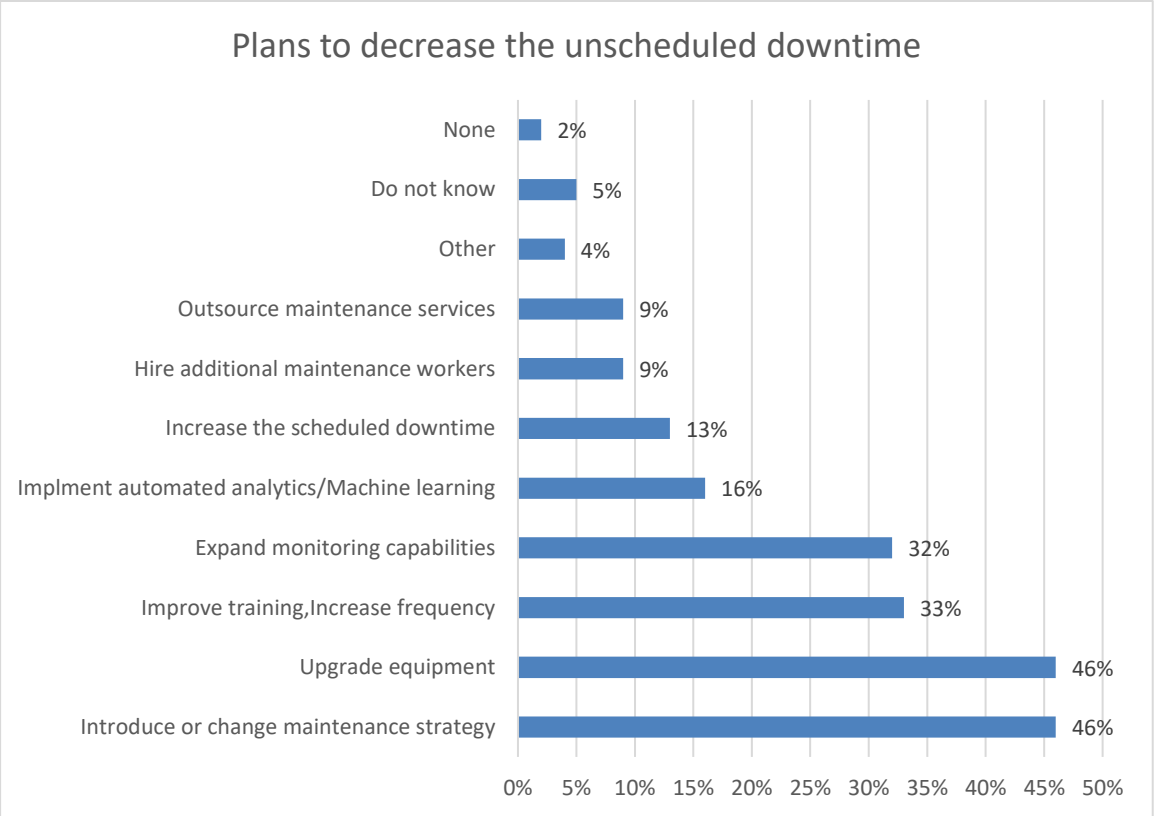

Figure 5 Plans to decrease the unscheduled downtime[18]

The following figure 6 describing the effect of The Industrial Internet of Things on maintenance process. There are 32 per cent of participants consider that using The Industrial Internet of Things can help them to understand the condition of machine. Also some participants think that The Industrial Internet of Things can help them to predict the machine breakdown, the percentage is 27%. Meanwhile, 25 per cent of participant present their opinions that The Industrial Internet of Things can change the maintenance way. The percentage of participants who consider The Industrial Internet of Things have no effects on the maintenance and have no ideas about The Industrial Internet of Things are 25% and 20%.

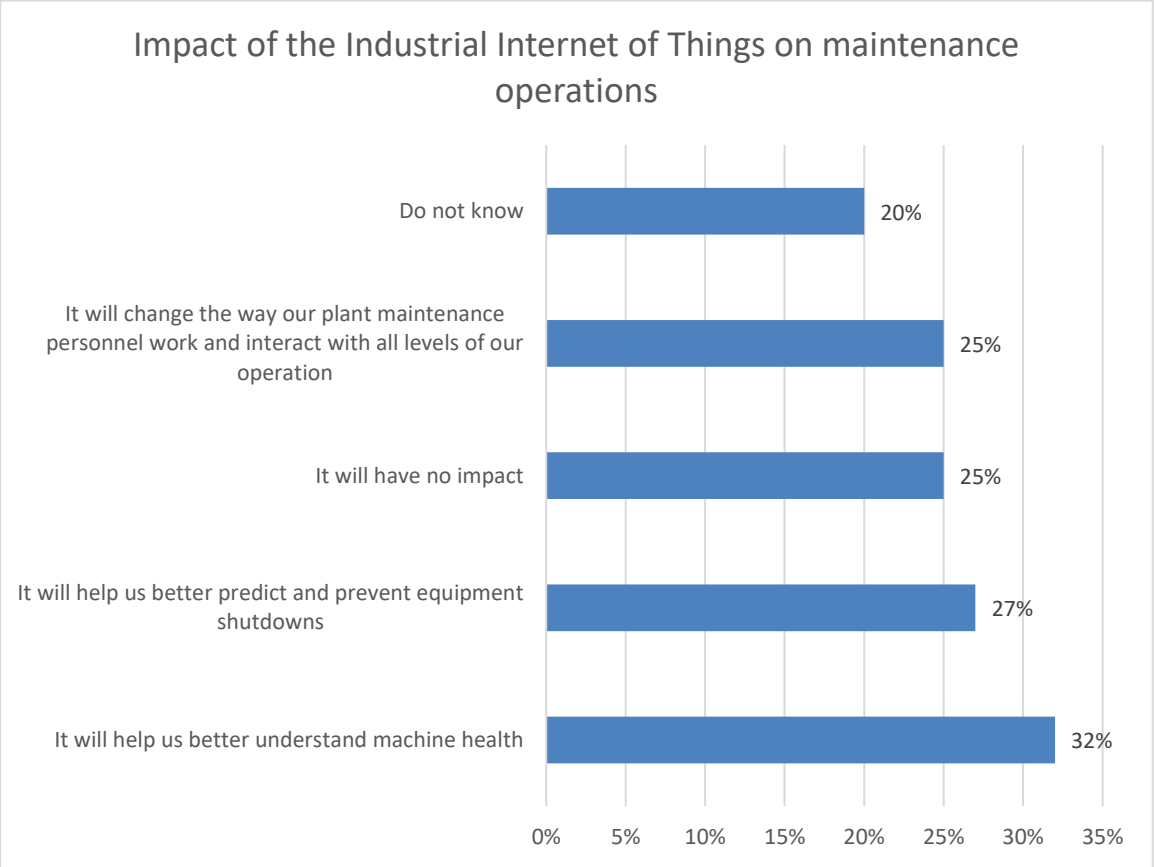

Figure 6 Impact of The Industrial Internet of Things on maintenance operations[18]

The following figure 7, it is easy to find that there are only 17 per cent of participants adopt advanced technologies to collect the machine data. Meanwhile, there are near half (47%) of participants present their opinions that they will adopt advanced technologies to collect the machine data in the future. Some participants show that they will not use advanced technologies to collect the machine data in the near future, they account for 31 per cent. It seems that using advanced technologies to collect the machine data is a trend in the future.

The following figure 8, it is easy to find that there are 96 per cent of participants say the data is analyzed, however, there are only 70 per cent will take further action. Meanwhile, some participants do not analyze and take action on the data, the percentage is 4%. It seems that most participants carry out machine data collected work, and then analyze the colleted machine data.

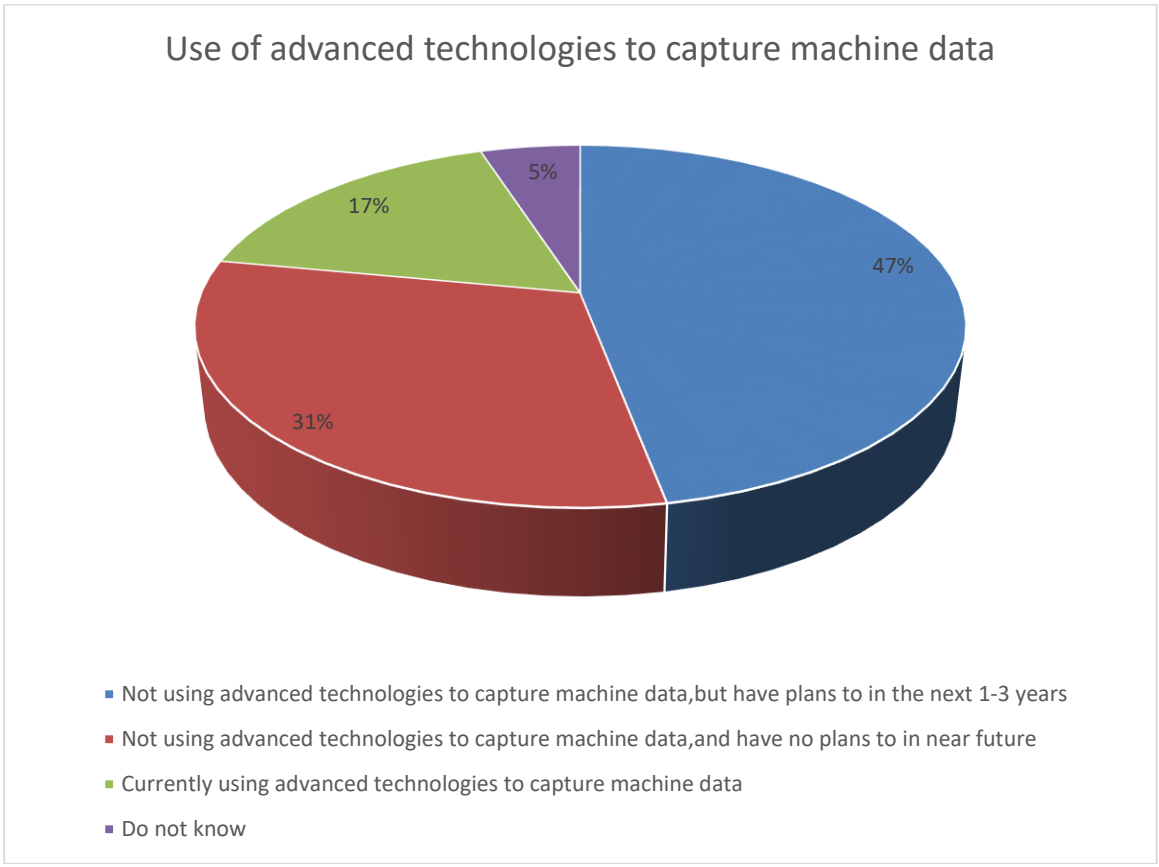

Figure 7 Use of advanced technologies to capture machine data[18]

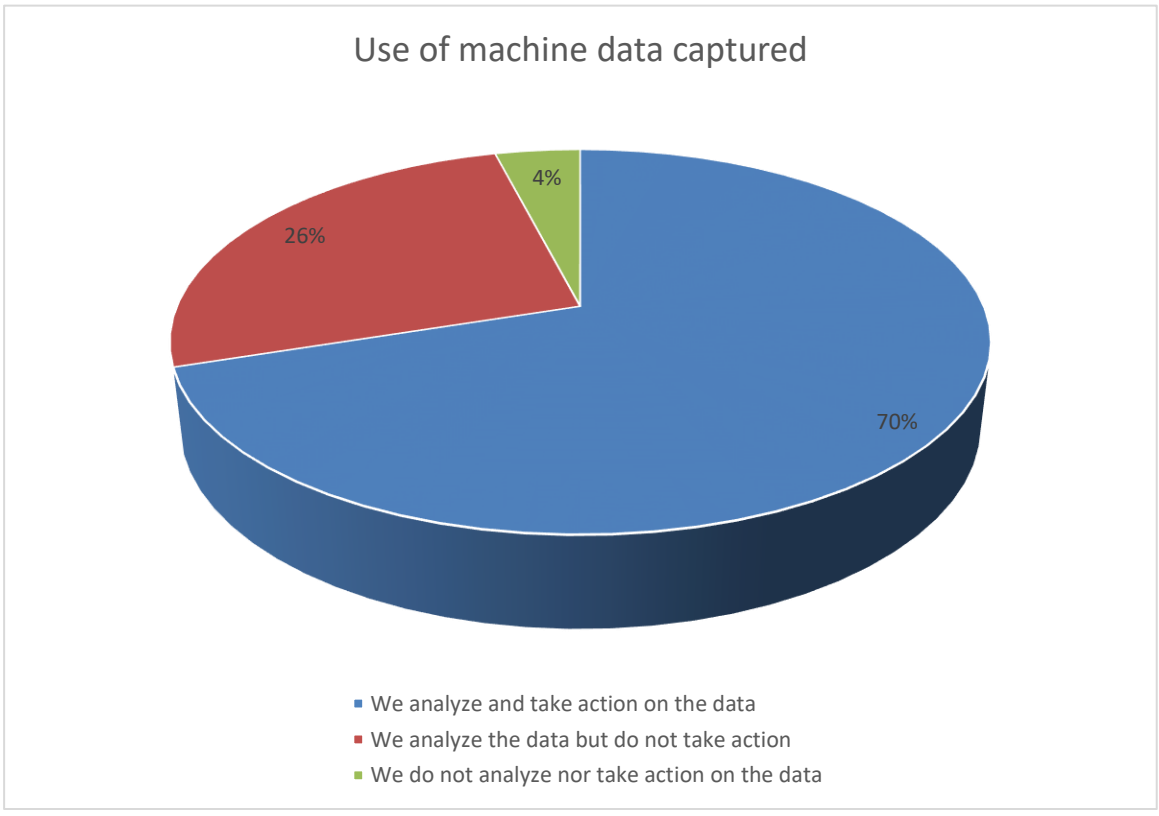

Figure 8 Use of machine data captured[18]

Here information in 2020 is presented, giving a picture of nowadays maintenance strategies and tools in use.

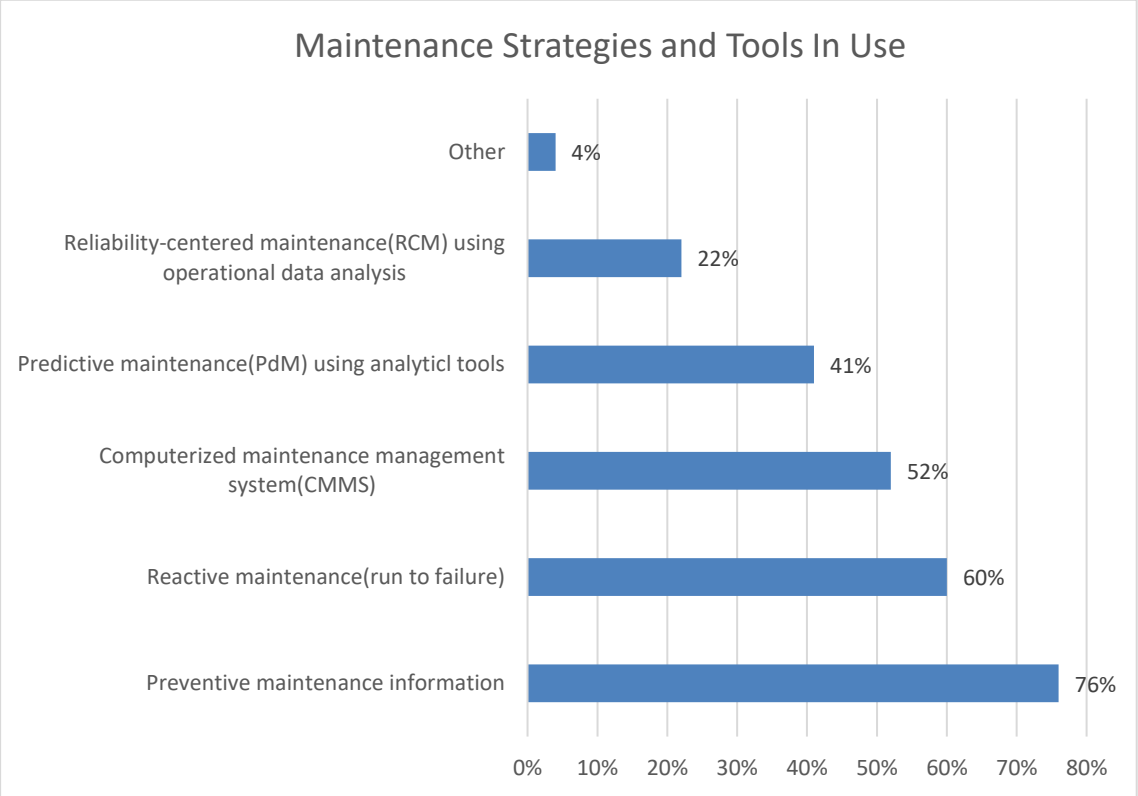

Figure 9 Maintenance strategies and tools in use[19]

Maintenance strategies: It is obviously to see that most manufacturing companies(76%) prefer to choose preventive maintenance, this is because preventive maintenance is one of the effective tools to reduce downtime and can decrease the cost of maintenance. There are 60 per cent of companies use reactive maintenance, this is means that companies perform maintenance activities after machine or equipment failed. Meanwhile 52 per cent manufacturing facilities take a computerized maintenance management systems strategy and 41% have implemented a predictive maintenance. The percentage of reliability-centered maintenance and others is 22% and 4%.

The budget of maintenance: There are 48 percentage of manufacturing companies present their point that they want to spent 10 per cent of their annual operating expenses on the maintenance and 39 per cent companies decide to cost more than 10% of their annual operating expenses. Meanwhile, the average time of companies want to spend on the maintenanc is 20 hours for each week.

Critial areas of maintenance: rotating machine, production machine, fluid power machine,theses three kinds of machine need most maintenance. Other systems like internal electrical distribution systems and material handing systems also need to pay attention a lot.

The reasons of unplanned downtime: Aging equipment is the main reason to cause increase of downtime (34%). Next is mechanical failure,it is account for 20 per cent. Operator fault is also a reaspon to result in a increase of downtime, the percentage is 11%. Meanwhile, there are 46% companies want to update their equipments and change their strategy of maintenance in order to reduce the downtime and improve the production.

Training: Most maintenance operators are skilled with basic mechanical knowledge, electrical knowledge and safety knowledge. The percentage is 77%, 70% and 71%. There are also other training ways like: motors, lubrication (51%), bearings (50%), gearboxes.

Outsourcing: The average percentage of companies outsource their mainteance tasks is 20%. There are 26% companies outsource their maintenance operation between 1% to 10%. Meanwile, the percentage of companies outsource their 11%-20% and 21%-30% maintenance tasks is 22% and 19%. Only 12% companies can carry out maintenance tasks by themselves.

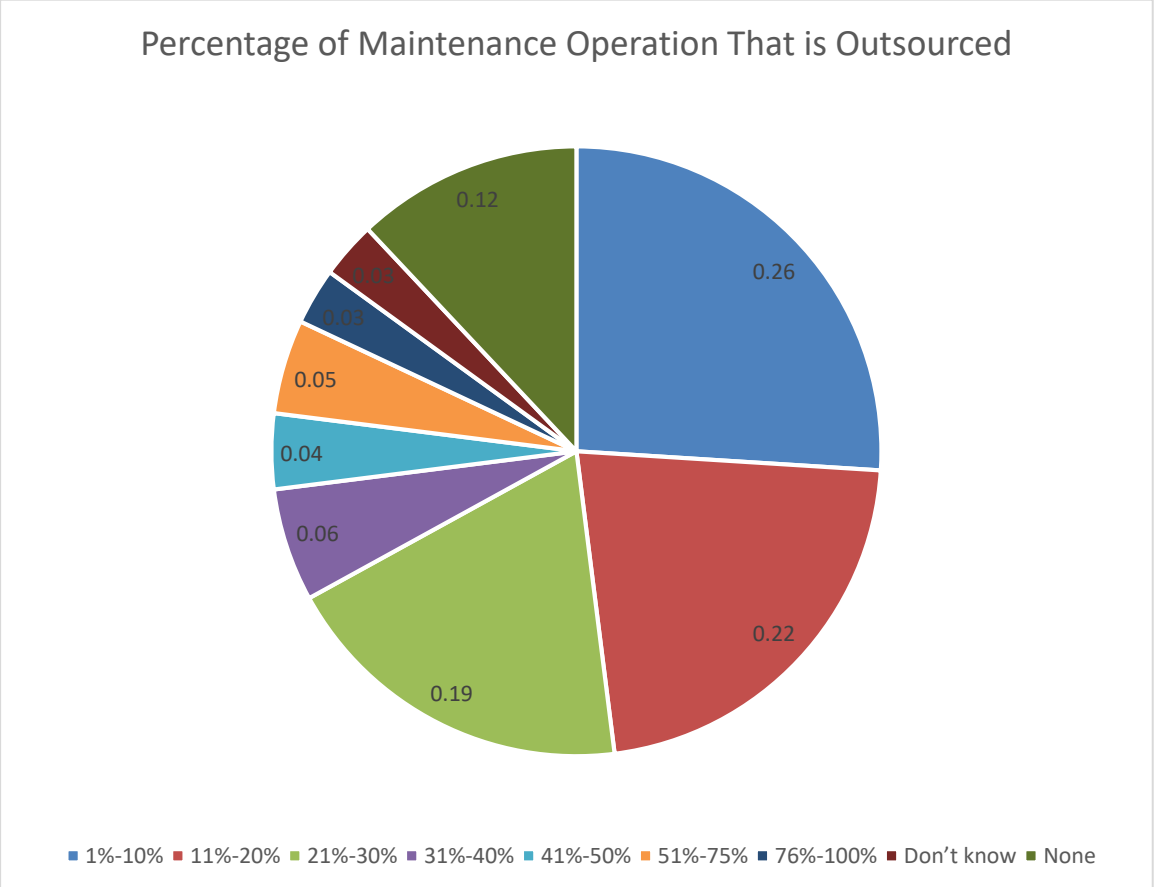

Figure 10 Percentage of maintenance operation that is outsourced[19]

Here is the picture about reasons for outsourcing maintenance operation. It is easy to see that the main reason is company don't have enough time and maintenance worker to perform maintenance activities. Meanwhile, companies do not have skilled maintenance worker, current employee do not have skills to perform the maintenance tasks and have agreement with equipment manufacturer are also critical reasons for outsourcing maintenance operation.

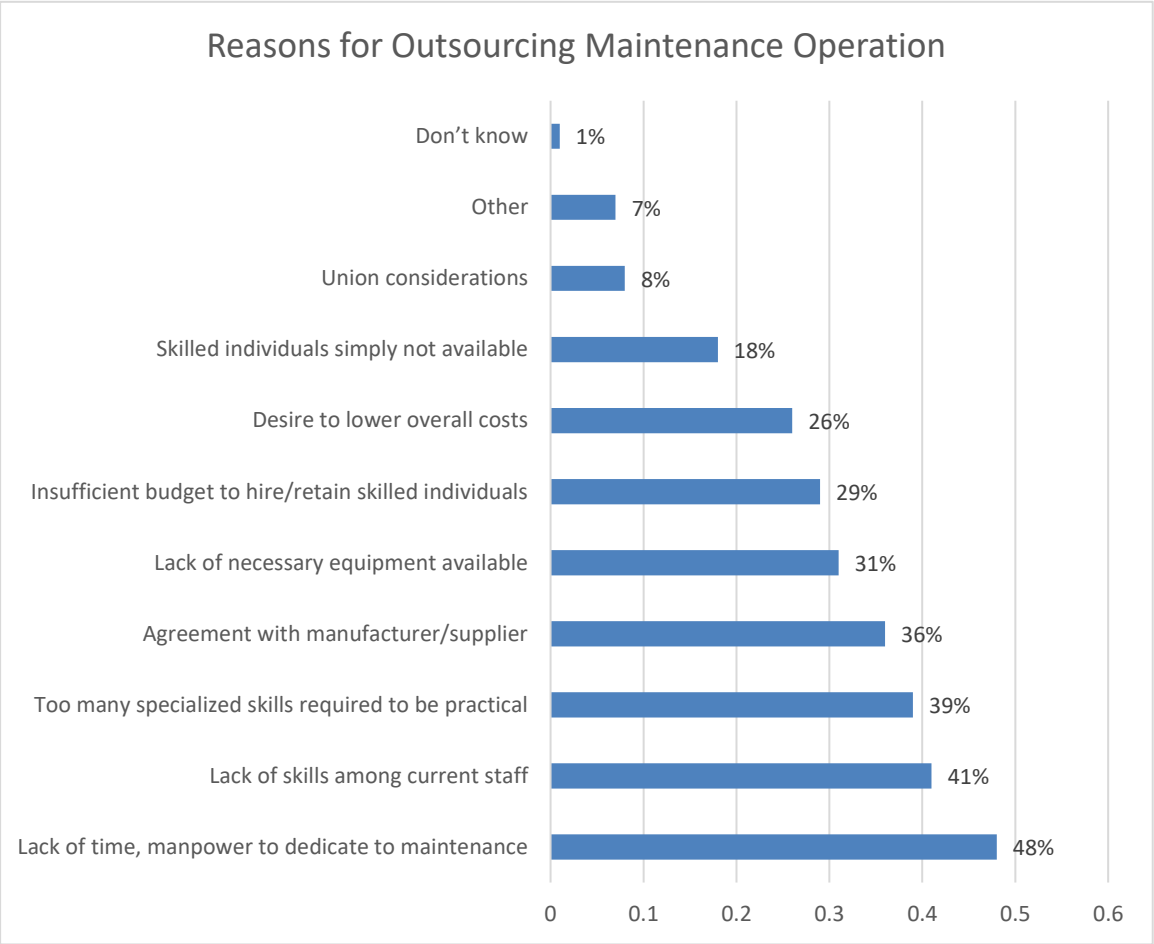

Figure 11 Reasons for outsourcing maintenance operation[19]

3 The safety problem during maintenance

European Standard 13306 [20], describes maintenance is “combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function”. Maintenance is a work that have an effect on not only worker’s health who directly operating machine, but also the safety of other workers, such as maintenance worker, when safety insturctions are not followed. Maintenance works always involve machine failure detection, disassembling, repairing or replacement of components, testing, tuning, adjustment and other operations.

Safety in maintenance is considered as during performing the maintenance work, keeping operators away from danger or protecting workers from hazardous environment. Different industry domains have their own equipment or machines. According to data come from Spain and France, there are 6 per cent of industrial workers are related to maintenance job [21]. Maintenance involves multiple occupations and need to perform a wide range of different tasks. When maintenance workers carrying out maintenance activities, it is common that maintenance workers always face a dangerous environment that have physical hazards, chemical hazards, biological hazards, psychosocial hazards [2]. It is important for maintenance employees to know the hazards in their work environment. Before carrying out maintenance tasks, maintenance operator should have a safety training and follow the safety instructions when performing maintenance work.

The information about Spanish working condition show that it is common for maintenance operators to be exposed in a noisy, vibratory, radiant environment when compare to other industrial workers [21]. Also maintenance operators are more likely to work in a heat condition in summer (44% versus 19% other industrial workers), perform tasks in a cold condition in winter (44% versus 17% other industrial workers) and in a wet environment (25% versus 13% other industrial workers).

The information come from EUROSTAT, showing the number of fatal accidents related to maintenance operations [21]. It is easy to that maintenance related fatal accidents account for 10%-15% of fatal accidents. It also presented that maintenance workers also suffer from occupational diseases and job-related health problems, like hearing loss, heart disease, cancer.

From the given information, it can be concluded that maintenance workers is more easy to be exposed in a dangerous environment compared to other industrial workers, so the safety of maintenance workers is a critical problem when they carrying out their maintenance tasks. In order to improve the safety of the maintenance workers, the maintenance strategy can be changed and some innovation maintenance approaches based on Industry 4.0 can be applied.

Maintenance now is considered as an essential part of company’s acticities. But there are a little attention to be paid on the risks related to the maintenance and a low quantity of research conducted to foucus on the effect of maintenance on the safety and health of maintenance worker.

Because of different maintenance requires, working condition and different equipments, maintenance operators face a lot of risks when performing their maintenance works [2].

Different working condition during maintenance

• Outdoor condition：Maintenance operators work in a changing climatic conditions.

• Indoor condition：Maintenance operators work in a plant with a high level of noise, vibration and chemical substances.

The risks relate to maintenance always decided by:

• Working condition and environment

• Which type of energy used

• Machine condition and tools correctly used

• Chemical and biological issues

Generally speaking, during maintenance process, there is always a variety of risks.

3.1 Physical hazards

3.1.1 Noise

Commonly, maintenance workers ususlly work for a long time in an environment with a high level of noise. The loud noise can come from machine, equipment and other sources. Maintenance operators work in a noisy environment, sometimes the value of noise levels more than limitation, long time exposed to such work environment can have a nagative effect on operator's health, directly result in temporary or permanent hearing loss and can led to non-hearing healthy problems.

Table 2 Effects realate to noise [22]

Type	The effect of noise
Hearing effects	Effect because of strong loud noise
	Acoustic trauma
	Temporary hearing loss
	Permanent hearing loss
Non-hearing effects	Uncomfortable feelings
	Difficult to communicate to each other
	Can't foucs on maintenance tasks
	Reduce work efficiency
	Increase the risk of accident
	Physiological effects
	Accelerated breathing
	Blood pressure increased
	Difficult to sleep

For example, Aircraft maintenance work can be considered a work that can be exposed to a high level of noise and fatigue has become most critical effect of noise for aircraft maintenance operator after work in a noisy environment [23]. Aircraft maintenance operators would feel tired and less energetic afier finish the maintenance

work. This bad effect would last few weeks, particularly in the afternoon and become more severe in the week. When carrying out maintenance work between two engine running airplanes, maintenance operators can not communicate to each other but only can feel the vibrations, this is the main reason result in fatigue.

3.1.2 Vibration

3.1.2.1 Hand-arm vibration

When maintenance operators carrying out tasks, they usually need to use hand-held tools. But machine or equipment vibrations can transmit to maintenance operator's hand by hand-held tools [27]. Maintenance operator is exposed to hand-arm vibrations can led to different kinds of operator's disease, it depends on the level of vibration, the operator's personal characteristics and the work environmental conditions.

Table 3 Disorders caused by hand-arm vibrations [24][25]

Type of disorder	Hand-arm vibration effects
Vascular disorders	Hand-arm vibration syndrome (Vibration white finger) or Raynaud's phenomenon
Neurological disorders	Reducing the touch feeling, manual dexterity and becoming sensitive to heat
Musculoskeletal disorders	Weakness of muscle, osteoarthritis in elbow or wrist, arthralgia in arms or hands

3.1.2.2 Whole body vibration

When most part of maintenance operator' body have a touch with surface of vibrating machine, then the whole body vibrations conditoin would happen. Normally when maintenance operators sitting to carry out their tasks, the whole body vibrations can be transmitted to operator by seats, or standing to perform maintenance work then vibrations transmitted by feet [28]. Maintenance operator exposed to whole body vibration can cause some diseases, which depend on the level of vibration, the operator's personal characteristics and the work environmental conditions.

Table 4 Disorders caused by whole body vibrations [25]

Type of disorder	Whole body vibration effects
Back	Back pains, intervertebral disc disorder, disorder of spine
Hearing	Exposed to high level of noises and vibrations at the same time can increase the risk of hearing loss
Digestive	Gastrointestinal disorders
Circulatory	Varicose veins

3.1.3 Heat atmosphere

Some researches indicate that performing maintenance opertions in nuclear power stations, the biggest hazard for maintenance operator is heat, especially when carrying out maintenance tasks in the period of nuclear reactor rundown [26]. In order to finish the maintenance operations, maintenance teams are always consist of two members. One responsible for measuring work meanwhile another one record the results.

3.1.4 Radiation

Radiation means a way to transmit energy, when interacting with some other things, radiation can have some effects on it. Particularly when interacting with human organs, healthy problems will exist. It depends on the level and type of radiation, exposure duration [29].

Radiations can be devided into two parts: ionizing and non ionizing, according to the energy level. Non ionizing radiations not mean more safer than ionizing radiations, non ionizing radiations also can result in some healthy problems.

Table 5 Diseases result from non ionizing radiations [30]

Type of radiation	Health problems
Laser	Having bad effects on skin, depending on the exposure duration, wavelength and intensity of the radiation
Microwave and radiofrequency	Thermal effects: can warm the organs
	Non thermal effects: can affect bioelectrical activities and biological membranes, affect the founction of pacemakers, led to genetic transmission diseases

Magnetic and static electrical fields and extremely low frequency radiation	Sensitive to light Would led to some certain kinds of cancer
Ultraviolet radiation	Erythema, conjunctivitis,and finally skin cancer
Visible and infrared radiation	Thermal effects: warm the surface skin
	Non thermal effects: cause a damage on retina and cornea

Ionizing radiation have different types, such as X, α , β , γ rays, they have high enough energy to disturb the electrons and make the electrons out of the normal orbits, then ionization occur. Ionizing radiation can do harm to the biological cell because of the hurt of DNA. Ionizing radiation can result in fragmentations in DNA molecules, making a damage of chromosome and finally death of cell. Ionizing radiation also can change the chemical structure of molecules and have an effect on genetic message. Ionizing radiation effects can be seen rapidly or after a period of time, depending on the type of ionizing radiation [31].

A studies show that maintenance operators are easily to be exposed in a radiation environment [21]. It is common for arc welders to face the risk of ultraviolet and visible light, so it is nessary to have more protection on eyes and exposed skin areas[32]. Some welding sticks include radioactive materials, using such welding sticks during maintenance operation increase the risk of cancer bacause of ionizing radiation [33].

3.1.5 Physical workload

Physically demanding work sometimes are required during maintenance operation, but it can led to high strain on body. Here some related maintenance actions are included [34]:

- Moving or carring heavy things
- Reaching
- Lifting
- Kneeling
- Bending
- Performing tasks in a narrow space
- Pushing or pulling
- Working in awkward postures
- Keeping the arms in the air for a long time
- Arms above shoulder level

Some activities should be prevented are given that can result in back or limb problems, such as[34]:

- carrying heavy materials on the shoulder in a small place
- performing maintenance tasks with non-ergonomic tools
- repeating motion because of unlocking and locking screws
- carrying out maintenance tasks in narrow space, at high space, on wet floors with cables or steps
- operations where the installation of parts need to be held for a long time, which would result in severe static muscle overload and local fatigue
- maintenance workers are not familiar with the operations result in unexpected physical risks or the need for force to lift parts of machines
- uncomfortable maintenance position cause high lifting loads because of bad design (difficult to reach the components of machine, providing a small space to move, performing maintenance tasks under knee height or above shoulders).

For ship maintenance operators who need to carry out a lot of manual maintenance work, like Sand blasting, high pressure water cleaning and painting, it is very commom for them to get musculoskeletal disorders (MSD) [35]. Car body maintenance workers always feel pain of back because of improper biomechanics [36].

A study focus on work-related musculoskeletal disorders and risk factors about workers in Norway's offshore petroleum industry, indicating that there are 53 per cent of work-related musculoskeletal disorders were upper limb disorders, 20 per cent were back disorders and 16 per cent were lower limb disorders [37]. Considering all the cases studied, maintenance workers occupied for 40 per cent of total number of work-related musculoskeletal disorders. From this study, it is easily to found that upper limb and back problems are the most critical problems for maintenance workers, the main reasons are repeating action and high physical workload [37].

SUMER conducted a survey, showing the percentage of maintenance employees reporting being exposed to postural and joint constraints [2]. It is convenient to find that the percentage of maintenance operators who are exposed to such postural and joint constraints is more than the percentage of all the professional families (87.16% vs 71.80%). And this situation also can be found for skilled maintenance workers, automotive repair workers, and maintenance and organisation technicians and supervisors, but it is critical for skilled maintenance workers and automotive repair workers (93.8% and 98.1%). So physical workload is a common safety problem in the maintenance domain.

Information about the percentage of maintenance employees reporting being exposed to constraints related to the manual handling of loads come from SUMER [2]. There are more than 50 per cent of maintenance workers (55%) presented their opinion that they need to deal with the load manually, meanwhile all the professional families corresponding accounted for 43 per cent. The percentage of maintenance and organisation technicians and supervisors (40.8%) is simialr to the percentage of all the professional families (42.8%). Automotive repair workers are most exposed to constraints related to the manual handling of loads, which account for 67.9 per cent. The next is skilled maintenance workers and percentage is 63.0%.

3.2 Chemical hazards

3.2.1 Work with asbestos

Despite asbestos is forbidden to use because it is do harm to people's health, but for maintenance worker it is still common to carry out maintenance tasks in a asbestos work environment. Maintenance workers are highly possible exposed to the highest level of asbestos when performing maintenance tasks, such as automotive workers repairing or replacing clutches and brakes [38].

Asbestos is still widely used in industrial activities owing to good ability of high degree of fire resistance, alkali resistance and acid resistance, making it ideal for thermal and acoustic insulation. Some examples are given to describe the wide use of asbestos in the construction industry [39][40]:

- used in acoustic panels
- necessray material used to manufacture tiles
- used in thermal insulation of pipelines
- used to manufacture pipes which made of cement-asbestos material
- used in asphalt, paint and putties
- used as a method to prevent fire accidents

In some other industrial domains, such as ship industry, nuclear and thermal indutry, aeroplane, train, asbestos can be provided to use as an insulating material. On the other hand, as for the household domain, such as in pipelines and boilers, asbestos has a large quantity of applications [40].

When maintenance workers performing their maintenance tasks relate to asbestos materials, maintenance workers are exposed to hazards of asbestos. This work environment will have a bad effect on worker's health. So it is necessary to take some actions to protect maintenance worker's health.

Here list some maintenance works related to asbestos:

- Maintenance operations relate to remove asbestos or other operations link to asbestos material, such as fire protection layer of machine or equipment, structure, buildings, some devices which contain asbestos
- Demolition and renovation of buildings containing asbestos
- Carrying out maintenance and repair work in building or other places where have a risk to be exposed in asbestos work environment
- Performing maintenance or repair work on Ships or units that dispose of asbestos materials

Here some maintenance operations would release asbestos fibres are listed

- Carrying out maintenance work on thermal insulation materials or sprayed asbestos: maintenance operations are performed at the place where sprayed

asbestos is exist (including electricity, heating, air conditioning, piping, placement or withdrawal of false roof, etc.) and scraping and piercing operations are needed to be carried out, or there have a chance of exposure to sprayed asbestos

- Handling of some materials which consist of asbestos:
- Dealing with filters and joints, some disassembly or assembly operations finished by sanding, brushing, scraping off, etc
- Coating: carry out maintenance or renovation works (e.g. placement of supports, removing partial parts, piercing, sanding) where plaster or adhesive is made of asbestos
- When performing maintenance tasks with asbestos sheeting, operations such as cutting, placement, and dealing with the fireproof plates contain asbestos by cutting machine, etc
- Dealing with some friction products, performing maintenance work on friction linings, brakes or clutches, maintenance operations such as removing, assembling and disassembling, dusting, machining (rectifying, rectifying, sanding, piercing)
- Dealing with woven asbestos and some opertions: operation on asbestos tapes, ropes or braided asbestos,such as placement, cutting, removal, etc.
- Different kinds of work link to asbestos,including the storage and management of asbestos:
- Cleaning works that need to be finished during maintenance work, maintenance work carried out on the machine or equipment which used to product asbestos or work with asbestos
- Some works (Removal, storage, transportation) to deal with waste made up of asbestos
- Some works (transportation, storage, maintenance) to deal with objects made up of asbestos
- Performing maintenance work on elements of asbestos:
- Maintenance operations involving slicing, cutting, grinding, piercing, removing, carried out on elements which made up of asbestos

Maintenance workers at significant risk who exposed to asbestos-containing materials (ACM) when carrying out their maintenance work and this trend in the future will continue. It is really a difficult work to find samples and evaluate the the exposure of maintenance workers, because there are a large number of maintenance works do not know if they are exposed to asbestos-containing materials (ACM) or not. A survey was conducted in United Kingdom to focus on the awareness of industrial maintenance operators working with asbestos, and compared to the measured actual level of asbestos. The results of this survey show that the expected asbestos level of maintenance operator in their work environment was much lower than the actual measured value[41][42].

There is a study have been conducted to assess the effects of breathing on maintenance workers who are exposed to asbestos environment. For example, the study indicate that maintenance workers who are exposed to asbestos environment and need to work with fragile materials which are made up of asbestos may be related to the frequency of pleural thickening seen by chest X-ray [43].

There are also a large number of studies to analyze the asbestos exposure of car maintenance worker. One of such study [44] provides a historical analysis of published data focus on the asbestos exposure of brake maintenance worker when carrying out their maintenance tasks. In the late 1960s, this hazard were first time taken into consideration. This analysis concentrate on data collection during vehicle brake maintenance activities. There are about two hundreds jobs samples were taken into consideration to evaluate the variation of asbestos concentration by:

- Time duration
- Ways of brake cleaning
- Country where the maintenance operators worked
- Kinds of vehicle used

From result of this analysis, it is convenient to conclude that maintenance workers who carry out repairing tasks on heavy trucks and buses have more risk of asbestos exposures than maintenance workers who work on light trucks. When a brake dust control method was taken in some garages, in order to decrease the level of air asbestos concentration, and led to a 10 times decrease in the air concentrations of asbestos [44].

3.2.2 Working in confined spaces

A confined space refer to an enclosed space or partially enclosed space, when someone is in the enclosed space where under atmospheric pressure [45]. Access to or departure from the space may be restricted, and even if is not mainly used or designed as a workplace, it still allows that people can enter the space to work. At least one of the following listed should be contained or may be contained for a confined space at any time [45]:

- An atmosphere with possibly pollutant which will do harm to people's health
- Something which may led to engulfment
- An atmosphere without a safe oxygen level

Some examples of confined spaces are listed below [45][46]:

- Sewers, pipes, shafts, sewer pump stations containing dry wells or wet wells
- Some tank like carriages, such as tank cars, pressure vessels, silos, process vessels, boilers, storage tanks and others
- Pits and degreasers
- Some spaces on ship entered by narrow hatches or small entry points, such as cellular double bottom tanks, duct keels, cargo tanks, ballast or oil tanks and void spaces

There are harmful gases and toxic vapors in the confined space, which make the confined space become a hazard place for maintenance worker and atmophere in the confined space will have the bad effect on worker's health. The combination of some gases like carbon monoxide, carbon disulphide, hydrogen sulphide, hydrogen cyanide

with the condition of having not enough oxygen may led to the death of maintenance worker. A study found that the most of poisoning deaths related to confined spaces[47].

There are usually two reasons can account for the accidents in confined spaces:

- The person who in charge of the work knows nothing about the risks in the workplace and in the process of completing the work
- Between maintenance department and production department lack necessary communication

Meanwhile some operations in confined spaces may also result in risks [48].

3.2.3 Welding work

Maintenance operators usually need to carry out electrical arc welding work, this requirement will result in maintenance operators at risk of harmful smoke and toxic gases because electrical arc can release smoke and gases. According to the which type of protective gases or electrode coating are uesed, as well as the base material or auxiliary material, the way of inhalation will be different. Usually maintenance operators are at risk of metal smoke such as oxides of iron, copper, chromium, aluminum, nickel and harmful gases such as oxides of nitrogen, carbon monoxide, ozone, etc [49].

There is a study indicate that they could not show the exposure of harmful smoke and toxic gases because of electrical arc can directly led to lung cancer, but maintenance operators work in such environment for a long time will cause an increase risk of lung cancer [50]. There is a study aim to find the morbidity rate of both systemic disorders (metal fume fever) link to welding work and respiratory disorders (occupational asthma) link to welding work in a sample of maintenance workers who carry out welding work, and try to find the importance of relationship between systemic disorders and respiratory disorders. As a result, the authors of the study found that there is a strong relationship between systemic disorders (metal fume fever) link to welding work and respiratory disorders (occupational asthma) link to welding work. Therefore, welding work related metal fume fever can be regarded as an advanced symbol of occupational asthma link to welding work [51]. Also when maintenance operators carrying out welding work, the smoke and toxic gases may interfere with the steady state of trace elements in human circulation and induce oxidative stress [52].

3.2.4 Exposed to dangerous substances when performing maintenance on industrial equipments

When maintenance operators performing maintenance work on machine or equipment that need to use chemical substances or the machines are used to produce dangerous chemical substances, maintenance operators would be exposed to an environment with dangerous substances.

People can contact the dangerous chemical substances mainly by skin or by breathing. For instance, during the shutdown period of a factory which used to produce toluene diisocyanate (TDI), a high exposure level of dangerous chemical substances was measured [53].

Here is a table to describe how chemicals enter the body [54]

Inhalation	In the polluted work environment, breathing is the most common way that chemicals enter the maintenance workers' body
Skin contact	When maintenance worker's skin contact some chemicals, these chemicals maybe result in the damage of the maintenance worker's skin
Ingestion	If the food or hands of maintenance worker are polluted, the chemicals maybe swallowed occasionally, this also can make a damage to maintenance workers
Injection	When a maintenance worker deal with a sharp object, and it punctures the skin, then the injection can happen.

Table 6 The ways of chemicals enter the body

There was a survey conducted by BAuA (German Federal Institute for Occupational Health and Safety) in the period of maintenance activities[55]. Meanwhile some measurements such as stationary sampling and personal air sampling were made in the workplace. As regarding to personal protective equipment (PPE), it is necessary to record and analyze the information such as the quality of protective equipment, the sizing and the usage condition of personal protective equipment. There are a variety of chemical products (such as vinyl chloride, chlorine and organic solvents) produced by the companies which are invested in the survey.

As the result of the measurements carried out in the survey showing that there are about a quarter of total number of workplace (about 170) have a high value more than the occupational exposure limits. This more than occupational exposure limits situation usually take place in cleaning work, then replace the valves [55].

Not only breathing exposure was studied but also skin exposure was still analyzed. Skin exposure was different from the breathing exposure. Comparing with the normal operations, the skin exposure had a large area exposure when carrying out maintenance work. It was found that there were more than 75 per cent of total cases could not use personal protective equipment (PPE) correctly [55]. Chemical hazards is common during the maintenance activities, but personal protective equipment can not be used correctly in some maintenance cases, so it is necessary to provide suitable personal protective equipment and use them correctly, in order to increase the safety of maintenance worker.

3.3 Biological hazards

Maintenance operators who have been exposed to biological agents, particularly those from the following departments [56]:

- Performing maintenance work in some place in hospital such as diagnostic laboratories, veterinary and clinical room
- Carrying out waste management work
- Exposure to pharmacological plants
- Requiring to use biotechnology during maintenance

3.31 Maintenance work in the hospital: COVID-19 virus

Nowadays, Coronavirus are spreading in the worldwide, until 2 March 2021, there are more than 114 million cases have been confirmed, with more than 2.53 million deaths attributed to COVID-19, making it one of the deadliest pandemics in history [57]. Hospital is one of the locations where can contact the Coronavirus easily, when a maintenance worker need to carrying out maintenance tasks in the hospital, maintenance worker need to pay atttention to this problem.

There are two main spreading ways of the Coronavirus [59]:

- Close contact: The Coronavirus can spread by close contact, when someone is speaking loudly or coughing or sneezing, the droplets will come form nose and mouth. So keeping a safety social distance is a necessary work to reduce the spreading of the Coronavirus.
- Infected surfaces: If someone who with the Coronavirus sneezes or coughs, droplets will attach to the surface of around objects. When people touch the polluted surface by their hands and then touch their eyes, nose or mouth, and finally will be infected.

Here is a table to list the symptoms of COVID-19 [58]

Most common symptoms	Fever
	Dry cough
	Fatigue
Less common symptoms	Loss or change of taste or smell
	Nasal congestion
	Conjunctivitis (also known as red eyes)
	Sore throat

	Headache
	Muscle or joint pain
	Different types of skin rash
	Nausea or vomiting
	Diarrhea
	Chills or dizziness

Table 7 The symptoms of COVID-19

Here some actions can be taken in order to protect maintenance workers who work in the hospital maybe contact the Coronavirus [59]:

- After finishing the maintenance operations, maintenance workers need to wash their hands using soap and water or alcohol hand sanitiser, because the hands contact the tools or objects which may have Coronavirus.
- During the maintenance process, the maintenance workers need to wear the face masks, because the Coronavirus can apread by air.
- Do not touch eyes, nose or mouth if the hands of the maintenance worker are not clean after using the tools or contacting the objects.
- If possible do not share own maintenance tools to others, clean and disinfect frequently touched tools or objects and surfaces.
- Keeping social distance with other people, and avoiding any crowded places.
- If possible, finishing the maintenance operations alone, trying to avoid the team work.

3.3.2 Maintenance work in wastewater treatment plants

Maintenance work in wastewater treatment plants always include chemical process, biological process, physical process to remove pollutants[60]. During these maintenance work peocesses, maintenance operators can be exposed to a variety of harmful biological agents and dangerous chemical substances. According to the concentration of wastewater and species spectrum, the composition of microbial community in wastewater treatment plant can be changed, some other elements such as the type of chemical substances in wastewater, the introduce of microorganism, climatic conditions also can change the composition [60][61].

A study foucs on the disorders of maintenance operators carried out maintenance processes at wastewater treatment plants. Here list three related disorders[62]:

- ‘flu-like and systemic disorders’
- ‘lower respiratory and skin disorders’
- ‘upper respiratory disorders’

The result found that if maintenance workers who were exposed to an environment with a high value of endotoxin (usually more than 50 endotoxin units per m^3 EU/m^3), the risk of disorders would increase [62].

3.3.3 Maintenance work in solid waste treatment plants

Maintenance operators carry out maintenance work in solid treatment plants also at risk of a variety of biological hazards. It is a common condition for maintenance workers, because fungi, viruses, mould, spores, bacterial cells and degradation products appear in the form of bioaerosols or biological agents attached to biodegradable waste [63]. When maintenance workers carrying out maintenance operations in such work environment may led to not only a variety of breathing disorders (such as bronchitis, allergies) but also some other diseases such as viral hepatitis, hemorrhagic fevers, Q fever, tuberculosis, bacterial dysentery, brucellosis, leprosy, meningitis, diphtheria and cholera[64].

3.4 Psychosocial hazards

Some studies [65][66][67] presented examples that psychosocial fators that can result in safety problems during maintenance operation.

- There are some difficult problems need to be solved during maintenance process and have a time limition. When maintenance operators carring out maintenance tasks, the productivity of the plant will decrease. The plant want to begin their production activities as quickly as possible in order to carry out manufacturing tasks and workers also wait to continue their works. This condition will increase the risk of mistakes and accidents, because maintenance workers are at pressure and stress. Meanwhile, bad work environment (such as hot work environment) also can increase the stress level, led to an increase risk of mistakes and accidents.
- Working at night, working on weekends, shift work, on call work, and working at irregular time. This condition can result in increase of stress and cause mental health problems such as fatigue, sleeping problems, lose balance between work and life, etc [68].
- Maintenance operators performing maintenance work in a place with unexpected safety risks
- Having difficulties to contact with maintenance workers who come from contractors can increase the accidents risk
- Maintenance workers need to solve complicate problems by using non-routine methods. With the development of technology, machines and equipments become more and more complex. To carry out maintenance operations on modern machines and equipments, worker required to understand the specific knowledge. Sometimes maintenance workers need to carry out operations on machines without human-machine interface, this means that maintenance workers can not know the related parameters

- Sometimes maintenance worker required to carry out operations alonely, this condition will result uncertainty and nervous, and workers can not get necessary support from others. Maintenance workers can help themselves by using their own abilities when an accident take place. If a serious accident happen that maintenance workers can not help themselves, in such condition maintenance workers can do nothing only waiting for help. When workers performing the maintenance operations alonely, the others do not know the accurate position of maintenance workers, it make difficulties to help them, the risk of accidents is very high
- In the whole industrial system, maintenance works sometimes are considered as manual work which need little or no mental work. This situation make maintenance workers consider their job is not a professional work, decreasing the confidence and satisfaction, increasing the related stress.

3.4.1 Working time characteristics

Talking about the working time characteristics, there was a survey conducted by SUMER focus on some characteristics of the working time of maintenance employees, and found that comparing with whole professional families, maintenance operators did not have higher constraints [2].

The results of the survey are listed here:

- From availability in case of emergency aspect, maintenance workers needed to be more available in an emergency than the whole professional families, the percentage of maintenance worker was 24.39% and the whole professional families accounted for 10.5 per cent. This situation can be particularly found in skilled maintenance workers (27.3%) and maintenance and organisation technicians and supervisors (28.5%).
- Talking about Occasional night work (need to work between midnight and 5 AM), skilled maintenance workers accounted for 22.3 per cent and the proportion of maintenance and organisation technicians and supervisors was 15.2 per cent. it was easy to find that the percentage of the whole professional families (9.3%) lower than skilled maintenance workers and maintenance and organisation technicians and supervisors.

3.4.2 Limitions linked to pace of work

There was a survey which conduced by SUMER show the information about limitions linked to pace of work [2]. Some results were listed here:

- From the point that maintenance workers needed to give up a task and continue to carry out unplanned operations, the percentage of maintenance workers was 67.3 per cent meanwhile the whole professional families account for 58.1 per cent. And this condition was particularly for automotive repair workers, the proportion was 73.1%.

- Comparing with other type of employees in the survey, maintenance workers had more limitions linked to pace of work. The limitions usually included characteristics were listed following:

- No instant answer requirement for outside requests, the proportion of total maintenance domain and the whole professional families were 60.12% and 58.9%. This condition was particularly for automotive repair workers which account for 65 per cent.

- Achieving the production requirements or deadlines in one hour or more, the proportion of total maintenance domain and the whole professional families were 26.64% and 19.9%. The percentage is similar for skilled maintenance workers (27.2%), automotive repair workers (28.7%) and maintenance and organisation technicians and supervisors (25.1%).

- In case of preventing absences, workers were required to rotate around different workstations, the proportion of maintenance workers and the whole professional families were 30.58% and 27.1%. This condition was particularly for maintenance and organisation technicians and supervisors, the percentage was 31.8%.

3.4.3 Job control and autonomy

Some characteristics related to the autonomy and job control of maintenance workers were analyzed by SUMER [2]. Some results were shown here：

- There were about 32 per cent of maintenance workers considered that when performing maintenance operations, their actions were controlled or computerised follow-up, meanwhile, the whole professional families accounted for 27.2 per cent. And percentage of maintenance and organisation technicians and supervisors was higher than others, about 37.4%. As for the skilled maintenance workers and automotive repair workers, the percentage are 33.3% and 20.6%.
- There were about half of maintenance workers were required to report their maintenance activities by writing at least once a week. At the same time, the percentage of the whole professional families required to record maintenance activities was 30.8 per cent. For skilled maintenance workers had a higher percentage than others which was 59.3%. As for the automotive repair workers and maintenance and organisation technicians and supervisors, the percentage are 41.6% and 49.2%.
- Comparing with the percentage of the whole professional families that could not change the order of tasks to be completed (14.8%), the proportion of maintenance workers was relatively low, the percentage was 7.54 per cent. Maintenance and organisation technicians and supervisors was particularly, the percentage was only 4.8 per cent. As for the skilled maintenance workers and automotive repair workers, the percentage are 6.5% and 14.3%.

For maintenance workers in the survey [2], the difficultis linked to inadequacies more than the whole professional families:

- Lack of necessary work informtion (22% VS. 19%)

- Lack of professional training (24% VS. 20%)
- Lack of necessry critical materials (24% VS. 20%)
- Lack of enough number of employees (27% VS. 26%)

3.4.4 Difficulties related to subcontracting maintenance

Subcontracting maintenance is a necessary part in modern industrial manufacturing system, it can help plants restart their production activities as soon as possible. But from safety and health point of view, subcontracting maintenance itself can increase the risk of maintenance operators.

If miantenance operators carry their maintenance operations not in their familiar workplace or need to change their work environment frequently, then maintenance workers need to familiar the new work environment, and most subcontracting maintenance works are not routine works, this condition will increase the mental stress of maintenance workers, if have the time limitation, maintenance operators maybe make a mistake during maintenance process, such as missing one of the maintenance steps or using a wrong tool, this may increase the safety risks of the maintenance worker [69]. Meanwhile maintenance operators required to travel from one workplace to another frequently, also can make them exposed to road related hazards [70].

Subcontracting maintenance activities can result in some subcontracting maintenance companies carry out maintenance operations at the same time, where user company manage the task assignment and may give time pressure on subcontracting maintenance companies [70].

So it is can be concluded that carrying out maintenance operations in a variety of workplace can increase the safety risks: comparing with long-term employees, subcontractors who seldom work in the facilities can not manage their work environment, this condition can make maintenance operations finished incorrectly, increasing the risk of the maintenance workers.

4 Industry 4.0 and technology

4.1 Backgroud of Industry 4.0

Industry 4.0, also can be called as the Fourth Industrial Revolution (4IR), it is a technical revolution period nowadays consists of a vareitey of modern technolofies, such as artificial intelligence (AI), augmented reality (AR), big data, cloud, simulation, the Internet of Things (IoT), robotics, additive manufacturing, horizontal and vertical system integration, cyber security [71]. In a study, researcher sometimes considers that Industry 4.0 have a more accurate meaning, they present their opinion that Industry 4.0 is a part of 4IR, but in most situations, using Industry 4.0 as the same meaning of 4IR [72].

Because Industry 4.0 technologies can bring a variety of competitive advantages, so more and more companies adopt modern advanced technologies such as artificial intelligence (AI), augmented reality (AR), big data, cyber-physical systems (CPSs), the Internet of Things (IoT), robotics, automation and machine learning (ML) into their company strategies. And apply these technologies into manufacturing, maintenance, plant management and business procedures. Through the digitization and automation of products and services result in a large number of new business operating models. Industry 4.0 will have a variety of benefits to the society, business, economy and jobs [72].

There are four industrial revolutions in the history, but the the Fourth Industrial Revolution is different from the other three industrial revolutions, because the Fourth Industrial Revolution have a significant effect on the future of society and the way of our work. The Fourth Industrial Revolution change the way of training, the way of education, the way of work and the way of life [73].

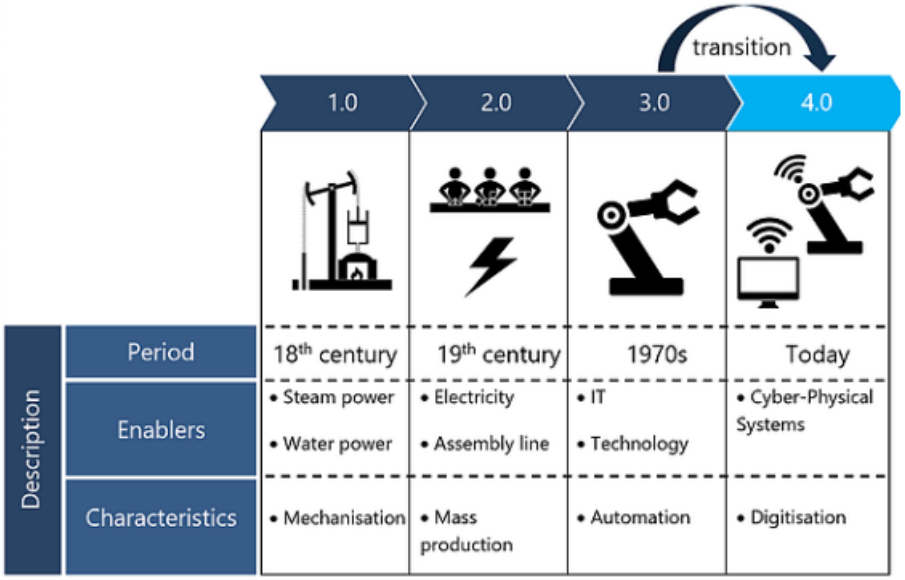

Figure 12 Industry 4.0 concept development [75]

Nowadays, the Fourth Industrial Revolution is undergoing. Industry 4.0 is developing based on the third industrial revolution and the digital revolution, which were happened in the middle of the last century [73]. Industry 4.0 can combine the physical, digital, and biological domains, so that we can construct a new virtual world, making a better understanding of physical world. Some Industry 4.0 technologies such as the Internet of Things (IoT), big data, cloud computing can link mahines or equipments and allow to communicate in real time. Artificial intelligence (AI) can apply in most industries, such as self-driving cars and virtual assistants like Siri, which is a augmenting precess. Artificial intelligence (AI) and automation are change the way of transport and manufacturing [74]. These changes will have a global effect on upgrading of production, manufacturing, management and governance systems. Meanwhile Industry 4.0 also bring changes on the way of communication, learning, entertainment, and help us better to deal with difficult problems.

On the one hand, Industry 4.0 can make a variety of advantages and benefits. A variety of advanced technologies are being created and applied in a fast rate. Innovation technologies based on Industry 4.0 can improve the operational efficiency,

this means that greater output can be achieved from the same input. With the increasing the efficiency, better products and services can be provided. Overall, Industry 4.0 can offer a much more meaningful and convenient lives to us [76]. On the other hand, Industry 4.0 can introduce a larger inequality, paiticular it can make a significant effect on labor markets, sometimes can interfere the order of labor markets. Owing to Artificial intelligence (AI) and automation become more and more smart and can instead of labor in the almost entire indutries, meanwhile the replacement of labor will greater the gap between returns to capital and return to labor [77].

Through history can find almost all industrial revolutions can bring advantages and disadvantages. But by studying and understanding the bad effects, such as high cost, need for highly skilled labor, cybersecurity threats, increasing social and income inequality, possible unemployment and replacement. Some actions can be taken to manage the technical development process and try to reduce the bad effect. In order to make sure technological development cater to humanity's needs and values [76] [77].

4.2 Advantages of Industry 4.0 to increase the safety of the maintenance [78]

- Training: Modern machine or equipment are becoming more and more complex, so related maintenance steps also becoming complicated. If a maintenance worker carrying out maintenance operations on a not familiar machine, or not familiar his maintenance operations, this condition maybe can increase the risk of safety during the maintenance process. However, comparing with the traditional training instructions, Augmented Reality (AR) and Virtual Reality (VR) are the effective tools to create the new training ways. These technologies can help maintenance workers more familiar with their maintenance operations, and during the real maintenance process decrease the risks of forgetting to perform one of the maintenance steps or carrying out wrong maintenance operations, increasing the safety of the maintenane workers
- 3-D work instructions: Usually, maintenance works involving assembly and disassembly process, the steps of the assembly and disassembly process sometimes is significant, because if steps are carried out incorrectly, this will increase the risk of maintenance workers. But using 3-D work instructions, maintenance workers can better understand their tasks and how to finish them, the hazards also can be highlighted in the 3-D work instructions, so this can increase the awareness of the safety and help maintenance workers know about the hazards during the maintenane process.
- Assistance from remote experts: Maintenance works are not routine works in most condition, maintenance workers often have problems that they can not deal with during the maintenance, so a remote assistance is necessary. If a maintenance worker not skilled enough to perform maintenance operations, in this condition, the risk of safety will increase, but remote assistance can make a collaboration with the maintenance workers and knowledgeable experts, so guidance can be provided to the maintenance workers, this can increase the safety of the workers.

- Real time monitoring: Monitoring the condition of the machine by using sensor technology, Industrial internet of things, and cloud, the condition of machine or critical parts of machine can be monitored. This can help maintenance workers better understand the machine and find anomalies. Before the machine breakdown, maintenance workers can replace a new one part or repair it. This also can help maintenance workers locate the broken parts quickly, in case of a maintenance worker can not find the broken parts. If a maintenance worker do not know which part is broken during maintenance process, this maybe increase the risk of safety. And with big data and machine learning can be used to provide the prediction of failure, help maintenance workers to schedule the maintenance activities in a appropriate time.

  Meanwhile, the healthy condition of maintenance workers who are regularly exposed to hazardous environment also can be monitored. Wearable sensors can be used to monitor the condition of maintenance workers, such as blood pressure, behavior information, environmental information. By tracking these information, a warning can be sent to maintenance workers to remind them need a rest or they are in a hazardous condition.
- Autonomous robots: Robots can be used to finish some maintenance operations instead of an operator. Some maintenance operations need to be finished in a hazardous environment, in this condition, robots can be used to replace human workers, this can increase the safety of maintenance workers.
- Additive manufaturing: Sometimes maintenance workers need to use special tools in order to finish the maintenance tasks, and these special tools can not be found easily. So using additive manufaturing technology can produce a customized tool for maintenance workers. This can reduce the risk of maintenance workers using an inappropriate tool. Additive manufaturing technology also can produce a part that maintenance workers want to use it to replace the broken one, but temporary can not find.

4.3 Design principles of Industry 4.0 [101]

- Interoperability: Through The internet of things, sensors, machines, devices, and human can connect and communicate to each other. It is convenient for maintenance workers to know the information about the machine condition, then maintenance activities can be scheduled according to the machine cindition.
- Information transparency: The information system have the ability that can build a virtual copy of the real word through the digital models and information from the sensor. The virtual word can be used to train the maintenance workers before the real maintenance process, this can help maintenance workers more familiar their maintenance works.
- Technical assistance: The support system have the ability that can help maintenance worker by visualizing information, this useful maintenance information can help to solve the problems during the maintenance process, increasing the safety of the maintenane workers.

4.4 Technologies of industry 4.0

There are some studies [79] [80] [81] conclude that nine modern advanced technologies whether used alone or used in a set can improve technological developments in some appointed domains.

Nine modern advanced technologies are: Big Data and Analytics, Cloud computing, Industrial Internet of Things (IIoT), Simulation, Augmented Reality (AR), Additive manufacturing, Autonomous Robots, Horizontal and vertical system integration and Cyber Security. These nine modern advanced technologies of Industry 4.0 can make the normal factory become more 'smart' or 'intelligent', which means the factory more integrated, automated and production process can be optimized.

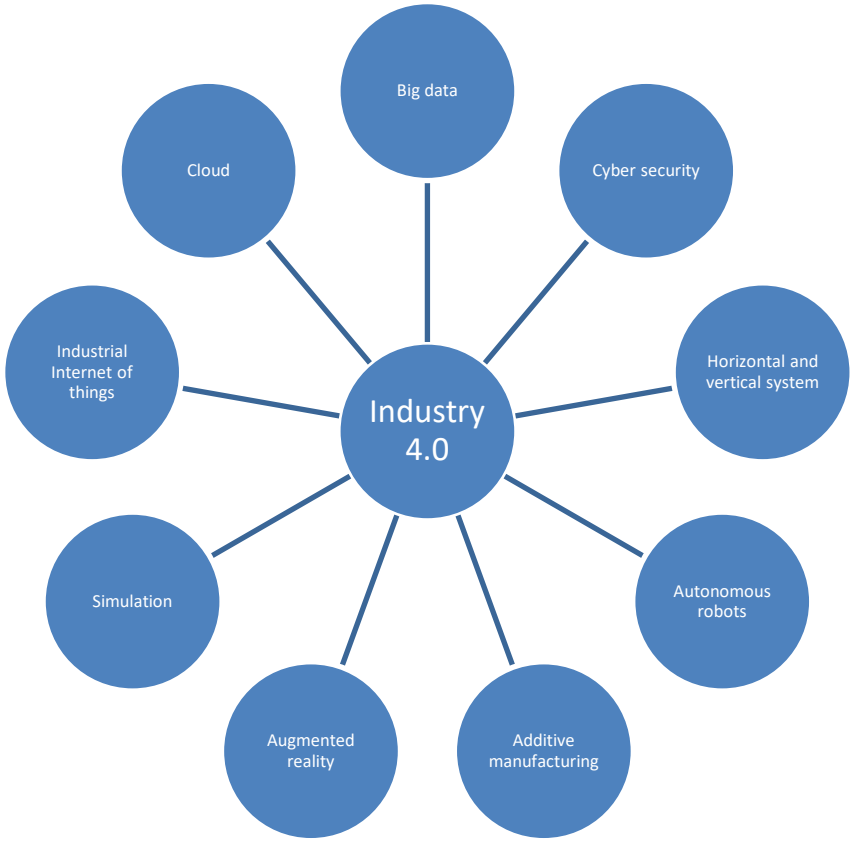

Figure 13 Industry 4.0 engines

4.4.1 Big Data and Analytics

Most cases in Industry 4.0 are data intensive, data flows always come from a variety of data source. The definition of big data come from Witkowski [82], big data is consist of four parts: Volume of data, Variety of Data, Velocity of generation of new data and analysis, Value of Data, most of the Industry 4.0 cases are based on these features. Big data, cloud and CPS build an indutrial network and result in the smart factory. The example of big data using is predictive maintenance, comparing the sensor data with the enterprise system data , to evaluate machine condition and predict machine breakdown. So big data and related tools are the significant elements in the Industry 4.0. Since a lot of industrial cases require to integrate a variety of

scattered data sets and need to store data in a reliable and effective way, so Industry 4.0 usually use big data technology to collect useful information, integration and storage. But the most important thing is data analysis by using big data analytics technologies, such as machine learing. There are a variety of domains that big data analytics and machine learning can be applied, such as production precess monitoring and control, trend analysis, product quality control.

4.4.2 Cloud computing

According to Zolotová [83] and Hassan [84], Cloud computing is a technology can provide an effective way to share information or even devices. Through using cloud technology, it is convenient to share production information in the whole factory production sysytem. This is a significant operation to increase the reliability and flexibility of smart manufacturing systems. Cloud usually used in CPS manufacturing systems and applications, because cloud have it's own advantages like big capacity, good flexibility and high quality of service. Nowadays more and more companies prefer to use their enterprise systems in a cloud way.

4.4.3 Industrial Internet of Things (IIoT)

According to Atzori [85] and Gubbi [86], Industrial Internet of Things (IIoT) is an extended meaning of Internet of Things, which mainly applied in industrial domian. It describes an interaction between a variety of machines without worker's interference. By using standard internet protocols, The Industrial Internet of Things can connect the machines or equipments through sensors which are usually mounted in the critical part of machine or equipment.

Nunes [87] present that in order to construct the cyber-physical systems (CPS), Internet of Things is one of the basic elements, it is a system that can offer the function of computation, communication and control. Cyber-physical systems (CPS) provide a way to combine the virtual world and physical world, removing the boundaries between them. Cyber-physical systems (CPS) also can be described as 'the systems in which natural and human made systems (physical space) are tightly integrated with computation, communication and control systems (cyber space)' [88]

Cyber-physical systems (CPS) are considered as one of the significant elements in the Industry 4.0 system. There are a large number of machines or equipments are cyber-physical systems (CPS) which not only can offer a way to collect digital data from the physical objects, but also can provide a way of operating and control on machine or equipment. In other word, Cyber-physical systems (CPS) is a type of Industrial Internet of Things, it can realize interaction and data exchange. Meanwhile, Industrial Internet of Things (IIoT) systems provide a way for old machines to interconnect with IT systems and also considered as cyber-physical systems (CPS). To perform the reliable operations and achieve high performance in a smart factory, complex and heterogeneous systems need to be combined each other. Big data analysis has two basic elements: data collection come from cyber-physical system (CPS) and come from customer-management system [79]. Overall, CPS and IIoT systems will play a critical role in the Fourth Industrial Revolution in the years to come.

4.4.4 Simulation

According to Chong [89], simulation is a digital tool which can help to design manufacturing systems in order to realize the effective, safe and reliable maintenance. Simulation is also involved in value networks and real time optimization of data from intelligent systems. Through using 3D simulation, physical objects can be builded digitally or recreated through field tests, this can increase the safety of workers during the operation precess, even though workers are not familiar with the work environment. Usually augmented reality is combined with simulation to help workers during their operations, increasing the safety level for workers and keeping the duration time as a same level as before.

4.4.5 Augmented Reality (AR)

Accoring to Figueiredo [90], augmented reality (AR) technology can provide an interaction between human and machine, which combines the digital data and reality, mixing them coherently in order to realize the augmention of reality. Augmented reality (AR) technology have the ability of offering useful real time information for maintenance operations or other manufacturing operations [91] [92]. By using smart devices such as wearable AR devices, useful information can be shown. Meanwhile, augmented reality (AR) technology has been applied in factory for many years. It has been developed since the appearance of accurate tracking technologies and new more complex devices. Augmented reality (AR) can be applied in a variety of ways to take part in industrial activities. For example, Augmented reality (AR) can provide remote assistance for maintenance workers when carrying out their maintenance tasks. With augmented reality (AR) technology maintenance workers do not need to consult paper materials or ask a phone assistance. Maintenance workers only need to view online maintenance instructions offered by experts. Another example of using augmented reality (AR) technology is to train maintenance workers who need to carry out complex maintenance tasks, through showing them the operation ways which performed by ecperts or experienced maintenance workers.

4.4.6 Additive manufacturing

3D Printing is a typical example of additive manufacturing and it is one of the digital automation platforms and processes [93]. 3D Printing also can benefit to the cyber-physical manufacturing systems (CPS). The digital data come from Industry 4.0 intelligent system can be used in the 3D Printing process, for example a twin of a part come from a machine or equipment that can be printed [94]. When implementing the digital manufacturing usually along with the additive manufacturing. For example, 3D Printing have the ability to speed up the maintenance process, because it can print necessary tools or broken machine parts that will be replaced, instead of waiting for a new machine part or keep a large inventory. Meanwhile, 3D Printing process can be integrated to realize the production line and products produced more flexible to be customized [94].

4.4.7 Autonomous Robots

Autonomous Robots can offer a variety of more autonomous, cooperative services and usually applied in different areas. According to Djuric [95], Sadik and Urban [96], Autonomous Robots can interconnect to each other and can support workers when they performing their operations or can even help workers to carry out tasks directly. Additive manufacturing provide a ability to transform a digital desigen like 3D-CAD to a physical object by using 3D Printing technology [89]. This manufacturing method is often used to produce small scale customized products [97].

4.4.8 Horizontal and vertical system integration

According to Peres [98], Stock and Seliger [99], horizontal and vertical system integration means that an integration of the whole supply chain, realizing a goal to interconnect to each other between all the elements in a highly dynamic system.

4.4.9 Cyber Security

According to Wells [100], cyber Security is the technology able to protect shared information and CPSs from cyber-attacks. Industry 4.0 applications can result in a variety of security risks. So Industry 4.0 solutions should have a high cyber security in order to protect datasets and IT assets, make sure the new devices work in a reliabe and effective way.

5 Industry 4.0 Solutions to increase the safety of the maintenance

5.1 Predictive maintenance

In intelligent factories, a large number of manufacturing precess data are available result in new advanced maintenance approach. This new maintenance approach can make maintenance workers to monitor the machine condition instead of machine faults, in order to predict the possible machine breakdown and optimize the utilization of assets. Usually this new approach is called predictive maintenance (PdM), sometimes predictive maintenance (PdM) can be considered as preventive maintenance with real time work. Predictive maintenance (PdM) of industrial machine is one of the most significant applications in the Industry 4.0.

One of the basic elements of Industry 4.0 is machine real time monitoring, and there are a lot of systems have been created to diagnose a machine or parts by monitoring different kinds of variables in industrial factories such as pressure, speed, temperature, vibration, noise, etc. With the development of micro-electromechanical

systems led to a large number of sensors can be used, these sonsors have the ability of sensing, computing and communicating wirelessly in order to collect useful machine real time condition data. Internet of things (IOT) plays an important role to make the machines connected through using related sensors in order to realize the wireless networks. Collected data will be sent to cloud for storage or further analysis in the future. There are a lot of cloud servers provide Internet of things (IOT) services of real time storage and extracting analytics from the data using IoT protocols and technologies. Owing to this, it is possible to predict machine breakdown in the future through using historical data.

Sometimes, a lagre amount of machine condition data need to be sent to cloud or a long latency time to send machine condition data to cloud. Under this condition, computation part can be scheduled closed to sensors, this reduce the resource consumption in the cloud. The fog computing method can facilitate to fully use resource of sensors which are amounted on the machine or critical parts of mahine or equipment and gateways which can interconnect sensors and along with cloud resource. To implement the fog computation, it need to create the topology structure to interconnect sensors and gateways offering to connect the cloud. Usually the datasets come from sensors can be pre-processed, filtered before sent to the cloud. Meanwhile, gateways also can perform data analytics work. Overall, it is important for fog structure to balance the computation load and network resource consumption, to decrease the cloud costs and to reduce the latency time [102].

Real time machine condition monitoring to monitor the abnormal operation condition is a kind of predictive maintenance, it is possible to be performed when no historical failure data can be used. When historical failure data is available, data analysis method such as Machine Learning models can be used to predict machine breakdown in the future, in order to schedule the maintenance work in advance. The models used to predict machine failure are tested and trained by using historical failure data of machine or equipment. The amount of historical failure data of equipment always large, so it is very important to take real time storage in the cloud into consideration, this also can led to predictive maintenance based on cloud.

5.1.1 Predictive maintenance on electrical motors [102]

In most industrial plants, it is important to monitor the machine working condition of electrical motors because they are commonly used as actuators, so predictive maintenance based on cloud technology is a good maintenance method for electrical motors.

Usually vibrations along with the mechanical failures for electrical motors. These vibrations have different amplitude at different frequency. So vibrations and temperature are the most critical variables during monitoring the machine working condition.

According to L. Magadan, F.J. Suarez, J.C Granda, D.F. Garcia [102], they built a real time monitoring system to measure the vibration of the motor, in order to carry out the predictive maintenance on electrical motors.

The system structure is consist of three layers in which data can be processed. The first layer is called “Edge” layer, which is consist of sensors mounted on the machine or critical part of machine. The second layer is called “fog” layer, which is consist of

gateways. The third layer is called “cloud” layer, in which the machine condition information can be stored, analyzed and visualized here.

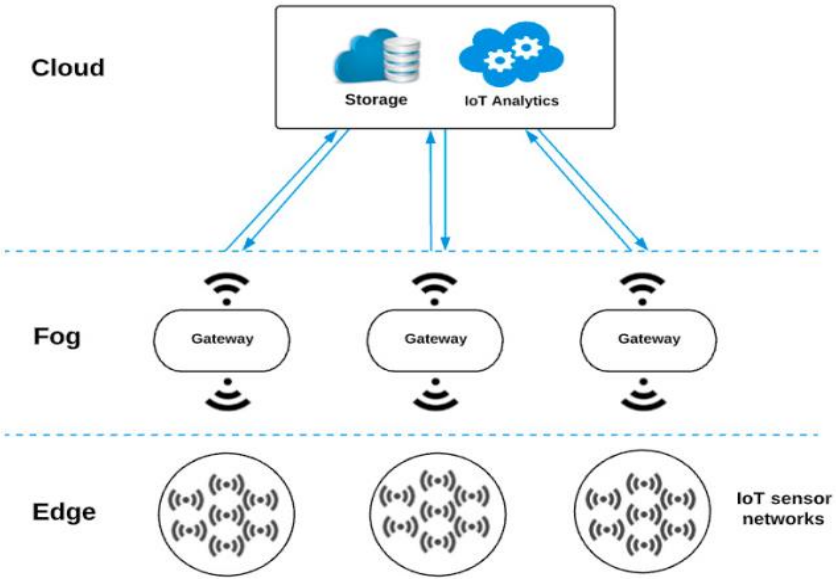

Figure 14 The stucture of the monitoring system[102]

All the three layers the have the ability of computation. In the first edge layer, the sensors can directly perform some tasks, such as data can be filtered, gathered and transformed in the sensors. In the second fog layer, data come from the sensors which are mounted on the machine or critical machine parts can be collected wirelessly by using the gateways and then the data can be processed. The first edge layer and the second fog layer all contribute to process the machine condition data from sensors to cloud, this in order to reduce latency time and decrease the amount of data need to be sent to cloud.

Measurement method

In order to perform the predictive maintenance on electrical motors, the authors using two different scenarios.

In the first scenario, the authors carried out measurement work on a a low power motor measured with no workload in the laboratory. Shown in the following figure 11, a singlephase asynchronous electrical motor is used to tested, The multi-sensor module was placed on the electrical motor plate and the the electrical motor was mounted on the ground of laboratory. Meanwhile, the gateway was put in a place where was close to the multi-sensor module.

In the second scenario, the authors using two motors in the industrial factory,which are measured placed close to each other. Seen from the figure 14, all the two motors are mounted with the multi-sensor module in order to communicate to gateway. Through a WiFi Access Point (AP), the gateway can connect to the cloud layer. From the following figure 15, the position of the second pump and gateway in the industrial plant.

Measurement results

Results in the first Scenario

From the following figure 15, for the first Scenario, these two pictures all can give three fundamental harmonics with large amplitudes of 100, 200 and 300 Hz. These frequency can be found that they are all multiples of the base frequency (25Hz) of the electrical motor.

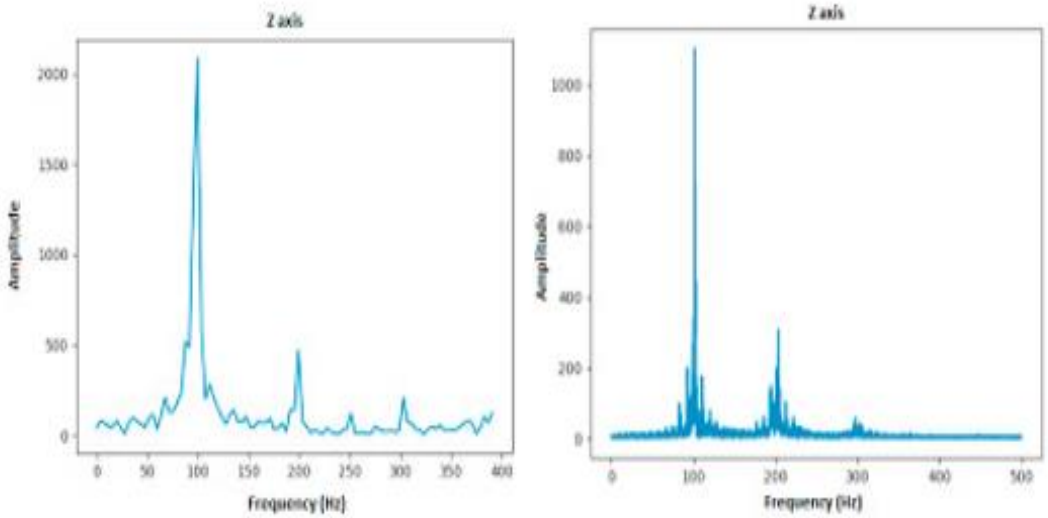

Figure 15 Scenario 1: Results in module (left) and gateway (right)[102]

Results in the second Scenario

The following figure 16, it is easy to find that the first pump has three obvious harmonics, which are 25 Hz, 100 Hz, 300 Hz. But as for the second pump, it has two obvious harmonics, which are 25 Hz and close to 200 Hz.

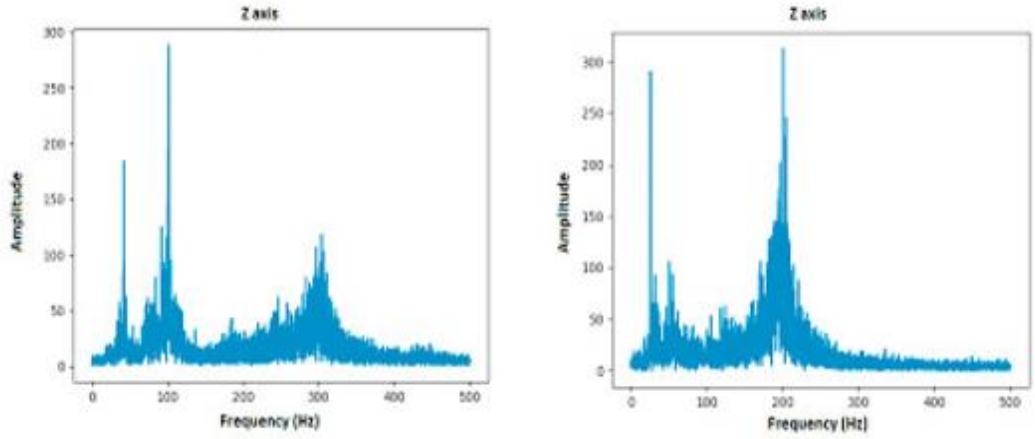

Figure 16 Results for two pumps[102]

Vibration is a significant parameter for the electrical motors, a strong vibration usually represents a mechanical failture, so by measuring the vibration of the

electrical motor then the work condition of the electrical motor can be known. The real time vibrations of the electrical motors can be measured by using sensor technology, industrial internet of things, big data, and cloud. It is very convenient for maintenance workers to know the real time or historical vibration data. These data are helpful to maintenance workers, because data can help maintenane workers increase the maintenance safety:

- Real time vibration data can be seen directly in the wearable device, such as tablet or smart phone, maintenance workers can know the real time wrok condition of the electrical motors, a limitation vibration value can be set, if real time vibration is more than the threshold, a warning will be sent the maintenance workers, reminding the maintenane workers if there is a mechanical failure. Then maintenance workers can perform the maintenanec operations in order to bring the motor back to a normal work condition before the motor breakdown. If a maintenance worker do not know there is a potential mechanical failure in the electrical motor, the safety risk maybe increase during the maintenane process. When after finishing the maintenance operations, the real time vibration data can be used to check the maintenance operations finished correctly or not, instead of a maintenance worker close to the electrical motor to check the work condition, this also can help to increase the safety of the maintenance workers.
- The vibration historical data collected from the sensor stored in the cloud can be labelled with the motor condition information. From the measurement results above in two conditions, it is easy to find that at some centain frequency, there are some strong vibrations. At these frequency, the vibration data can be labelled. For example, at a certain frequcency, a strong vibration because of the bearing failure. If the vibration value exceed the threshold, the maintenance can quickly locate the broken parts, reduing the safety risk of can not find the roots. And these historical data can be used to better understand the work condition of the electrical motors, such as how the motors is likely to deteriorate, so maintenance workers can understand their maintenance operations more easily.
- Sometimes the maintenance workers need to stand or lean on the working electricity motor due to the job requirement, this can make maintenance workers exposed in hand-arm vibration hazards or whole body vibration hazards. In this condition, real time vibration measurement is very important, because when a strong vibration occur that can affect the health of the maintenane workers, a warning will be sent to the maintenance workers that they should stop their work. This can help maintenane workers to decrease the safety risks of vibration hazards.
- Predictive maimtenance on the electrical motors allows to estimate the next motor failure by using the historical data stored in the cloud and Machine Learning. This can help maintenance workers to schedule their maintenance activities. On the one hand, for example, if a motor enters a fail state approximately every six months, then in normal condition maintenance workers will perform maintennance operations in every five months. However, predictive maintenance can give a more accurate day to carry out maintenance operations, it helps to reduce the frequency of maintenance, avoiding excessive maintenance, decreasing the possibility of maintenance workers exposed in a hazardous environment, so increasing the safety of maintenance workers. On the other hands, predictive maintenance can be used to optimize the maintenance schedule. A good maintenance plan can bring some benefits to maintenance workers , such as

schedule an appropriate time for maintenane workers, avoiding night work, weekend work, and emergency work, making the working times more flexible, reducing the psychosocial stress of maintenance wokers. overall, good maintenance schedules can help maintenance workers away from the psychosocial hazards, increasing the safety of the maintenane workers.

5.2 A maintenance support system based on augmented reality technology [103]

C.Y. Siew, S.K. Ong, A.Y.C. Nee [103] created a maintenance support system based on augmented reality have the ability to offer assistance and feedback to maintenance workers when they carrying out their maintenance tasks.

In this maintenance support system, there are three important elements in this system which are the visualisation module, the haptic and motion tracking module, the image-based diagnostic module. The maintenance support system produces augmented visual and audio information can transmit to maintenance worker by using a head-mounted display (HMD). Three modules have their own related functions, and three modules are working together in order to offer necessary assistance to maintenance worker.

Haptic and motion tracking module aiming to offer position awareness and operation awareness to a maintenance worker when they carrying out their maintenance work. This module through tracking the wrist position of maintenance worker in order to offer useful support to maintenance worker when they performing maintenance tasks. In order to offer haptic assistance to the maintenance workers, a definition of $C^{i,N}$ space is used. $C^{i,N}$ can be describe as a space which have a size and it is a type of virtual space. This space can be used to describe the expect location of maintenance worker's wrist when carrying out maintenance tasks with necessary tools in the virtual space, and this corresponding to the position in the real space. Usually only the maintenance worker's wrist location is within $C^{i,N}$ then the maintenance operation can be thought finished. Meanwhile the time that the maintenance workers stay within $C^{i,N}$ to finish the maintenance operation will be collected and stored.

The following figure 17, there is a sample describing the $C^{i,N}$ of a screwdriver and a socket wrench. But it is different between screwdriver and socket wrench, because a wrist circular motion is required in socket wrench, so for socket wrench, two $C^{i,N}$ are used.

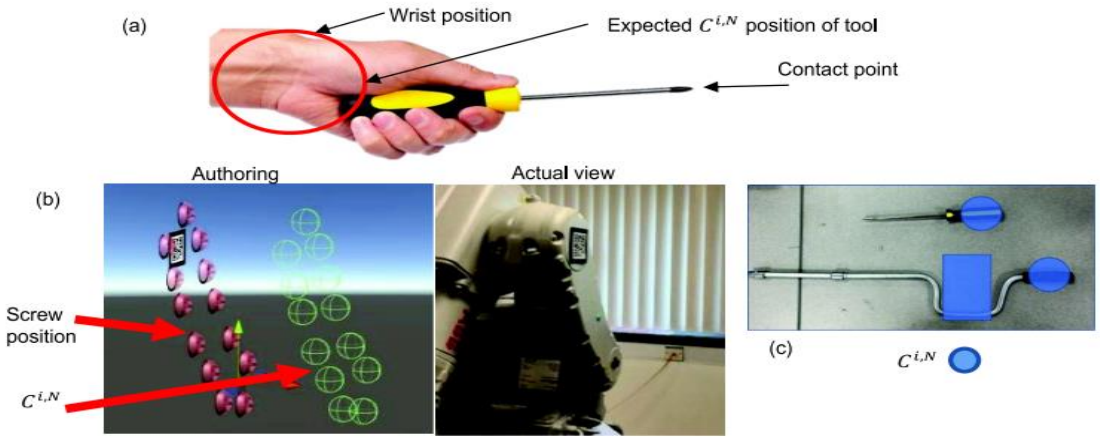

Figure 17 Example of $C^{i,N}$ [103]

Visualisation module is used to provide useful information to maintenance workers. Usually during maintenance process, different maintenance workers have different data visualized requirements. Relative young maintenance workers need more information than experienced maintenance workers. There is an advanced AR-HMI method which in order to build a flexible maintenance support system based on the augmented reality technology. Due to considering the maintenance worker's actual needs, in order to offer the appropriate information and supports to maintenance workers when they performing their maintenance operations, the information presentation ways and augmentation levels can be changed.

There is a camera used in the image-based diagnostic module, through comparing the finished maintenance image with the correct one, in order to check a maintenance operation is carried out correctly or not.

The maintenance support system created by the authors is benefit to maintenance works, due to that it can increase the safety of maintenance worker during maintenance process:

- In the maintenance support system, the real time wrist position of maintenance worker can be detected. If the maintenance worker's wrist position within the expected $C^{i,N}$ space, the duration time that the maintenance worker's wrist position keep stay in the expected $C^{i,N}$ area will be recorded and analyzed. If maintenance worker's wrist position not enter the $C^{i,N}$ space or entering the $C^{i,N}$ space but doesn't stay for enough time, then this maintenance operation can be considered to carry out incorrectly. This can help maintenance workers to check their operations finished successfully or not, preventing maintenance workers to continue the next maintenance step after making an operation error. If a maintenance worker still performing next maintenance operations after finishing the last operation incorrectly, sometimes maintenance accidents are easy to occur and affect the maintenance worker's health, so this can increasing the safety of maintenance workers during the maintenance process. Meanwhie, when an operation completed incorrectly, the system will give a flag to the related $C^{i,N}$. It is convenient for maintenance workers to find the wrong performed maintenance operations, then correct them, this can decrease the safety risk of can not find which maintenance operations are completed incorrectly.

- In most industrial conditions, maintenance works are always not daily routine works, so it is a common condition that during maintenance process, maintenance workers will meet some difficult problems which maintenance workers can not deal with. However, the maintenance support system can provide useful information to maintenane workers, such as augmented visual and audio information, helping them to solve the problems during the maintenance process, decreasing the safety risk of performing a wrong maintenance operation. Meanwhile, when a maintenance worker need to carry out maintenance operations alone, unsolved problems maybe increase the maintenance worker's psychosocial stress, but maintenance support system can provide necessary assistance and helpful information to the maintenance worker, reducing the risk of maintenance worker exposed to psychosocial hazards, increasing the safety of the maintenance worker.

- During maintenance operations, visual augmentation can be used to transmit most maintenance sopprt information. Virtual arrows can guide a maintenance worker to the correct position, it can help maintenance workers to carring out their maintenance tasks in a correct position, this can reduce the risk of a maintenance worker finishing the maintenance operation incrorrectly. Usually textual information can be directly seen from the screen. But not all information is suited to be transmitted through visual augmentation. Because if too much support information transmitted to a maintenance worker, may result in screen in a mess and cause misunderstandings of the support information, this maybe can casuse maintenance operations finished incorrectly, increasing the risk of maintenance worlers exposed in a hazard environment. So in the most situations, visual augmentations are always combined with other types of augmentation, such as audio augmentation, and haptic augmentation, in order to make the maintenance operations to be performed conveniently and correctly, increasing the safety of maintenance workers.
- Haptic augmentation aims to provide vibration information to a maintenance worker by using devices which can produce vibration. Here, for haptic augmentation, an armband is used to offer physical vibration, a maintenance woker need to wear it during maintenance operations. If the arm of a maintenance worker close to the correct work area, a worker will feel vibration come from armband which was worn in the arm. So haptic augmentation can have the ability to offer position awareness assistance to a maintenance worker when performing maintenance operations. This can guide maintenance workers's hands to a correct working area, preventing that maintenance workers performing wrong maintenance operations due to working in a wrong position.
- When maintenance workers carrying out maintenance tasks, according to the difficulty of the maintenance operations which will be performed and other reasons, a maintenance worker usually need to experience some condition transformations. So in this maintenance support system, there are 4 augmentation levels are used. For each level, there are different augmentation schedules. Usually level 1 can be consider as expert level. However, from level 2, augmentation schedules can be used to offer some useful augmented information and necessary assistance to the maintenance workers. The system offers a method that can change the augmentation level according to the knowledge and requirement of maintenance workers. This can offer most suitable information

and necessary support to a maintenance worker, decreasing the safety risk of maintenance workers achieving inappropriate or misleading information during maintenance process. Sometimes inappropriate or misleading information can result in a maintenane worker carrying out maintenance operations incorrectly, this usually can led to maintenance accidents. Providing appropriate and correct information to maintenance workers can help them to deal with difficult maintenance problems efficiently, reducing the risk of maintenance accidents, increasing the safety of maintenance wokers. If a maintenance worker chooses level 4, in this condition the maintenance worker is considered to take part in training activities before carrying out maintenance operations, this can reducing the risk that maintenance workers are not knowledgeable to perform the maintenance operations or not familiar with the maintenance operations, in order to increase safety of the maintenance workers.

- When a maintenance worker finishes the maintenance operations, the worker can use the diagnostic module. Then an related picture will be taken by using the camera. And the picture then will be sent to Matlab. By using the Image Processing Toolbox of Matlab, and a comparison can be made between the finished picture and the ideal picture. Before performing the next operation, the comparison result will be given to a worker. If a positive result is provided, then maintenance workers can performing the next operations, but if a nagative result is provided, maintenance workers are required to check operations they have performed before. This can prevent that maintenance workers continue to perform next maintenance operations after making an incorrect maintenance operation. If a maintenance worker carrying out next maintenance steps after last maintenance operations are performed incorrectly, accidents maybe happen, it will affect the health of maintenance workers, so the diagnostic module also can help maintenance workers increase the safety during the maintenance process.
- If a maintenance worker finished all the maintenance operations, there is a spaghetti chart is created in order to evaluate the maintenance performance of the maintenance worker. The wrist position of maintenance workers can be mapped in the 3D spaghetti chart, the length of the line is equal to the wrist moving distance of a maintenance worker. If the color is green, this means that the maintenance woker's wrist position is within a correct area, however, if the color is blue, this means that the maintenance woker's wrist position is within an incorrect area. Through studying the spaghetti chart, a maintenance worker can clearly know where he makes an error, if he need to perform the same or similar maintenance operations next time, maybe less mistakes will be made, helping maintenance workers to increase their safety during maintenance process.

5.3 Remote-assisted maintenance based on Augmented Reality [104]

From the previous part: The situation of maintenance today, it is easy to know that the shortage of skilled maintenance workers is one of the challenge of maintenance nowadays. There are a large number of maintenance problems need to be solved by

using more expert knowledge. But usually, this kind of professional knowledge can not be found on the internet, because experts are rare sources, and usually in a remote place. So in order to increase the efficiency and safety of maintenance works during maintenance process, it is necessary to build a remote consulations between experts and maintenance workers.

The authors [104] building an innovation remote-assisted maintenance system by using Hololens, and applied it in the automotive industry. Microsoft HoloLens which is Microsoft's latest generation of Optical Head Mounted Displayers, it was used as a remote assistance tool during maintenance process. Optical Head Mounted Displayers have the ability that maintenance workers can see the real objects and virtual augmented objects.

The authors using four cameras in order to better understand the environment, which are equipped in the HoloLens. Each side of the HoloLens have a camera, a depth camera and an ambient light sensor are required to be used, meanwhile, a 2MP photo/HD video camera also need to be used. Such combination can make the real-time spatial data shown in the video information. The real-time spatial data is the basic element in the Augmented Reality features of the system. Maintenance workers who wearing the HoloLens can create 3D-Holograms, meanwhile, 3D-Holograms also can be created by the experts. For the experts, the live maintenance condition video can be directly seen in a first-person view taken by the maintenance workers who wearing the HoloLens. During the maintenance process, the a scene of live maintenance condition video can be stopped, and experts can make some useful notes information and 3D Holograms, then these can be transmitted to the HoloLens. These notes created by experts will be augmented in the real view of the maintenance workers. The position of the notes will be placed in the initial postion where experts created, regardless of the movement of the maintenance worker's head.

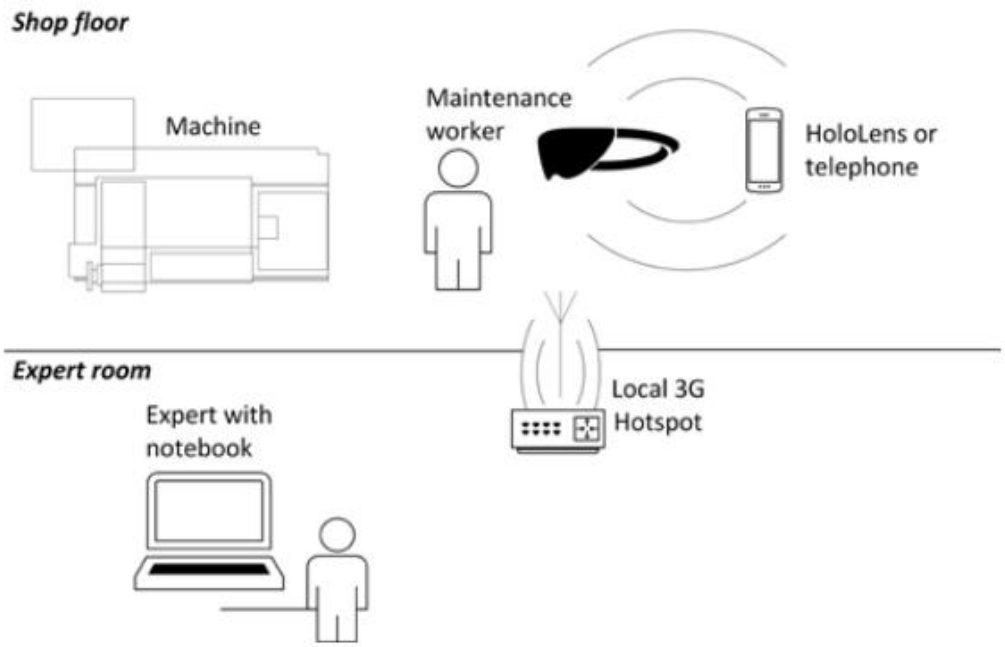

Figure 18 The structure of the Remote-assisted maintenance system [104]

For maintenance workers, the creation of remote-assisted maintenance system, on the one hand can increase the efficiency of maintenance works, on the other hand, it can increase the safety of maintenance workers.

- Nowadays, machine and equipment is becoming more and more complex, this situation cause maintenance problems become more complicated. So more professional and expert knowlege is required to solve difficult maintenance problems. When a maintenance worker have a difficult maintenance problems which he can not deal with during his maintenance work, the remote-assisted maintenance system can help to deal with the difficult maintenance problems during maintenance process and make sure maintenance operations are carried out correctly. If a maintenance worker do not know how to solve the problems during maintenance, some wrong maintenance operations will be made, it can led to maintenance accidents, so remote-assisted maintenance system can increase the safety of maintenance workers. Meanwhile, difficult maintenance problems during maintenance process without help from experts can led to mental pressure, maintenance workers performing maintenance operations with mental pressure also can led to some wrong operations. So the remote-assisted maintenance system can make maintenance workers feel more safe, reducing the psychological stress of mainteannce workers, avoiding maintenance workers exposed to psychological hazards, increasing the safety of maintenance worlers.
- When maintenance workers work in a complex maintenance condition, remote-assisted maintenance system allows oral and visual communication to describe the problems, making experts better understand the problems and giving appropriate solutions. If just using oral description, experts maybe misunderstand the problems, then inappropriate solutions will be given, making maintenance workers finish maintenance operations incorrectly.
- The visual feedback from the experts can make the maintenance workers more easy to understand the solutions from experts, so maintenance workers can perform maintenance operations correctly and easily, reducing the risk of performing the wrong operations.
- In case where no experts or maintenance workers are not skilled enough are required to carry out maintenance tasks, in this condition, the safety risk will increase. However, useful information and necessary support can be provided to the maintenance worker by using the remote-assisted maintenance system, so maintenance workers can successfully and safely finish the maintenance tasks with guides of experts. In this case, an inexperienced maintenance worker also can complete the maintenance operations correctly without safety issue, increasing the maintenance worker' safety.
- If a maintenance worker communicate with a expert by using a telephone, usually the maintenance worker need to clamp the phone between shoulders and head when the maintenance worker needs to use his hands. This uncomfortable position can increase physical load on the head and shoulder. If the maintenance worker need to keep this position for a long time, this will led to some disorders. Meanwhile, a maintenance worker working in a uncomfortable position, this can decrease the efficiency of maintenance work and result in some maintenance operations carried out incorrectly. But using the remote-assisted maintenance system instead of telephone, the hands of maintenance worker can be used as uaual.

5.4 An advanced training method based on Virtual Reality [105]

Industrial maintenanece tasks are complicated operations that need to know specific knowledge and technologies for each tasks. So a training method is necessary for maintenance workers, in order to increase the maintenance efficiency and safety during maintenance.

Usually traditional training carried out in the classroom by using the real world physical simulation, the training course main focus on the emergency issues. In this condition, the real world physical simulation always need to use detailed information and real objects, such as real machine and real tools. Sometimes even people and physical objects (machine and tool) are available, the training still can be limited by the time that required to perform the practise and the cost. A maintenance worker without any experience is easily to be hurt from the real objects during training process.

L. Di Donato et al using an advanced training method based on Virtual Reality to train maintenance workers in confined or pollution suspected space [105]. Comparing with the traditional training method, this training method based on Virtual Reality can provide a varity of emergency situations and better to cater the actual requirements of maintenance workers. The training environment for confined space were built based on a 3-D virtual, immersive, interactive simulantion, such training environment can offer maintenance workers a chance to experience the maintenance process simulation with a real feeling by using the wearable technologies. In the virtual confined environment, maintenance workers are required to carry out maintenance operations, if maintenance workers perform the maintenance operations incorrectly, this may cause the maintenance workers exposed to a hazardous environment.

In the virtual confined space, the oxygen is limited. The maintenance worker is allowed to choose the Personal Protective Equipment (PPEs) and necessary tools in order to make sure that the maintenance worker can carry out maintenance tasks safely and correctly in the virtual confined space. If the maintenance worker can not finish all the maintenance operations correctly, such as the maintenance worker forgets to perform one operation, the maintenance worker forgets to take gas mask, and the maintenance worker stays in the virtual confined space for a long time, the maintenance worker will begin to lose consciousness. Then the vision of the maintenance worker will be reduced in the simulated virtual confined space, then finally the maintenance worker will lose consciousness and the training will be finished. In this condition, the maintenance worker can be considered that he is not suitable to carry out such maintenance operations safely.

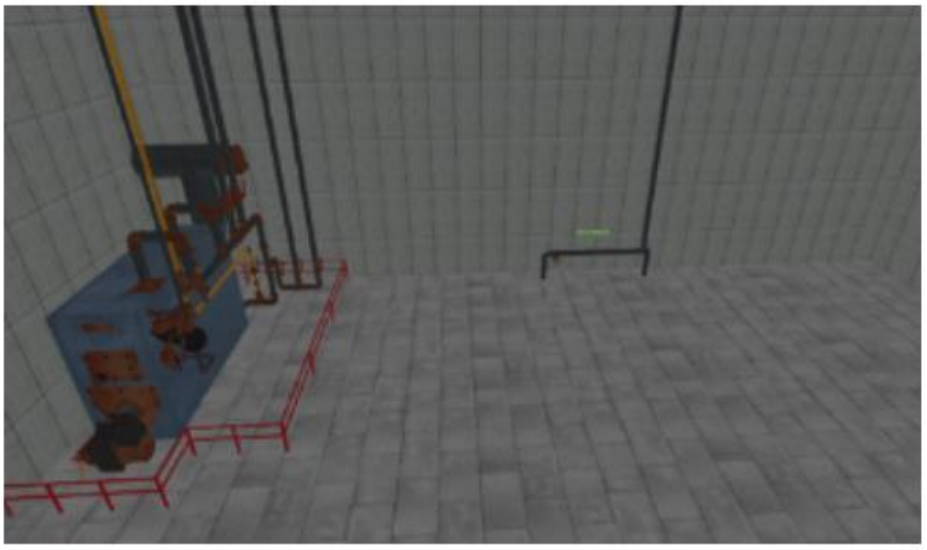

Figure 19 The confined space within the virtual environment[105]

The advanced training method based on Virtual Reality can bring some benefits to the maintenance workers:

- Sometimes, during the traditional physical training, real machine and real tools are required to use, the maintenance workers with out any maintenance experience may get hurt from the physical objects (real machine and tool) because they do not follow the safety instructions, decreasing the safety of maintenance workers during the training process. However, using training method based on Virtual Reality, the maintenance workers do not have safety issue during training process, because the hurt from the virtual environment can not have any bad effect on the maintenance worker's health.

Figure 20 Training by using Virtual Reality Headset [105]

- Comparing with the traditional training method, training method based on Virtual Reality can provide more emergency scenarios, due to that traditional training method is limited by time or cost, and other reasons. By using Virtual Reality training method, more emergency scenarios can be provided to the maintenance workers for practising and experiencing, so the efficiency of training will increase. During the real maintenance process, because most of emergency scenarios have been practised, the maintenance workers can understand the ongoing situation, so the safety risk of the maintenance worker will decrease when they performing their maintenance tasks.
- Before the real maintenance work, the training method based on Virtual Reality can be used to decide if a maintenance worker is suitable to carry out maintenance tasks or not. If a maintenance worker failed to perform all maintenance operations correctly, then the maintenance worker will be considered that he can not take part in the maintenance activities. This can reducing the risk of a not skilled enough maintenance worker performs wrong maintenance operations, increasing the safety.
- The Virtual Reality training method can give the maintenance workers a real feeling, making them can perform maintenance operations like usual. This can help the maintenance workers better to understand their tasks, then they will more familiar to the maintenance operations which will be performed, decreasing the risk of the maintenance workers forget to perform one operations or using inappropriare Personal Protective Equipment (PPEs), increasing the safety of maintenance workers.

5 Conclusion

With the develop of technology, machine and equipment become more and more compilicated, this result in a higher difficulty level of maintenance work than before. From the previous section: The situation of maintenance today, there are about 48 per cent of participants in the survey [18] consider that the main challenge of maintenance is shortage of skilled maintenance workers. Meanwhile, there are 68 per cent of participants think maintenance safety should be improved. So participants want to improve maintenance safety and efficiency by using skilled maintenance workers and adopting advanced technology. And participants in the survey believe that maintenance operations based on the Industrial Internet of Things can bring a lot of benefits to maintenance, in the next 1-3 years they will adopt advanced technologies to improve the safety and efficiency. So maintenance safety is a critical issue in the maintenance domain nowadays, physical hazards, chemical hazards, biological hazards, and psychosocial hazards are common in the maintenance space, the main limitations to improve maintenance are skilled maintenance workers and advanced technologies. The Industry 4.0 brings some modern technologies, such as Industry Internet of things (IOT), Big Data, Cloud computing, Augmented reality (AR), Virtual Reality (VR). These technologies can be used to train maintenance workers and to develop some advanced maintenance methods, such as predictive maintenance, adaptive maintenance support system, remote-assisted maintenance system. I have collected different examples of techniques pertaining to Industry 4.0 can enhance maintenance and safety.

On the one hand, before carrying out maintenance tasks. Predictive maintenance is used to diagnose a machine and its components by monitoring parameters such as noise, speed, pressure, temperature, humidity, vibration, etc. The sensors are located in the critical part of the machine, in order to collect the values of these parameters, the maintenance workers can know real time machine condition, if machine work in a abnormal condition, using the real time condition value, maintenance can easily find the broken part, then repair it or replace a new one, this can help maintenance workers reducing the risk of can not find the failure root. When enough machine condition data stored in the cloud, machine learning can be used to estimate the next failure. This can help maintenance workers to schedule their maintenance activities, avoiding night or weekend work, emergency work, reducing the psychosocial stress of maintenance workers, preventing them exposed in psychosocial hazards. Comparing with preventive maintenance, predictive maintenance can know the more accurate failure day than preventive maintenance, so maintenance workers do not need to perform maintenance operations in a high frequency, reducing the chance of maintenance workers exposed in a hazardous maintenance environment. Training is a good method to make a maintenance workers become more skilled. An training method based on Virtual Reality can provide virtual maintenance space in which maintenance can practise their maintenane operations without safety issue, because virtual objects can not hurt the maintenance workers. By practising maintenance operations in the virtual maintenance space, maintenance workers can familiar to their maintenane environment and operations, decreasing the risk of maintenance workers perform operations incorrectly.

On the other hand, when maintenance workers performing maintenance operations in the real condition. An adaptive maintenance system and a remote-assisted system can be used to support maintenance workers. In the adaptive maintenance system based on Augmented reality, a combination of augmented information and neceaasry assistance can be provided to a maintenance worker, in order to make sure maintenance operations complete correctly and safely, reducing the risk such as forgetting to perform a maintenance step or performing a maintenance step incorrectly, so increasing the maintenance worker’s safety. The real time wrist position of maintenance will be tracked, and correct wrist position during maintenance operations can be set, comparing the real time wrist position with the correct wrist position, the maintenance operation if correctly performed or not can be known. This can prevent a maintenance worker continue to carry out next maintenance steps after making an incorrect maintenance operations. From the safety point of view, if a maintenance worker performing next operations regardless of last operation finished correctly or not, this can led to fatal maintenance accidents. So check the maintenance operations performed correctly or not can increase the safety of maintenance worker. If maintenance wokers failed in the maintenance operations, the system will give a flag, reminding maintenance workers to have a check and helping maintenan workers find the failure roots easily. Haptic augmentation can provide position awareness to maintenance workers, when real time wrist position close the the designed position, a vibrarion can be provided to the maintenance worker, this also can help the maintenance worker finish their tasks correctly and safely. Some different augmentation level can be provided to the maintenance worker, according to the knowledge and requirements of the maintenance worker, the suitable assisted information will be offered to maintenance workers, making sure the maintenance workers can use appropriate information to help them finish the maintenance operations correctly and safely. When finishing maintenance operations,

the diagnostic module also can be used to check if maintenance operations finished correctly or not, comparing the finished picture with idea picture, the feedback will be sent to the maintenance worker, this also can prevent a maintenance worker continue to carry out next maintenance steps after making an incorrect maintenance operations. Remote-assisted maintenance is another effective method to help maintenance solve difficult maintenance problems. Remote-assisted maintenance develop an innovation communication way between maintenance workers and experts. Maintenance workers can finish the maintenance operations correctly and safely with the knowledge from experts, decreasing the risk of performing a wrong maintenance operation. Maintenance workers can describe the maintenance problems orally and visually, this can make experts better to understand the problems and give correct solutions, this can decrese the risk of proforming the operations incorrectly because the wrong solutions which from experts. Meanwhile, the feedback from the experts also can be visual, making maintenance workers better to understand the solution, prevent that maintenance workers misunderstand the solution and perform maintenance tasks incorrectly.

6 Reference

[1] https://www.advancedtech.com/

[2] Malgorzata Milczarek, Joanna Kosk-Bienko, European Agency for Safety and Health at Work (EU-OSHA) “Maintenance and Occupational Safety and Health: A statistical picture”

[3] API STD 689, ‘Collection and Exchange of Reliability and Maintenance Data for Equipment’, First Edition, July 2007

[4] API RP 8B, ‘Recommended Practice for Procedures for Inspections, Maintenance, Repair and Remanufacture of Hoisting Equipment’, Seventh Edition, August 2012

[5] Simeu-Abazi, Z. and Sassine, C. (2001), “Maintenance integration in manufacturing systems: fromthe modelling tool to evaluation”,International Journal of Flexible Manufacturing Systems, 267-285

[6] Bagadia, Kishan, ‘Computerized maintenance management systems made easy: how to evaluate, select, and manage CMMS’, McGraw-Hill Professional, 2006. ISBN 0071469850, 9780071469852

[7] What is Reactive Maintenance?, https://www.enertiv.com/resources/faq/what-is-reactive-maintenance.

[8] The Ultimate Preventive Maintenance Guide: Nearly Everything You Need to Know, https://www.getmaintainx.com/what-is-preventative-maintenance, June 6, 2020

[9] Industrial maintenance: history and evolution, July 17, 2018, https://www.mobility-work.com/blog/history-of-maintenance-in-industry

[10]Aziz, Iftekhar, Sazedul Karim, and M. Hossain. "Effective implementation of total productive maintenance and impacts on breakdown time and repair & maintenance—a case study of a printing industry in Bangladesh.", Proceedings of the Global Engineering, Science and Technology Conference. 2012.

[11] Nakajima, S. (1988), ‘Introduction to TPM: Total Productive Maintenance (preventative maintenance series)’, ISBN 0-91529-923-2.

[12]Legat, V. ‘Management and maintenance engineering’, Praha: Professional Publishing, 2013, ISBN 978-80-7431-119-2.

[13] Baron Petr et al., ‘Research and application of methods of technical diagnostics for the verification of the design node’, 2016. In: Measurement, 245-253, ISSN 0263-2241

[14] Moubray, J. (1997), ‘Reliability-centered maintenance’, Industrial Press Inc

[15] Mihalov Juraj, Pietrikova Emilia , Balaz Anton, Mados Branislav , Adam Norbert, ‘Potential of Low Cost Motion Sensors Compared to Programming Environments’, In: Acta Polytechnica Hungarica, 155-177, 2018

[16] Heinz P. Bloch, Fred K. Geitner, “ Machinery Failure Analysis and Troubleshooting 4th Edition ”, Practical Machinery Management for Process Plants 2012

[17] Chris Coleman, Satish Damodaran, Mahesh Chandramouli, Ed Deuel, "Making maintenance smarter-Predictive maintenance and the digital supply network", May 09, 2017

[18] https://www.advancedtech.com/resource/2020-state-of-industrial-maintenance-report-download/

[19] The Evolution of Industrial Maintenance, https://www.advancedtech.com/blog/evolution-of-industrial-maintenance/

[20] BS EN 13306:2010, Maintenance — Maintenance terminology, http://irma-award.ir/wp-content/uploads/2017/08/BS-EN-13306-2010.pdf

[21] Maintenance and OSH — A statistical picture, https://osha.europa.eu/en/publications/factsheet-90-maintenance-and-osh-statistical-picture/view

[22] Vardhan, H., Karmakar, N.C., Rao, Y.V., 'Experimental study of sources of noise from heavy earth-moving machinery', Noise Control Engineering Journal, Vol.53, No. 2, 2005, pp. 37-42.

[23] Kjellberg, A., Sköldström, B., Andersson, P., Lindberg, L., 'Fatigue effects of noise on aeroplane mechanics', Work & Stress, 62-71

[24] Occupational exposure to vibration from handheld tools, https://www.who.int/occupational_health/pwh_guidance_no.10_teaching_materials.pdf

[25] What are the health effects of whole-body vibration?, Canadian Centre for Occupational Health and Safety, https://www.ccohs.ca/oshanswers/phys_agents/vibration/vibration_effects.html

[26] Binder, J., Petrequin, A., Rumpler, F. , 'Evaluation strategy and work conditions improvement in hot environment : study of hot assays in nuclear power plant', Revue de Médecine du Travail, 98-102.

[27] Hand-arm vibration at work, https://www.hse.gov.uk/vibration/hav/index.htm

[28] Whole body vibration at work, https://www.hse.gov.uk/vibration/wbv/index.htm

[29] Radiation, https://www.who.int/health-topics/radiation#tab=tab_1

[30] Kuala Lumpur, 'Non-Ionizing Radiations – Sources, Biological Effects, Emissions and Exposures', Proceedings of the International Conference on Non Ionizing Radiation at UNITEN

https://www.who.int/peh-emf/meetings/archive/en/keynote3ng.pdf

[31] Health effects of ionising radiation, https://www.arpansa.gov.au/understanding-radiation/what-is-radiation/ionising-radiation/health-effects

[32] Tenkate, T.D., Collins, M.J., 'Angles of entry of ultraviolet radiation into welding helmets', American Industrial Hygiene Association Journal, 33-38.

[33] Cole, H., Epstein, S., Pearce, J., 'Particulate and gaseous emissions when welding aluminium alloys', Journal of Occupational and Environmental Hygiene, 2007, 678-687

[34] Rolf Ellegast, 'Assessment of physical workloads to prevent work-related MSDs', Institute for Occupational Safety and Health of the German Social Accident Insurance,https://oshwiki.eu/wiki/Assessment_of_physical_workloads_to_prevent_work-related_MSDs

[35] Van Wendel de Joode, B, Verspuy, C., Budorf, A., Physical workload in ship maintenance:Using The Observer to solve ergonomics problems, Wagenignen, Noldus Information Technology, 2004

[36] Harbine, K.L., 'Health hazards in automobile repair shops', Clinics in Occupational and Environmental Medicine, 2003, 45-60.

[37] Morken T., Mehlum, I.S., Moen, B.E., 'Work-related musculo-skeletal disorders in Norway's offshore petroleum industry', Occupational Medicine, 2007, 112-117.

[38] How to Safely Work With Asbestos, June 20, 2019, https://safestart.com/news/how-to-safely-work-with-asbestos/

[39] Why Asbestos Was Used In So Many Building Products, 2018, https://www.haspod.com/blog/asbestos/why-asbestos-was-used-building-products

[40] Safe maintenance -asbestos in building maintenance, http://www.osha.mddsz.gov.si/resources/files/pdf/48-maintenance_asbestos.pdf

[41] Burdett, G., Bard, D., 'Exposure of UK industrial plumbers to asbestos. Part I: Monitoring of exposure using personal passive samplers', Annals of Occupational Hygiene, 2007, 121-130

[42] Burdett, G. Bard, D., 'Exposure of UK industrial plumbers to asbestos. Part II: Awareness and responses of plumbers to working with asbestos during a survey in parallel with personal sampling', Annals of Occupational Hygiene, 2007, 113-119.

[43] Matrat, M., Pairon1, J.-C., Paolillo, A.-G., Joly, N., Iwatsubo, Y., Orlowski, E., Letourneux, M.,Ameille, J., 'Asbestos exposure and radiological abnormalities among maintenance and custodian workers in buildings with friable asbestos-containing materials', International Archives of Occupational and Environmental Health, 307-312

[44] Paustenbach, D.J., Richter, R.O., Finley, B.L., Sheehan, P.J., 'An evaluation of the historical exposures of mechanics to asbestos in brake dusts', Applied Occupational and Environmental Hygiene, 2003, 786-804

[45] Workplace Health and Safety Queensland, Guide to working safely in confined spaces, Brisbane, Queensland Government Department of Industrial Relations, 2003

[46] Occupational safety and health management in renovation and maintenance works for the property management industry, https://www.labour.gov.hk/eng/public/os/D/pm_renovation.pdf

[47] Dorevitch, S., Forst, L., Conroy, L., Levy, P., 'Toxic inhalation fatalities of US construction workers', Journal of Occupational and Environmental Medicine, 2010, pp. 657-662.

[48] Bond, J., 'Confined space entry: be aware of hidden dangers', Loss Prevention Bulletin, No. 158, 2011, 12-14.

[49] Welding - Fumes And Gases, OSH Answers Fact Sheets, https://www.ccohs.ca/oshanswers/safety_haz/welding/fumes.html

[50] Danielsen, T.E., Langard, S., Andersen, A., 'Incidence of cancer among welders and other shipyard workers with information on previous work history', Journal of Occupational and Environmental Medicine, 101-109

[51] El-Zein, M., Malo, J., Infante-Rivard, C., Gautrin, D., 'Prevalence and association of welding related systemic and respiratory symptoms in welders', Occupational and Environmental Medicine, 655-661

[52] Li, G.J., Zhang, L.L., Lu, L., Wu, P., Zheng, W., 'Occupational exposure to welding fume among welders: alterations of manganese, iron, zinc, copper and lead in

body fluids and the oxidative stress status', Journal of Occupational and Environmental Medicine

[53] Héry, M., Diebold, F., Hecht, G., 'Exposure of contractors to chemical pollutants during the maintenance shut-down of a chemical plant', Risk Analysis, 645-655

[54] Chemicals - Health and Safety Authority, https://www.hsa.ie/eng/Publications_and_Forms/Publications/Safety_and_Health_Management/Section%207%20Chemicals.pdf

[55] Hartwig, S., Rupp, A., Puls, E., Kim, J.-H., Binder, F., Cleaning and maintenance of industrial installations: exposure to hazardous substances [in German], Hazardous Substances GA 61, Federal Institute for Occupational Safety and Health (BAuA), 2003

[56] What work activities might involve exposure to biological agents? https://www.hsa.ie/eng/Topics/Biological_Agents/Biological_Agents_Introduction/Biological_Agents_Frequently_Asked_Questions/

[57] COVID-19 pandemic, https://en.wikipedia.org/wiki/COVID-19_pandemic

[58] Coronavirus disease (COVID-19), 12 October 2020

https://www.who.int/emergencies/diseases/novel-coronavirus-2019/question-and-answers-hub/q-a-detail/coronavirus-disease-covid-19#:~:text=symptoms

[59] Symptoms of COVID-19 and how to protect yourself, 1 March 2021

https://www.gov.ie/en/publication/472f64-covid-19-coronavirus-guidance-and-advice/

[60] Mohamed Samer, 'Biological and Chemical Wastewater Treatment Processes', October 14th 2015, https://www.intechopen.com/books/wastewater-treatment-engineering/biological-and-chemical-wastewater-treatment-processes

[61] Bo Zhang, Xiangyang Xu & Liang Zhu, 'Structure and function of the microbial consortia of activated sludge in typical municipal wastewater treatment plants', Scientific Reports ,volume 7, Article number: 17930 (2017)

[62] Smit, L.A.., Spaan, S., Heederick, D., 'Endotoxin exposure and symptoms in wastewater treatment workers', American Journal of Industrial Medicine, 30-39

[63] A. GUERCIO, G. GIAQUINTA AND R. GIOVINAZZO, 'Prevention and management of workers' exposure to biological agents in municipal solid waste plants', September 2013

https://www.researchgate.net/publication/257866068_PREVENTION_AND_MANAGEMENT_OF_WORKERS%27_EXPOSURE_TO_BIOLOGICAL_AGENTS_IN_MUNICIPAL_SOLID_WASTE_MSW_PLANTS

[64] Jacques Lavoie & Serge Guertin, 27 Dec 2011, 'Evaluation of Health and Safety Risks in Municipal Solid Waste Recycling Plants', Journal of the Air & Waste Management Association

[65] Psychosocial risks and stress at work,

https://osha.europa.eu/en/themes/psychosocial-risks-and-stress

[66] Safe maintenance – hazards,https://www.hseni.gov.uk/articles/safe-maintenance-hazards

[67] Health Impact of Psychosocial Hazards at Work: An Overview,

https://apps.who.int/iris/bitstream/handle/10665/44428/9789241500272_eng.pdf?sequence=1

[68] Expert forecast on emerging psychosocial risks related to occupational safety and health, https://osha.europa.eu/en/publications/reports/7807118

[69] SAFE MAINTENANCE: WORKING WITH CONTRACTORS AND SUBCONTRACTORS, https://osha.europa.eu/en/publications/e-facts/e-fact-62-safe-maintenance-working-with-contractors-and-subcontractors

[70] Place of work and working conditions – France, https://www.eurofound.europa.eu/publications/report/2007/place-of-work-and-working-conditions-france

[71] Arianna Martinelli, 'The enabling technologies of industry 4.0: examining the seeds of the fourth industrial revolution', FEB 2019

https://siecon3-607788.c.cdn77.org/sites/siecon.org/files/media_wysiwyg/257-martinelli.pdf

[72] Keng Siau, 'Industry 4.0 — An Introduction', August 7, 2019, Cutter Business Technology Journal, https://www.cutter.com/article/industry-40-—-introduction-504396

[73] The Fourth Industrial Revolution: what it means, how to respond, JAN 2016

https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond/

[74] Giuseppe Lugano, 'Virtual assistants and self-driving cars', May 2017, Conference: 2017 15th Internation Conference on ITS Telecommunications

[75] Piotr Nowotarski and Jerzy Paslawski, 'Industry 4.0 Concept Introduction into Construction SMEs', 2017, IOP Conference Series: Materials Science and Engineering

[76] Graham Immerman , 'Industry 4.0 Advantages and Disadvantages', February 2018,https://www.machinemetrics.com/blog/industry-4-0-advantages-and-disadvantages

[77] Michael Sony, 'Pros and cons of implementing Industry 4.0 for the organizations: a review and synthesis of evidence', Production & Manufacturing Research 2020

[78] Greg Kaminsky, '4 ways Industry 4.0 technology can improve safety', October 2019, https://www.ptc.com/en/blogs/ar/4-ways-technology-can-improve-worker-safety

[79] Vaidya, S., Ambad, P., Bhosle, S., 'Industry 4.0 – a glimpse', 2018, Procedia Manufacturing,20,233–238

[80] Pierdicca, R., Frontoni, E., Pollini, R., Trani, M., Verdini, L., 2017, 'The Use of Augmented Reality Glasses for the Application in Industry 4.0', Lect. Notes Comput.

Sci. (Including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics).

[81] Cristians, A., Methven, J.M., 2017, 'Industry 4.0: fundamentals and a quantitative analysis of benefits through a discrete event simulation', Challenges Technol. Innov. An Agenda Futur. - Proc. Int. Conf. Sustain. Smart Manuf.

[82] Witkowski, K., 2017, 'Internet of things, big data, industry 4.0 - innovative solutions in logistics and supply chains management', Procedia Eng., 763–769

[83] Zolotová, I., Papcun, P., Kajáti, E., Miskuf, ˇ M., Mocnej, J., 2018, ‘Smart and cognitive solutions for Operator 4.0: laboratory H-CPPS case studies’, Comput. Ind. Eng.,

[84] Hassan, Q.F., 2011, ‘Demystifying cloud computing’, CrossTalk 24,16–21

[85] Atzori, L., Iera, A., Morabito, G., 2010, ‘The internet of things: a survey’, Comput. Networks 54, 2787–2805

[86] Gubbi, J., Buyya, R., Marusic, S., Palaniswami, M., 2013, ‘Internet of Things (IoT): a vision, architectural elements, and future directions’, Future Gener. Comput. Syst. 29, 1645–1660

[87] Nunes, D.S., Zhang, P., Silva, J.S., 2015, ‘A survey on human-in-the-loop applications towards an internet of all’, IEEE Commun. Surv. Tutor. 17, 944–965

[88] Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sihn, W., Ueda, K., 2016, ‘Cyber-physical systems in manufacturing’, CIRP Ann. 65, 621–641

[89] Chong, S., Pan, G.-T., Chin, J., Show, P.L., Yang, T.C.K., Huang, C.-M., 2018, ‘Integration of 3D printing and industry 4.0 into engineering teaching’, Sustainability 10, https://www.mdpi.com/2071-1050/10/11/3960

[90] Figueiredo, M.J.G., Cardoso, P.J.S., Gonc ¸ alves, C.D.F., Rodrigues, J.M.F., 2014, ‘Augmented reality and holograms for the visualization of mechanical engineering parts’, 2014 18th Int. Conf. Inf. Vis., 368–373

[91] Nee, A.Y.C., Ong, S.K., Chryssolouris, G., Mourtzis, D., 2012, ‘Augmented reality applications in design and manufacturing’, CIRP Ann. Manuf. Technol. 61, 657–679

[92] Ong, S.K., Yuan, M.L., Nee, A.Y.C., 2008, ‘Augmented reality applications in manufacturing: a survey’, Int. J. Prod. Res. 46, 2707–2742

[93] What is Additive Manufacturing? https://www.ge.com/additive/additive-manufacturing

[94] John Soldatos, ‘Introduction to Industry 4.0 and the Digital Shopfloor Vision’

https://www.riverpublishers.com/pdf/ebook/chapter/RP_9788770220408C1.pdf

[95] Djuric, A.M., Rickli, J.L., Urbanic, R.J., 2016, ‘A framework for collaborative robot (CoBot) integration in advanced manufacturing systems’, SAE Int. J. Mater. Manuf. 9, 457–464

[96] Sadik, A.R., Urban, B., 2017, ‘An ontology-based approach to enable knowledge representation and reasoning in Worker-Cobot agile manufacturing’, Future Internet 9(4), 90, https://www.mdpi.com/1999-5903/9/4/90

[97] Chua, C.K., Leong, K.F., Lim, C.S., 2010, ‘Rapid Prototyping: Principles and Applications’, 3rd ed.

[98] Peres, R.S., Dionisio Rocha, A., Leitao, P., Barata, J., 2018, ‘IDARTS – towards intelligent data analysis and real-time supervision for industry 4.0’, Comput. Ind. 101, 138–146

[99] Stock, T., Seliger, G., 2016, ‘Opportunities of sustainable manufacturing in industry 4.0’, Procedia CIRP 40, 536–541

[100] Wells, L.J., Camelio, J.A., Williams, C.B., White, J., 2013, 'Cyber-physical security challenges in manufacturing systems', Manuf. Lett. 2, 74–77

[101] Giovane, R., Giuseppe, V., Eleonora, B., 2018, 'A conceptual framework for the selection of an "Industry 4.0" application to enhance the operators' safety: the case of an aseptic bottling line', IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)

[102] L. Magadan, F.J. Suarez, J.C Granda, D.F. Garcia, 2020, 'Low-cost real-time monitoring of electric motors for the Industry 4.0', Prodedia Manufacturing 42 (2020) 393-398

[103] C.Y. Siew, S.K. Ong, A.Y.C. Nee, 2019, 'A practical augmented reality-assisted maintenance system framework for adaptive user support', Robotics and Computer Integrated Manufacturing 59 (2019) 115-129

[104] Wolfgang, V., Johannes, G., Helena, W., Dietmar, N., Philipp, U., ' Assessing augmented reality in production: remote-assisted maintenance with HoloLens', Procedia CIRP 88(2020) 139-144