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Performance Measurement using Deep Digital Maintenance (DDM) Concept

A Technique for Minimizing "Hidden Factory"

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Master in Reliability, Availability, Maintainability, and Safety (RAMS)
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Supervisor: Per Schjølberg
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Reliability, Availability,
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MASTER THESIS
Department of Mechanical and Industrial Engineering
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Supervisor 1: Per Schjølberg (The main supervisor)
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Preface

This master's thesis was carried out by Christopher Ogochukwu Okafor, a RAMS student at NTNU. The thesis was conducted for the Norwegian University of Science and Technology (NTNU). It counts as 30 credits and as a requirement for the subject TPK4950, fall semester of 2021.

The thesis was written with the guidance from main supervisor Per Schjølberg from NTNU and co-supervisor Harald Rødseth from Oceaneering AS.

The topic of the thesis is "Performance Measurement using Deep Digital Maintenance (DDM) Concept: A Technique for Minimizing "Hidden Factory" ". The various forms of production losses have been categorized and the metaphor "hidden factory" has been described as the consequence of waste in production. Profit loss indicator (PLI) has been regarded as the future tool for measuring "hidden factory". The Deep Digital Maintenance (DDM) concept was applied in determining the performance measurement system of physical asset in a digitalized maintenance system.

This report is written for readers who are curious in understanding how to determine the performance measurement system of a physical asset in a digitalized maintenance system using DDM concept.

Trondheim, 2021-12-20

Christopher Okafor

Acknowledgment

My gratitude goes to my main supervisor, Per Schjølberg, for providing his valuable insights and guidance throughout this thesis. I am equally grateful to my co-supervisor, Harald Rødseth, for his contributions and support through his plenitude knowledge and experience. I cannot measure the quality of materials received from both supervisors, and I, therefore, say a huge thanks to them.

I will also say a big "thank you" to all the lecturers in charge of RAMS courses, especially TPK 4140, for giving me a start-up foundation for this thesis. My former employer (Onsite Engineering Limited), who exposed me to the oil and gas onshore and offshore facilities, can never be left unappreciated. Those few years of experience had significantly contributed to building my foundation for my master's degree.

I would also love to thank my parents, who have always supported my academic and professional career. A big thanks also go to my fellow RAMS students for always having me as friends and colleagues. I will never forget persons like Olav, Tord, Dan, Adewale, who always stood beside me in times of difficulty.

Kudos and farewell to you all!

C.O.

Executive Summary

Due to the way competition is driving both cost and innovation today, production companies are looking for any possible means to minimize cost, reduce risks associated with physical assets, improve asset's performance, and at the same time adopt innovative technologies as a part of the strategies to reach their long-term objectives. Due to the evolution of the production industry, the need for proper maintenance plays a very vital role in cost and efficiency optimization. For this reason, any solution with the possibility to reduce maintenance costs and risks associated with production plants while ensuring a high level of operational availability and performance is often actively pursued. To minimize waste and time losses in production, performance measures should be linked to the smart maintenance strategy of an organization in order to provide useful information for making effective decisions. To ensure that plant/equipment achieves their desired performance, maintenance management requires a good track of the performance of maintenance functions. This can be possible if a performance measuring system with suitable indicators is developed and implemented to measure different elements for equipment performance.

This master thesis investigates and determines the performance measurement system of maintenance functions in a digitalized maintenance platform. In the earlier stage of this thesis, the "16 Big Losses" which impede the efficiency of a production plant were investigated and restructured with respect to the 3 OEE losses (availability, performance, and quality losses). Further research revealed that "4 Safety Losses" were emanated from the conventional "16 Big Losses" which are all attributes of the metaphor "hidden factory" in production. The earlier investigations also showed that a severe safety loss in a production plant could result in loss of asset, fatality, loss of company's reputation, and or environmental pollution (e.g., GHG Emission, Oil Spillages) which impedes the sustainability of a production company. At this stage, the report introduced Total Productive Maintenance (TPM) with the main objective of eliminating equipment downtime. The TPM goal is to ensure that the 3 OEE losses were eliminated. For this reason, the profit loss indicator (PLI) was introduced as a promising tool used for the identification and measurement of the "hidden factory" in production. Also, ISO 55000 was introduced with main objectives which ensure that production companies realize values from their assets. The main organizational values which include cost efficiency, risk reduction, and equipment availability and performance were considered as focal points for the development of maintenance functions.

The later part of this thesis introduced the smart maintenance model DDM as a future technique for performance measurement of the physical asset in a digitalized maintenance system. The DDM modules were used to make a criticality assessment of physical assets on a smart

maintenance platform. From the demonstration made, the DDM concept uses its modules (PLI, Remaining Useful Life, and Planning) to make a criticality assessment of equipment. The concept uses a cyber-physical system where artificial intelligence with machine learning method (Remaining Useful Life estimation) monitors and measures the degradation level of equipment and at the same time uses the PLI to measure the financial consequences (penalty) if early preventive maintenance were not administered due to that degradation. The main aim of this technique is to establish maintenance functions where the maintenance planner makes effective and smart decisions in prioritizing preventive maintenance for the minimization of time losses and waste ("hidden factory") in production which impede the actualization of organizational values (reduced risk, high equipment performance and cost-efficiency).

Sammendrag

På grunn av måten konkurranse driver både kostnader og innovasjon på i dag, leter produksjonsselskaper etter alle mulige måter å minimere kostnader, redusere risiko forbundet med fysiske eiendeler, forbedre eiendelens ytelse og samtidig ta i bruk innovative teknologier som en del av strategiene. for å nå sine langsiktige mål. På grunn av utviklingen i produksjonsindustrien, spiller behovet for riktig vedlikehold en svært viktig rolle i kostnads- og effektivitetsoptimalisering. Av denne grunn blir enhver løsning med mulighet for å redusere vedlikeholdskostnader og risiko knyttet til produksjonsanlegg, samtidig som man sikrer høy driftstilgjengelighet og ytelse, ofte fulgt aktivt. For å minimere sløsing og tidstap i produksjonen, bør ytelsesmål knyttes til smart vedlikeholdsstrategi for en organisasjon for å gi nyttig informasjon for å ta effektive beslutninger. For å sikre at anlegget/utstyret oppnår ønsket ytelse, krever vedlikeholdsstyring en god oversikt over utførelsen av vedlikeholdsfunksjoner. Dette kan være mulig dersom et ytelsesmålesystem med passende indikatorer utvikles og implementeres for å måle ulike elementer for utstyrets ytelse.

Denne masteroppgaven undersøker og bestemmer ytelsesmålesystemet for vedlikeholdsfunksjoner i en digitalisert vedlikeholdsplattform. I det tidligere stadiet av denne oppgaven ble de "16 store tapene" som hindrer effektiviteten til et produksjonsanlegg undersøkt og omstrukturert med hensyn til de 3 OEE-tapene (tilgjengelighet, ytelse og kvalitetstap). Ytterligere forskning avslørte at "4 sikkerhetstap" kom fra de konvensjonelle "16 store tapene" som alle er attributter til metaforen "skjult fabrikk" i produksjonen. De tidligere undersøkelsene viste også at et alvorlig sikkerhetstap i et produksjonsanlegg kan føre til tap av eiendeler, dødsfall, tap av selskapets omdømme og eller miljøforurensning (f.eks. klimagassutslipp, oljesøl) som hindrer bærekraften til et produksjonsselskap. På dette stadiet introduserte rapporten Total Productive Maintenance (TPM) med hovedmålet å eliminere nedetid for utstyr. TPM-målet er å sikre at de 3 OEE-tapene ble eliminert. Av denne grunn ble profit loss indicator (PLI) introdusert som et lovende verktøy for identifikasjon og måling av den "skjulte fabrikken" i produksjon. I tillegg ble ISO 55000 introdusert med hovedmål som sikrer at produksjonsbedrifter realiserer verdier fra sine eiendeler. De viktigste organisatoriske verdiene som inkluderer kostnadseffektivitet, risikoreduksjon og utstyrs tilgjengelighet og ytelse ble ansett som fokuspunkter for utvikling av vedlikeholdsfunksjoner.

Den senere delen av denne oppgaven introduserte smart vedlikeholdsmodell DDM som en fremtidig teknikk for ytelsesmåling av fysiske eiendeler i et digitalisert vedlikeholdssystem. DDM-modulene ble brukt til å gjøre kritikalitetsvurdering av fysiske eiendeler på en smart vedlikeholdsplattform. Fra demonstrasjonen som er gjort, bruker DDM-konseptet sine moduler (PLI, Remaining Useful Life og Planning) for å foreta kritikalitetsvurdering av utstyr. Konseptet bruker

cyber-fysisk system der kunstig intelligens med maskinlæringsmetode (Remaining Useful Life estimation) overvåker og måler nedbrytningsnivået til et utstyr og samtidig bruker PLI for å måle de økonomiske konsekvensene (straff) dersom tidlig forebyggende vedlikehold var ikke administrert på grunn av disse nedbrytningene. Hovedmålet med denne teknikken er å etablere en vedlikeholdsfunksjon der vedlikeholdsplanlegger tar effektive og smarte beslutninger for å prioritere forebyggende vedlikehold for å minimere tidstap og sløsing ("skjult fabrikk") i produksjonen som hindrer aktualisering av organisasjonsverdier (redusert risiko, høy utstyrsytelse og kostnadseffektivitet).

Acronyms

ALARP As Low As Reasonably Practicable

AI Artificial Intelligence

CPS Cyber Physical System

DDM Deep Digital Maintenance

EIA Environmental Impact Assessment

FMECA Failure Mode Effects and Criticality Analysis

ICT Information Communication Technology

IMS Intelligent Maintenance System

IoTs Internet of Things (IoTs)

KPI Key Performance Indicator

LCC Life Cycle Cost

OEE Overall Equipment Effectiveness

PDM 4.0 Predictive Maintenance 4.0

PLI Profit Loss Indicator

OPE Overall Plant Effectiveness

RUL Remaining Useful Life

TPM Total Productive Maintenance

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Chapter 1

Introduction

Maintenance is one of the most sensitive departments in a production company, and this is because of its determinant of equipment's efficiency and productivity. Maintenance plays a very vital role in asset management and has a close interaction with production, safety, sales, supply chain, and logistics. This is because maintenance saves cost by increasing equipment's uptime which makes it possible to increase the quantity and quality of finished products for sale through its equipment's availability, performance, and safety. This master thesis focuses on describing Smart Maintenance and its Deep Digital Maintenance (DDM) model as a future technique for monitoring the productive capabilities of production assets. It shows how Profit Loss Indicator (PLI) is used in measuring the metaphor "hidden factory," which is denoted as the consequence of waste in production. This thesis also summarizes how Smart Maintenance with DDM application could improve the TPM's OEE, with a corresponding improvement on Asset Management and Sustainability of a production company. This chapter introduces the background and objectives of this master thesis. Limitations of the thesis are also presented in this chapter, the approach is highlighted, and the structure of the main thesis is outlined.

1.1 Background

As global competition in businesses increases, production companies are trying all their possible means of cutting down costs that deprive them of profit. The management is strategically looking for a tool for reducing maintenance cost and equipment downtime, and at the same time increase its production efficiency [Kigsirisin et al., 2016]. Recent developments in many industries are directing their investments towards capital-intensive and technologically advanced plants. But this idea implies that a capital-intensive installation will result in considerable downtime and breakdown costs if adequate preventive maintenance measures are not implemented. In most asset-intensive industries today, maintenance costs are significant to the total operational costs [Parida and Chattopadhyay, 2007]. Depending on the level of mechanization, recent investigations have proven that maintenance expenditure amounts up to 20-50 percent of production cost in the mining industry [Parida and Chattopadhyay, 2007]. In the more significant industries like the petroleum companies, reducing maintenance expenditure by 1 million dollars contributes as much to profits as increasing sales by 3 million dollars [Wireman, 2005]. In the USA, BP refinery paid a fine of 21 million dollars and spent 1 billion dollars for repairs due to an explosion during maintenance activity which led to 15deaths and 500 severe injuries [Parida and Chattopadhyay, 2007]. In September 1999, Alaska, BP also pleaded guilty for illegal disposal of hazardous materials during shutdown maintenance at Endicott Oil Field near Prudhoe Bay and was fined 7 million dollars as part of the plea agreement [Parida and Chattopadhyay, 2007]. In 2005, ExxonMobil paid a fine of 236 million dollars related to environmental violations for polluting groundwater with petrol additive [Chávez]. Despite the massive amounts of resources invested into maintenance, various unpredictable losses emanate from different facets of the department, thus, causing financial losses and threats to humans and their environment. Due to the hazard associated with the production facilities, other losses related to the safety of humans and the environment could be hidden [Council et al., 2010]. However, these losses were never considered in the past but should be considered as safety losses in businesses could result in fatality and or bankruptcy.

However, maintenance management could have effectively monitored the availability and performance of production assets right from the onset. A maintenance concept that is under the latest industrial revolution has the capability of monitoring the operational health of the plant equipment. Predictive Maintenance 4.0, which is one of the arms of Industry 4.0 is all about using the existing technology to digitalize the production plant [Bousdekis and Mentzas, 2021]. Systematic deployment of cyber-physical systems through which information between physical factory floor and computational space would be actualized through a digitalized system [Jazdi, 2014]. With the application of this technology, the goal of predicting failures before they occur with the use of sensors, Big Data, IoTs, Artificial Intelligent, Machine Learning, RUL etc. is achieved [Diez-Olivan et al., 2019]. To attain the highest level of asset performance, an intelligent maintenance system (IMS) must bring together technology, data, analysis, prognosis, and resources [Rødseth et al., 2017]. Therefore, the implementation of the Deep Digital Maintenance (DDM) concept, which enhances smart maintenance planning, becomes promising. Instead of the traditional maintenance strategies, more intelligent maintenance results in the fastest approach to ensure equipment's availability, performance, and safety. This would maintain an elevated efficiency throughout the equipment and plant life cycles.

To meet the objections of ISO 55000 and realize more values from production assets, it is essential to effectively control and govern production assets through criticality assessment of physical assets, enhancing the balance of cost, risk, and performance of physical asset. The regulatory environment in which organizations operate is challenging, and the inherent risks that many assets present are constantly evolving. To meet the EU's climate and energy target for 2030 and reach the European Green Deal's objectives, production companies need to also shift their investments into economic activities that can be environmentally sustainable [Lucarelli et al., 2020]. This would be possible if all forms of production and safety losses were identified and minimized so that companies could bring their products to the market at a low production cost without degrading the environment. From the economic point of view, total profit can be increased by either reducing the total cost of production or increasing the price of a product [Muchiri and Pintelon, 2008]. But to beat the competition, it is relevant to focus on reducing the total cost of production rather than increasing the price, which might lead to loss of customers [Van Horenbeek and Pintelon, 2014]. To meet the future demand for performance measurement, it is also important to model some existing performance measurement tools more generically to fit various business performance objectives. The cost of providing maintenance service to business can represent a considerable proportion of the total operating cost of a company [Andersson and Bellgran, 2015]. Therefore, the performance of maintenance functions could impact a company's financial performance either directly through labour and material costs or indirectly through equipment reliability performance [Muchiri and Pintelon, 2008]. For this reason, the performance of productive efficiency and productivity of assets should be regarded as significant indicators to determine competitiveness. This situation has led to a need to vigorously define a performance measurement system that considers physical assets as elements of productivity in a production company. It is then sure that improving the maintenance processes by minimizing production and safety losses and increasing plant/equipment performances can improve efficiency, effectiveness, sustainability, and the achievement of organizational objectives.

1.2 Objectives

The main objective of this thesis is to investigate and determine the performance measurement system of maintenance functions with the use of PLI through criticality assessments of physical assets in a digitalized maintenance system. This thesis uses PLI to measuree the "hidden factory" under a smart maintenance set up and determines the maintenance functional requirements in production. This thesis also illustrates how smart maintenance increases the OEE and influences the Asset management and the Sustainability of production companies, hence, other objectives include:

1. To describe the metaphor "hidden factory" as a consequence of waste in production and categorize the various forms of production and maintenance wastes.

2. To modify the "16 big Losses" with illustrations on how those losses impede the OEE and

OPE and with an extension showing how the "16 Big Losses" propagates to the "4 Safety Losses". A severe safety loss in the production plant could result loss of asset, fatality, loss of company's reputation, and or environmental pollution (e.g., GHG Emission, Oil Spillages) which impedes company's sustainability.

3. To highlight the main objectives of TPM and present its OEE models used as performance measurement tools; present the 3 OEE Losses; and introduce the profit loss indicator (PLI) as a future tool for measuring "hidden factory".

4. To present ISO 55000 as an asset management system standard and its main objectives designed to support proper handling of processes and risks, which will lead to current and future company's performance.

5. To illustrate how Smart Maintenance enhances an increased equipment availability and performance. Deep Digital Maintenance (DDM) was also introduced as a promising concept which measures and improves the performance capability of production asset.

6. A framework to illustrate the influence of Smart Maintenance and its DDM model in minimization of "hidden factory" ("16 Big Losses and "4 Safety Losses"); how smart maintenance increases OEE value, and how OEE improves the Asset Management and future of a production company.

1.3 Limitations

This thesis focuses on smart maintenance and is limited to the TPM, asset management, and the theory of "hidden factory." This report was written as theoretical research since there were limited possibilities to close interaction with industrial companies due to the covid-19 pandemic. The concept of OEE as a measurement tool was also limited as the scope of this thesis was to determine the future performance measurement system of a physical asset in a digitalized maintenance system (smart maintenance platform). ISO 55000 standard was also limited as it was only introduced to underline the main objectives of asset management towards the realization of organizational values.

1.4 Approach

Relevant literature was reviewed in order to reach the objectives of the thesis. These approaches also combined the theoretical research and different case studies (literature), which enabled the achievement of the final objectives of this report. A lot of papers and materials were received from my supervisors, which supported this study. I also visited the library on several occasions to borrow some relevant materials which were not available online.

1.5 Structure of Main Report

The rest of the main report are organized as follows:

- Chapter 2: Theoretical Background
- Chapter 3: Methodology
- Chapter 4: Analysis
- Chapter 5: Discussions
- Chapter 6: Conclusions and Recommendations

Chapter 2 provided literature on the metaphor "hidden factory" and categorized production and maintenance wastes. The "16 Big Losses" that impede production efficiency and plant performance were restructured, and the "4 Safety Losses" that interfere with production's sustainability were introduced. PLI was introduced as a future tool for measuring "hidden factory" in production. As OEE was introduced, TPM's objectives towards eliminating the 3 OEE losses were highlighted. The modified OEE tools used for various industrial performance measurements were also listed. The smart Maintenance concept was introduced, and PDM 4.0 was highlighted as one of the arms of Industry 4.0 that enhances condition-based maintenance. The deep Digital Maintenance (DDM) management model as an emerging concept for monitoring the productive capability of production assets was also introduced. Finally, ISO 55000, as a standard for asset management and its series of objectives that enables an organization to realize value from assets in achieving its organizational goals, was introduced.

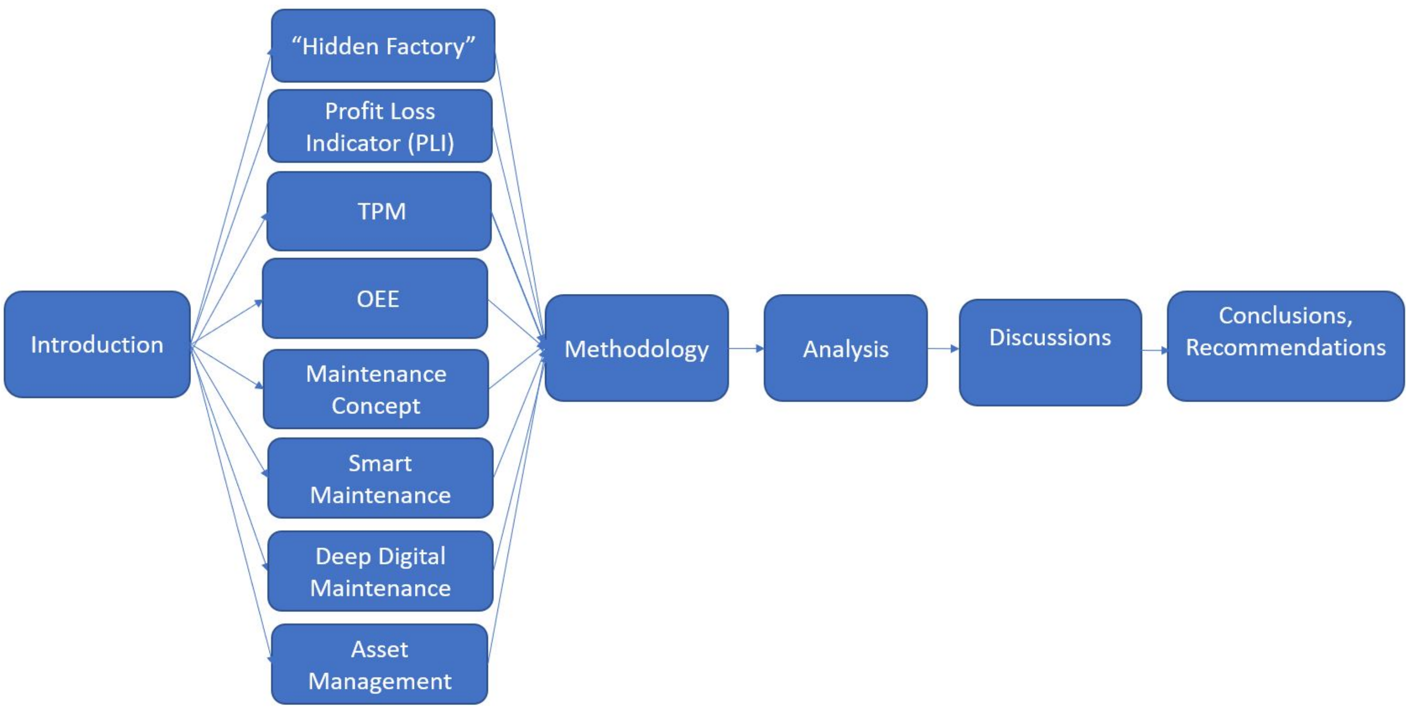

Figure 1.1: Structure of the master thesis

Chapter 2

Theoretical Background

2.1 "Hidden Factory"

In the industry today, efforts are made by production companies towards the development and operations of safer, more reliable, and easily maintainable assets for the production of quality products and services. In the process industries, for instance, products are produced in the plant, which comprises units such as columns, pumps, compressors, valves, etc., and all these equipment are usually connected by piping and instrumentation systems [JIPM, 2017]. Increasing production efficiency in a production company could be achieved by the maximization of 4 M's (Machine, Material, Man, and Method) [Liker, 2006]. For this reason, it is certain that the plant's efficiency and productivity would be increased if the 4 Ms were integrated and optimized. In order to increase plant production efficiency, it is also required to examine the losses due to the wastes induced by the 4 M's, which comprises the inputs to production. [Shingō, 1989].

The term "hidden factory" is a metaphor used to denote the consequences of flaws in production in terms of rework of low-quality jobs, unsatisfactory products from the process, errors in invoicing and customer's services, retrofit of rejected products in the field etc. [Feigenbaum, 1994]. The "hidden factory" is a term attributed to wastefulness during production. Harry and Schroeder [2005] defined "hidden factory" as all the processes, activities, and systems aimed at correcting errors arising in the various stages of production. Rødseth et al. [2015] described "hidden factory" as a metaphor for measuring the time losses in the industry through the maintenance KPI overall equipment effectiveness (OEE). Miller [2011] described "hidden factory" as the generated problems connected to costs which usually increases a company's requirements for fulfilling customer's expectations. Miller [2011] further emphasized that the generated problems connected to costs often increase due to lack of awareness of such a phenomenon. Kosina [2013] said that the savings resulting from the reduction of the costs connected to "hidden factory" are directly proportional to the savings due to quality projects. Miller [2011] also said that the difference between rolled throughput yield and final yield should call the attention of the company on the efficiency of their operations, which is relatively low. Juran and Godfrey [1999], a quality management expert who was one the first persons to reveal the concept of "hidden factory," used a similitude "gold in the mine" in quality management. His idea of this analogy was to express the numerous quality losses in terms of unnecessary defect costs. "Gold in the mine" is a metaphor used for the potential savings realized from quality improvement actions, and it is also used by quality management in expressing the various categories of quality losses in terms of what is regarded as "unnecessary defect costs" [Rødseth et al., 2015].

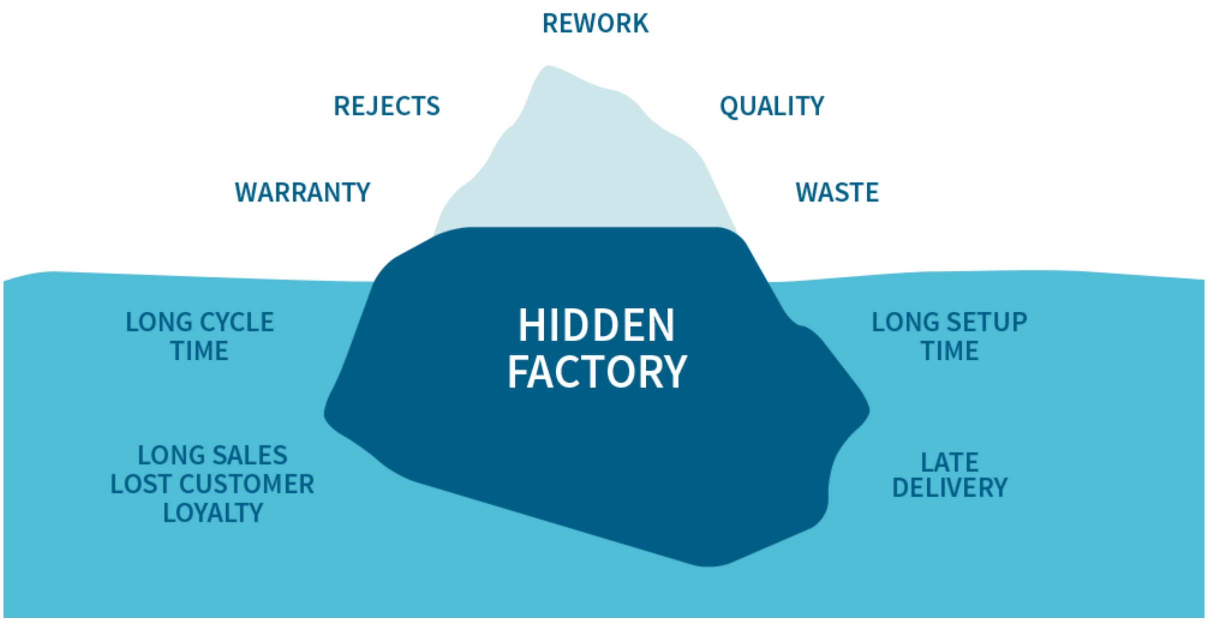

Figure 2.1: Elements of "hidden factory" in production adapted from Rao [2021]

2.1.1 Waste

In a production process, the two major operators who work side by side are maintenance and production [Ahuja and Kumar, 2009]. While the production department ensures that the right process stages are carried on, the maintenance department ensures that there is availability and reliability of the process equipment. One of the main targets of the Toyota Production System is to eliminate time losses during production by removing the non-value-added wastes [Liker, 2006]. But this target could be actualized when such wastes are identified and structured with respect to the "three (3) OEE Losses" [Muchiri and Pintelon, 2008] which will be illustrated later in this chapter. However, two major categories of wastes that were found by TPS relating to production and maintenance are briefly explained below [Shingō, 1989].

Production Waste

Production waste may include all waste related to any production activity. They are briefly discussed below [Chiarini, 2012].

Overproduction
Overproduction means making too many or too early products. Overproduction leads to a high level of inventory, which masks many of the problems within the organization.

Inappropriate Processing
Using an inappropriate set of inputs such as chemicals, tools, procedures or systems, techniques, oversize equipment, perform processes that are not required by a customer or that does not meet the standard is regarded as production waste and described as inappropriate processing.

Defect
Defective product refers to any required item that requires rework or replacement. It wastes resources and materials. It also creates paperwork and can lead to the loss of customers.

Excessive Transportation
This refers to the movement of materials or information that causes waste in time and cost.

Waiting
This is an obvious waste, an enormous amount of time spent in waiting for information or goods resulting in long lead times.

Unnecessary Motion
This refers to moving more than necessary when work is going on.

Excess Inventory
An excessive amount of storage that uses resources but does not add any value for the customer.

Underutilization of Employee
This is a case when an organization cannot obtain a maximum benefit from its employees, cannot wisely yield its workforce' or cannot load them with work effectively.

Maintenance Waste

Maintenance waste may include all waste related to any maintenance activity [Chiarini, 2012]. The goal of lean maintenance is to deliver maintenance excellence with zero unplanned stops and optimized overall maintenance cost [Shingō, 1989]. They could be discussed below:

Overproduction
Overproduction in maintenance means doing any work that does not add value to it. An example could be the act of performing a preventive and predictive maintenance task that is not necessary.

Poor Inventory Management
One of the consequences of inaccurate inventory is elevated risk of a stock-out condition as part as which would not be ordered on time, and parts could be flagged fore- ordering by the system even if not needed.

Transportation
This is unnecessary travelling that results to insufficient planning and scheduling.

Waiting
Waiting for equipment availability, job assignments, tools, parts, and instructions from other authorities like work permit approval etc. are forms of waiting loss during maintenance operations. Waiting does not add value to maintenance and should be eliminated or reduced as much as possible.

Process Waste
This refers to a result of a poor repair, with not enough time given to fix it properly.

Unnecessary Motion
This kind of waste is mostly found in preventive maintenance, doing inspection should be dependent on the criticality of that piece of equipment.

2.1.2 The "4 Safety Losses"

The three optimate goals of Total Productive Maintenance (TPM) are zero defect, zero accident, and zero breakdowns [Nakajima, 1988]. The general purpose of equipment maintenance is to improve its reliability, maintainability, and safety. But in the process of carrying out maintenance operations, safety-related losses sometimes occur. Such losses should not be neglected as they result in more damages to the equipment and tools, environmental degradation, loss of assets, injury to the victims, or fatality. Quantifying these losses in terms of cost also contributes to the effect of a "hidden factory" in production.

The Four (4) Safety Losses that could be emanated in production and maintenance processes could be categorized as Human Losses, Material Losses, Environmental Losses, and Socio-Economic Losses.

Human Losses

Human losses due to safety are the consequences of the accident on people who are directly involved in the operation of the system. The multitude of equipment and components in the production plant has increased hazards or threats to safety. In most cases, as production is ongoing, maintenance and other activities are ongoing (simultaneous operations). The process operators, inspector, maintenance crew, and other personnel sometimes incur injuries due to accident events. The injures (losses) due to accident events could be quantitatively expressed in terms of cost, and it is termed as ''Human Loss" due to safety. Other examples of human losses due to safety include loss of life (casualty), reduction in life expectancy, etc.

Material Losses

Material losses, which could also be referred to as Tool or Equipment losses, are safety losses which may include consequences of all the damages on tools, equipment, plant, and platforms due to an accident event. In a similar sense, consider if a breakable hand tool slips off the hand of a technician and gets damaged. The loss of the hand tool is termed a material loss. Other examples of material losses in the production plant due to safety include damage of equipment like pump during lifting operation at installation stage or damage of compressor during lifting operation at maintenance stage, the explosion of the plant which results to loss of assets, etc.

Environmental Losses

Environmental losses due to safety may include all the various forms of environmental impact during production or maintenance processes. Examples include damages to the environment (fauna, flora soil, air, climate, landscape, etc.), high emission of carbon due to poor equipment performance, the release of toxic gases during maintenance operations, investigation, and clean-up costs due to spillages, etc. The effect of environmental pollution is usually evaluated by the Environment Impact Assessment (EIA) [EIA, 2003]. One of the objectives of the EU Taxonomy is “Pollution Preventions and Control.” In Norway, The Norwegian Pollution Authority (NPCA) and the Strategic Environmental Authority (SEA) have been working on EIA for a broad competence in area use planning. Strict rules have been set up to control all the activities on the environment of the areas, namely: petroleum industry, shipping, fisheries, and aquaculture [EIA, 2003]. Also, the Norwegian Institute for Air Research is involved in the assessment of the effects of pollution on the ecosystem, human health, and materials. The main function of NILU is to provide scientific facts on the quantitative relationships between the aforementioned factors and make results available to responsible authorities for decision-making. Costs due to the tasks and fines are the resulting main effects of losses due to the environment, and all these are elements of the “hidden factory.”

Socio-economic Losses

Socio-economic losses include all other forms of losses that affect both the economic and social status of the organization, which are generated due to accident events. Such losses may include business interruption losses, loss of information, loss of reputation, legal action and damage claims, business sustainability consequences, societal disturbances, insurance deductible costs, etc. This form of safety loss could be initiated from poor maintenance activities, and it impedes the sustainability of a production company.

2.1.3 The “16 Big Losses”

The “16 Big Losses” was extended from OEE and have been identified by Shirose [1995] to be impeding the production performance and efficiency [Shirose, 1995]. To achieve production efficiency, TPM is aiming at eliminating the “16 Big losses” which are categorized in to four groups below [Ahuja and Kumar, 2009]:

Seven (7) main losses obstructing overall equipment efficiency (failure losses, set-up/adjustment losses, reduced speed losses, idling/minor stoppage losses, defect/rework losses, start-up losses and tool change over losses),

Losses that obstruct loading machine time (planned shutdown loss),

Five (5) major losses that obstruct human performance (distribution/logistic losses, line organisation losses, measurement/adjustment losses, management losses, and motion related losses) and,

Three (3) major losses that obstruct effective use of production resources (yield losses, consumable – jig/tool/die losses, and energy losses).

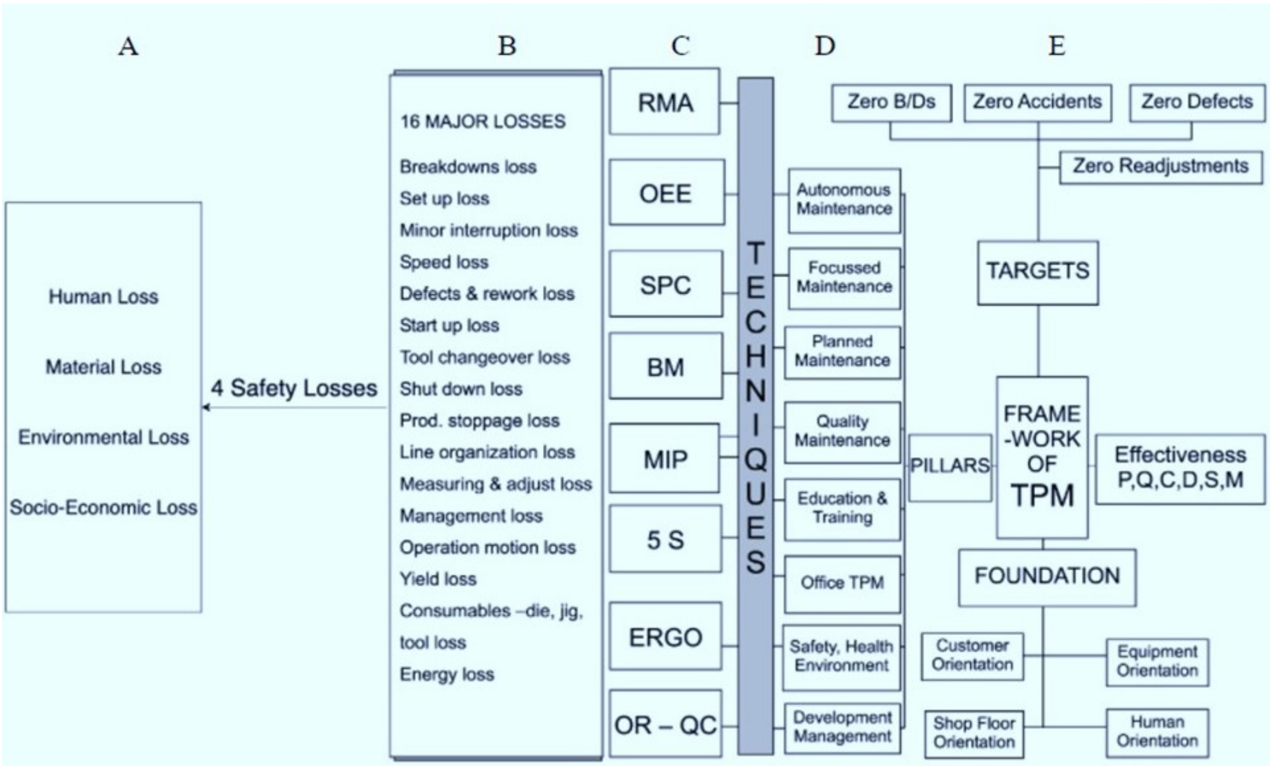

Figure 2.2: Modification of the Framework for TPM Implementation as inspired by [Ahuja and Kumar, 2009]

Figure 2.2 above shows the modification of the framework for TPM implementation. In this modification, the “4 Safety Losses” were captured.

Column A are the “4 Safety Losses” as explained in subsection 2.1.2

Column B is a list of the “16 Big losses” in the production plant.

Column C is a list of the techniques which should be applied to minimize those losses. The techniques are listed below:

RMA: Reliability and Maintainability Analysis

OEE: Overall Equipment Effectiveness

SPC: Statistical Process Control

BM: Breakdown Maintenance

MIP: Manufacturing and Inspection Plan

5S: Sort, Set in order, Shine, Standardize, Sustain

ERGO: Environmental Review Guide for Operation

OR-QC: Operational Requirement and Quality Control

Column D is the 8 Pillars Approach for TPM implementation. These pillars are actions that should be executed regularly by the management and personnel to drastically reduce the "16 Big Losses". They include Autonomous Maintenance, Focussed Improvement, Planned Maintenance, Quality Maintenance, Education and Training, Safety, Health and Environment, Office TPM, and Development Management.

Column E consists of the foundation, framework targets of the TPM. The foundation is the point at the grassroots where TMP implementation begins. These include the Shop Floor Orientation, the Human Orientation, the Customer and Equipment Orientation. The Framework consist of the TPN Pillar, which has been explained above, and its effectiveness. The effectiveness is used in benchmarking marking Overall Equipment Effectiveness (OEE), Productivity (P), Quality (Q), Cost (C), Delivery (D), Safety (S), Morale (M), etc. could enhance an organization to achieve these goals. The target, which includes three optimate goals of TPM is zero defect, zero accident, and zero breakdowns as well as zero readjustments.

TPM employs OEE as a quantitative metric for measuring the performance of a productive system [Nakajima, 1988]. The overall goal of TPM is to increase OEE.

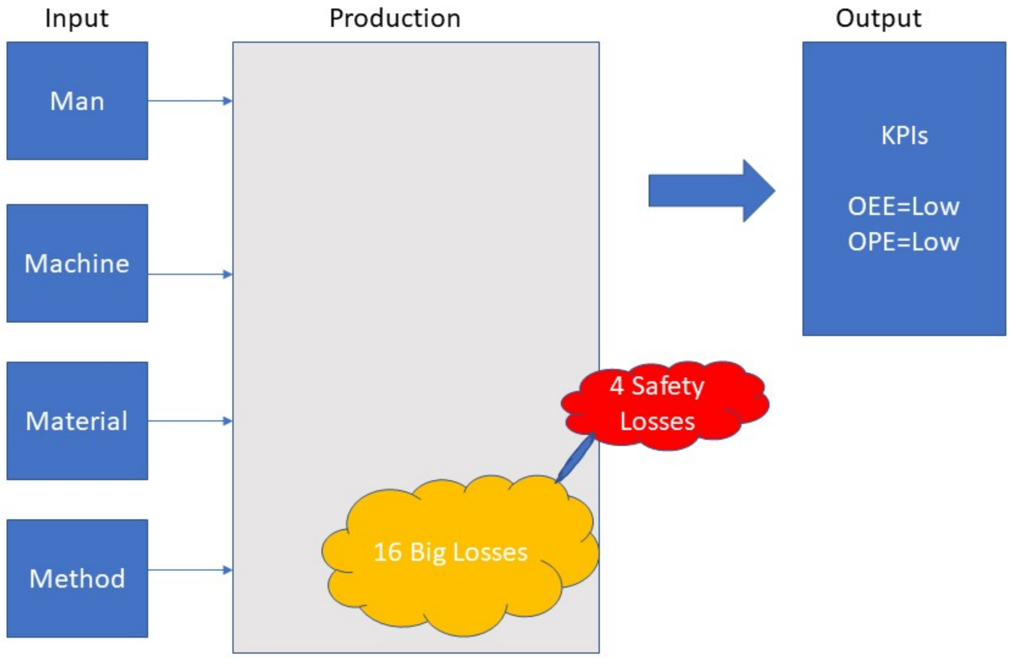

Figure 2.3: KPIs of a production plant with "hidden factory"

In the Figure 2.3 above, the 4M's were applied as an input to a production plant. The output showed that there was a "hidden factory" that was initially categorized as "16 Big Losses," which triggered the "4 Safety Losses". The "4 Safety Losses" drastically reduced the sustainability of production. This also resulted in a low OEE and OPE with a very high level of PLI. Low OEE and OPE values mean low effectiveness of equipment and production plant, respectively, and a high PLI value means a huge financial (monetary) loss.

2.2 Profit Loss Indicator (PLI)

"Remember, that time is money" - Benjamin Franklin

When calculating PLI a common proverb by Benjamin Franklin "remember, that time is money" should be well noted. PLI is a very important performance measurement tool for production companies. The KPI PLI will help to unveil "hidden" areas where waste and OEE losses affect business. The indicator is not only applicable to maintenance alone but can be used in various business aspects in an organization. The indicator consists of many underlying factors, each of which describes a real or potential (loss) cost within different parts of a company. These costs are broadly divided into two categories: the first category describes the direct cost, and the second describes the lost profit. The PLI calculation follows a similar principle to life cycle costs (LCC). Table 2.1 below shows the relationship between various costs, lost revenue, and profit. The topmost area of the figure describes the total revenue when production is 100 percent available, which is an ideal situation but usually not possible. The other curves show how much of the total possible earnings go to direct costs (e.g., level 6,7), and how much is not realized as earnings due to downtime or unavailability of equipment (e.g., level 5 causes loss in revenue). For example, 2 and 3 describe life cycle losses where losses due to planned and unplanned maintenance ("hidden factory") affects the revenue. The center with arrows shows a potential profit that can be realized if the organization manages to implement necessary measures to minimize "hidden factory". And lastly, the in the center of the figure is the real profit through the life of the equipment.

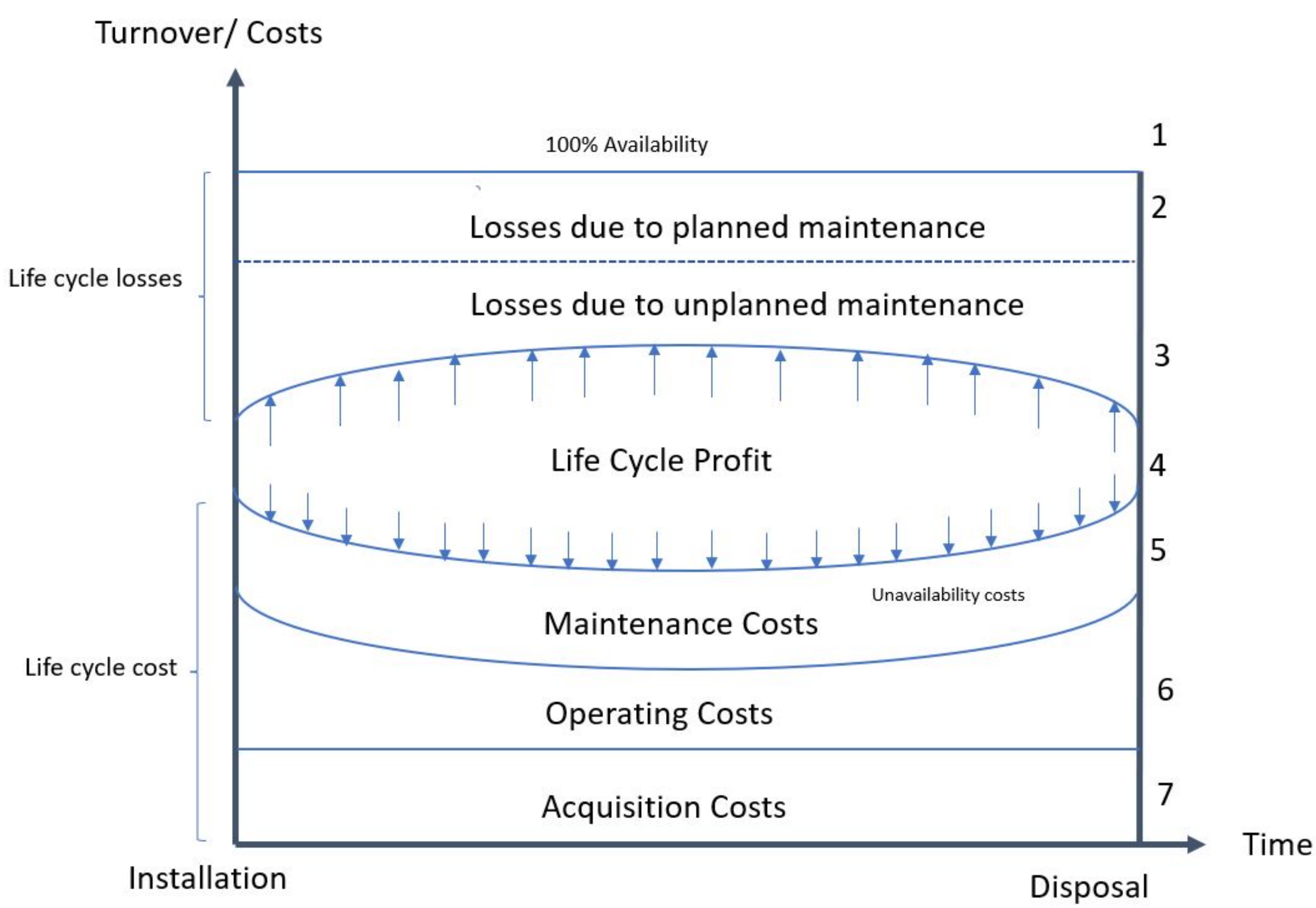

Table 2.1: Illustration of Life Cycle Profit adapted from [Rolstadås, 1999]

2.2.1 The PLI Cube

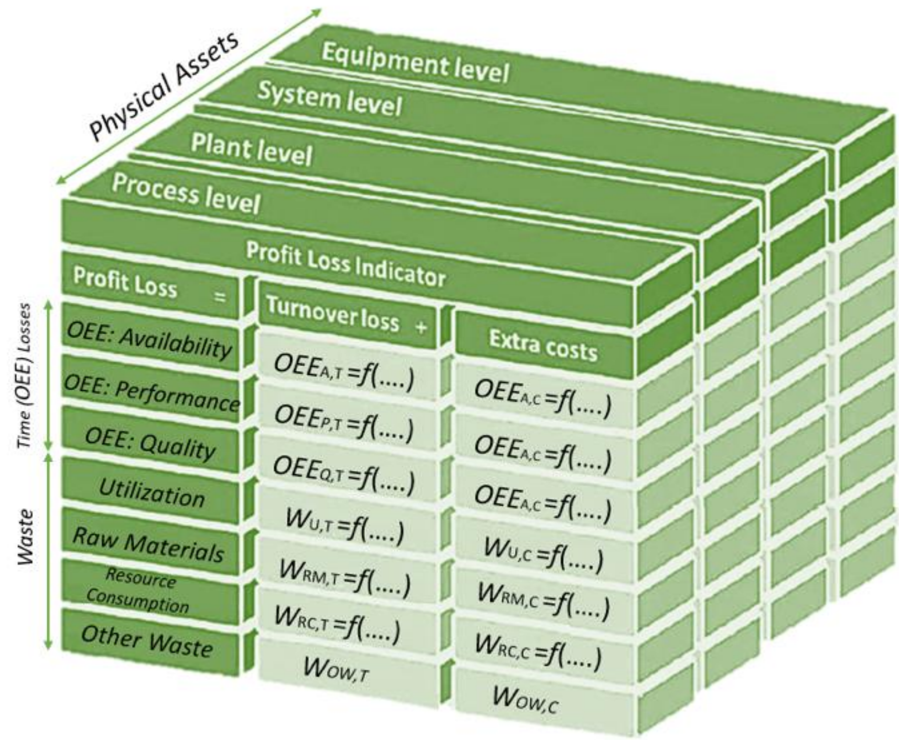

Figure 2.4: The PLI cube adapted from [Rødseth et al., 2015]

Figure 4.3 above shows all the parameter that are used in calculating the PLI. In financial accounting, profit can be calculated by subtracting costs of production from turnover in production. Therefore, profit loss in business will become the sum of turnover loss and extra costs of expenditure during the production processes.

Profit in business = Turnover in Production - Costs of Production
Proftloss in business (PLI) = Turnover Loss + Extra Costs

PLI can be calculated in various aspect of production. As explained in section 2.1, "hidden factory" can be emanated due to wastes generated from numerous sources and time losses due to OEE. Therefore, accounting for PLI can be captured from from both wastes and time losses in production. Since, it is obvious that time losses in production are influenced by OEE losses such as unavailability of equipment, poor equipment performance (speed losses), or rework due to quality of products, then PLI will calculate those time losses spent as they have proportions of financial value in turnover losses and extra costs in production. The time losses due to equipment's unavailability, poor performance, and or poor quality of products are formulated from

Figure 2.4:

Profit Loss = Turnover Loss + Extra costs
OEEavailability = OEE.A,T + OEE.A,C
OEEperformance = OEE.P,T + OEE.P,C
OEEquality = OEE.Q,T + OEE.Q,C

Just like same way time losses were categorized into 3 OEE losses so as wastes were categorized in 4 Wastes including utilization, raw material, resource consumption and other wastes. Wastes due to utilization comprises of the extra costs incurred due to over production and the costs due to unnecessary time spent in producing excess products which is turnover loss. Similar principle applies to raw material waste, which is the cost of the raw materials used in production; and resource consumption is the cost of the consumables, tools, spareparts and other resources used during production which are not classified as raw materials. Human resource is also part of resource consumption. Resource consumption here could be energy, spare parts, disposable coverall etc. Wastes could be emanated from various facets of a production company depending on their operations. However, the forth category of waste "other wastes" could be included as as an element of PLI depending on a company's scope of tracing the lost profit in business. "Other wastes" may include waiting time for tools, parts; instruction from authority like work permit; excessive transportation; excess inventory; under-utilization of employee etc. All these wastes contributes to "hidden factory". With the PLI cube, root causes of profit loss due to time losses or wastes can be analysed and management could plan for improvements. The main idea is being able to trace the lost profit through identifications of all possible elements of PLI. The calculation of profit loss due to the 4 categories of wastes are formulated from Figure 2.4:

Profit Loss = Turnover Loss + Extra costs
U = W.U,T + W.U,C
RM = W.RM,T + W.RM,C
RC = W.RC,T + W.RC,C

OW = W.OW,T + W.OW,C

Another interesting aspect of the PLI cube is that profit losses in production can be calculated in various asset levels. This will enable management to know which aspect of production that is contributing to "hidden factory" in business. From the PLI cube, profit loss can be calculate in process level, plant, system or equipment level. But this master thesis will focus more on profit loss for an equipment and will show how PLI enhances performance measurement of of physical asset.

The whole essence of the PLI calculation is to realize more values from an equipment by eliminating or drastically minimizing “hidden factory”. It is obvious that “hidden factory” is initiated from waste and time losses in production. From all indications, it also obvious that all the maintenance and production wastes as were listed in section 2.1 have connections with physical asset. For example, Overproduction which was listed as maintenance waste involves doing any work that does not add value to maintenance of asset. It could be a preventive maintenance task. But that could be unnecessary if it is not executed at the right time. Transportation which was also captured as a waste could be initiated due to insufficient planning and scheduling. This means that maintenance planning could distribute various forms of wastes if jobs are not well planned. It is also obvious that productivity, cost, safety, health, as well as quality of products all depend on equipment. Equipment might be available but with low performance. Therefore, performance could be often used because unavailable equipment will have zero performance. The resultant effects of equipment with poor performance could be categorized as:

a. Quantity issues: This is a situation where a machine produces less than expected quantity or more than expected quantity. Both situations can be captured as waste and severely contribute to “hidden factory”. In this situation, it would be necessary to have an estimate of the normal capacity of a machine for a day and or ideal capacity of the machine as this will enable engineers to measure wastes when production deviates from estimates in either positive or negative outcomes.

b. Quality issues: This is a situation where a machine produces scraps or products below quality standard. It always requires rework or reduced sale price. The main solution to this must be a continuous condition monitoring of machine.

c. Safety issues: Poor equipment performance will continue to increase in degradation level till a total breakdown (availability loss). Asides from that, the machine could become noisy, emit GHG, or leakages might occur depending on the process and equipment type.

Another advantage of PLI is its ability to measure time losses and waste in production and present them in financial measure and in different dimensions. Figure 2.4 above shows how physical asset at various levels (process level, plant level, system level, equipment level) could be analysed both in accounting dimension and in categories of time losses and wastes in production. This will enable management to trace the “hidden factory” in a structured manner [Rødseth et al., 2015]. For an example, if there is time loss (OEE loss) due to availability loss of equipment (like pump breakdown), management should be able to know if the availability loss was turnover loss due to reduced number of products sold to their customer due to reduced quantity (volume), or extra cost which might be the cost of hiring ad-hoc staff to execute a corrective maintenance when equipment was down. The same calculations apply to other time losses (OEE losses) like performance loss and quality loss.

2.3 Objectives of TPM

According to Chaneski [2002], TPM is a maintenance management programme with the objective of eliminating equipment downtime. TPM's objective is to maximize equipment effectiveness throughout the lifetime of the equipment. It intends maintaining an equipment in an optimum condition in order to prevent unexpected breakdown, speed losses, and quality defects occurring from process activities [Ahuja and Kumar, 2009]. It also describes a synergetic relationship among all organisation's functions, most especially between production and maintenance and safety, for the continuous improvement of product qualities, operational efficiency, productivity, and safety [Brah and Chong, 2004, Hooi and Leong, 2017]. Benchmarking on the Overall Equipment Effectiveness (OEE), Productivity (P), Quality (Q), Cost (C), Delivery (D), Safety (S), and Morale (M) etc. can enable an organisation in achieving zero breakdown, zero defect, zero machine stoppage, zero accidents, zero pollution, which are the ultimate objective of TPM [McKone et al., 2001]. TPM also focusses on improving the indicators of production success [Wireman, 2005]. TPM focusses in identifying the major losses and wastes within production systems by significantly improving the production facilities [Ahuja and Kumar, 2009]. It makes provisions for a comprehensive, life cycle approach to equipment management that reduces equipment failure to the lowest level as well as production defect, and accident [Nakajima, 1988].

2.4 Overall Equipment Effectiveness (OEE) and its Performance Measurement Models

OEE is defined as the measure of total equipment performance, that is, the degree to which the equipment is doing what it is supposed to do [Ahuja and Kumar, 2009]. Nakajima [1988] who was the originator of OEE defined it as a metric or measure for the evaluation of equipment effectiveness. According to him, OEE attempts to identify production losses and other indirect and "hidden" costs, which according to Koch [2007] are those that contribute with a large proportion of the total cost of production. OEE is used to track and trace improvements or decline in equipment effectiveness over a period [Dal et al., 2000]. The consequence of reducing breakdowns and defects is improvements in production rate, reductions in costs, reductions in inventory, and eventually increases in labour productivity [Muchiri et al., 2011]. According to Muchiri et al. [2011], OEE categorizes major losses or reasons for deficient performance and therefore provides the basis for setting improvement priorities and beginning of root cause analysis. This makes OEE to be regarded as a measurement tool under TPM, aimed at identifying production losses related to equipment [Jostes and Helms, 1994]. The OEE losses are formulated as a function of several mutually exclusive components [Productivity Development, 1999], namely: availability (A), performance (P) and quality (Q). According to Dal et al. [2000], OEE points to the hidden capacity in manufacturing process and lead to balanced flow. Initial performance of an industry can be used as "benchmark" helping the management team compare OEE values between initial and current to improve. Known as a quantitative metrics, Nakajima [1988] classified these losses into six in order if it had to be eliminated and does not consider all the factors reducing capacity utilization such as planned downtime, lack of material, labour etc. The losses are [Muchiri et al., 2011]:

1. Breakdown (Equipment failure)
2. Set-up and adjustment
3. Idling and minor stoppages
4. Reduced speed or speed losses
5. Quality defects and
6. Reduced Yield

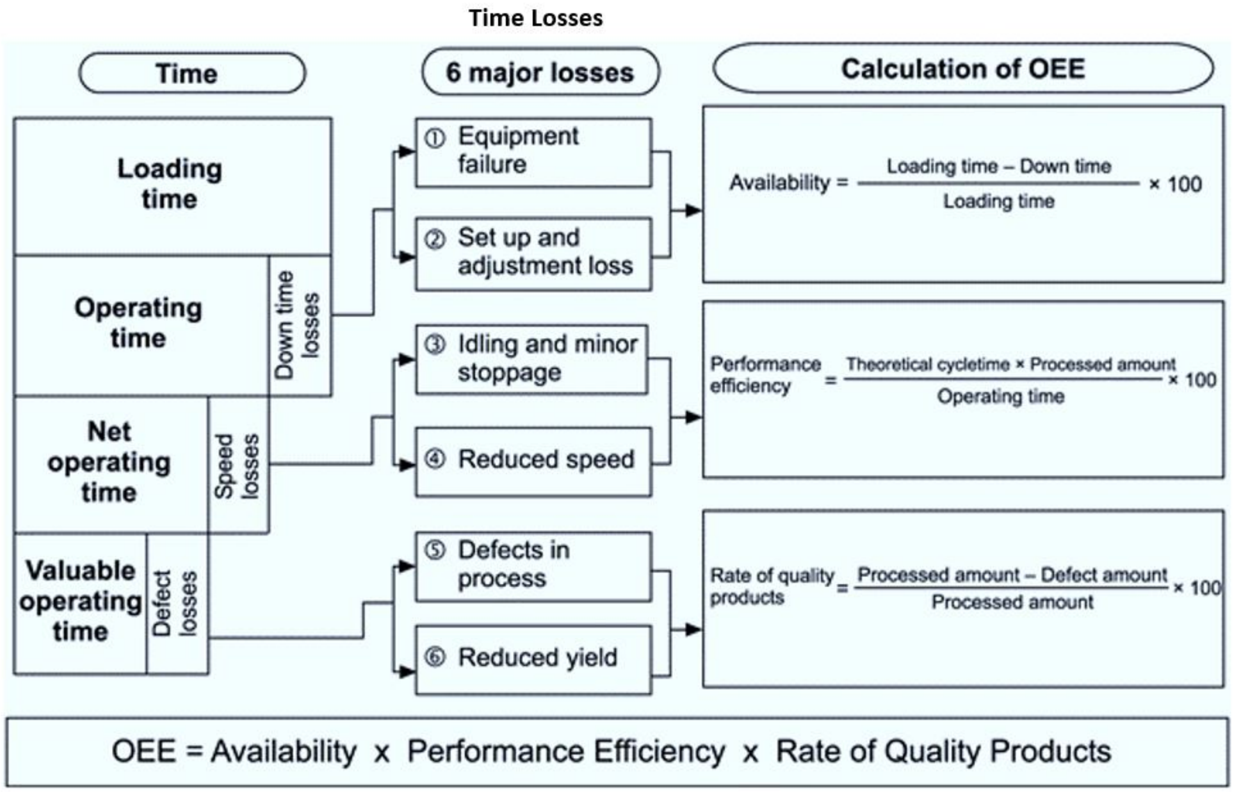

Figure 2.5: Calculation of OEE based on six (6) major production losses adapted from [Ahuja and Kumar, 2009]

Figure 2.5 above structures the 6 major equipment losses during production into three groups and how each group member contributes to each of the three OEE losses. The three groups include Downtime Losses (Availability Losses), Speed Losses (Performance Losses), and Defect Losses (Quality Losses).

Availability Losses

Equipment Failure Losses, Set-up and Adjustment Loss.

As illustrated in the above structure, equipment's availability is a function of its operating time. Availability considers equipment Failures, and Setup and Adjustment. It is the ratio of loading time to the time consumed by the operation. It considers all events that stop planned production long enough where it makes sense to track a reason for being down. It is also clear to say that availability score of 100 percent means that the process operation is always running during the planned production time. It is expressed as:

Availability = (loading time-downtime) / (loading time) x 100 ,

where loading time is the time needed for operating the equipment. While Loading time is referred as the planned production time, downtime is defined as all the time where the production process was supposed to be running but was not due to unplanned stops like breakdowns or planned stops such as changeovers. These are losses due to breakdown of equipment or equipment's component. Types of failure may include sporadic function-stopping failures and function-reducing failures in which the equipment's function drops below its required functional level. Example is breakdown of a centrifugal pump.

(i) Breakdown or Equipment Failure Loss
These are losses due to breakdown of equipment or equipment's component. Types of failure may include sporadic function-stopping failures and function-reducing failures in which the equipment's function drops below its required functional level. Example is breakdown of a centrifugal pump.

(ii)Set-up and Adjustment
These losses are caused by changes in operating condition. Such losses occur due to stoppages of equipment to change equipment's component. It requires a period of shutdown so that the tool can be exchanged. Example is change of a drill bit of a driller.

Performance Losses

Idling and Minor Stoppage Loss, Reduced Speed Loss.

As illustrated in the above figure, Performance Losses is inversely proportional to the Operating Time. Availability rate is the product of speed operating rate and net operating rate. Performance considers Idling, Minor Stops and Reduced Speed. Performance captures everything that causes production process to run at less than maximum possible speed when it is on operation. Such running also includes slow cycles and small stops. Performance should never be greater than 100 percent. If it is, that means the standard time cycle is set incorrectly.

Performance Rate = Speed operating rate x Net operating rate

The speed operating rate is the ratio between the ideal equipment speed (number of cycle time stroke) and its actual speed. It indicates if the equipment is running at the required speed (standard cycle time) otherwise, the identifies the amount of speed loss.

Speed operating rate = (Standard cycle time) / (Actual cycle time) , and
The net operating rate is used to identify if the equipment is running at a stabilized speed or not within the time unit. It is used to indicate whether the speed is faster or slower than the standard speed.

Net operating rate = (Product unit processed x actual cycle time) / (loading time-downtime)

Alternatively, we can say that:
Performance Efficiency = (Processed amount x Theoretical cycle time) / (operating time) x 100

(i) Idling and Minor Stoppage Loss
These kinds of losses occur when an equipment temporally stops control system failure or jamming of work. The equipment may operate normally through simple measures like removal of work and resetting or a quick check on the system.

(ii) Reduced Speed Loss
This kind of loss occur due to reduction in the required speed of an equipment. Example could be the drop in the rotational speed of the shaft of an engine. Or it could also be seen as the losses due to actual operating speed falling below designed speed.

Quality Losses

Defect in process, Reduced yield.

As illustrated in the above figure, rate of quality product is a function of valuable operating time. Quality Product Rate is the ratio of the quantity (material and energy) to be machined or loaded for machining to the actual quantity of quality products. Quality indicates the products that do not meet quality standards, including the parts that need rework. Good products on the other side are part that successfully pass through the production process for once without any need for rework. It also clear that a quality score of 100 percent means that when the process is running, it only makes good parts.

Quality product rate = (Product units procesed-defect units) / (product unit processed) , where defect product does not include only waste but also quantity of rework. It is also be expressed as:

(i)Defect in Process

These are resources and time losses due to defect and rework (Disposal Defect). The time and resources spend in reworking are part of the financial losses in the industry. Example is a process upset in the Liquid/gas separator in subsea production. If the separator is unable to separate Water, Oil, Gas as separate substances, it become a defective work and requires a rework.

(ii)Reduced Speed Loss

Reduced Yield accounts for the defective parts produced from start-up until stable state production is reached. It is also referred as the losses due to the time spent when starting up a plant or an equipment or the time loss before stabilization of production process could be included in the financial losses of an organisation. This is called start-up loss. Example is the start-up of a gas turbine plant.

Nakajima (1988) earlier suggested ideal values of OEE at 85 percent (known to be as a world class value) for a component measure as.

- Availability rate at 90 percent
- Performance rate at 95 percent and
- Quality rate at 99 percent.

Also, OEE as a performance measurement tool can be applied for different activities [Rødseth et al., 2015]:

a. Operational activities: measuring OEE in daily operation.

b. Tactical activities: a drop in OEE may trigger root cause analysis (RCA) where the root cause is identified and improvement are implemented in order to eliminate the root cause.

c. Strategic activities: investement in new machines may not be neccessary if the value of OEE for the existing machine is lower and can be improved.

Further investigations have been carried out in order to clarify the appropriate levels of availability, performance, and quality. Zennaro and his colleagues present an OEE value greater than 50 percent as a more evident and reality figure and more helpful as an acceptable benchmark [Zennaro et al., 2018]. Ljungberg [1998] presented an acceptable OEE value of between 60 percent and 75 percent while [Garza-Reyes, 2015] gave a value that varies between 70 percent and 80 percent. The OEE concept had been widely used as a quantitative tool essential for measurement of productivity in production plants [Huang et al., 2003]. The industrial application of different OEE models as it is today varies from one industry to another. Although the basis of measuring effectiveness is derived from the original OEE concept, many production companies have customized OEE depending on their industrial requirements and application concepts [Muchiri et al., 2011]. Some of the modifications include Overall Factory Effectiveness (OFE), Overall Plant Effectiveness (OPE), Overall Throughput Effectiveness (OTE), Overall Line Effectiveness (OLE), Production Equipment Effectiveness (PEE), Overall Asset Effectiveness (OAE), Total Equipment Effectiveness Performance (TEEP) [Muchiri et al., 2011]. Some of the modified formulations are limited to effectiveness at the equipment level (e.g., PEE and TEEP), while others have been extended to factory level effectiveness (e.g., OFE, OTE, OPE, and OAE) [Muchiri et al., 2011]. Although OEE has been successfully used as a performance measurement tool in the industry, its weakness as an indicator is the lack to be expressed as a financial indicator [Rødseth et al., 2015].

2.5 Maintenance Concept

One of the main objectives of maintenance is to ensure equipment's availability and performance. The maintenance management process begins with the program, planning, and execution of maintenance. Sometimes operators do not follow the maintenance management loop; for example, they implement their maintenance due to time-based, and sometimes it works (technical condition). But it is also very important to report it, analyze it, and try to make improvements on how to make the system work even better in the future. Sometimes the loop breaks after recovering their asset to a healthy technical condition, thereby skipping reporting and sometimes analysis. It is also important to make an analysis and gather experience for improvements in order to transfer the improvements back to the loop for new goals and requirements. Management and verification are placed at the center of the loop for continuous audit for implementation of maintenance work processes. While the organization, materials and documentation, and IT are the invested resources, risk level, and production performance are the output or results. The maintenance management loop is shown in Figure 2.6.

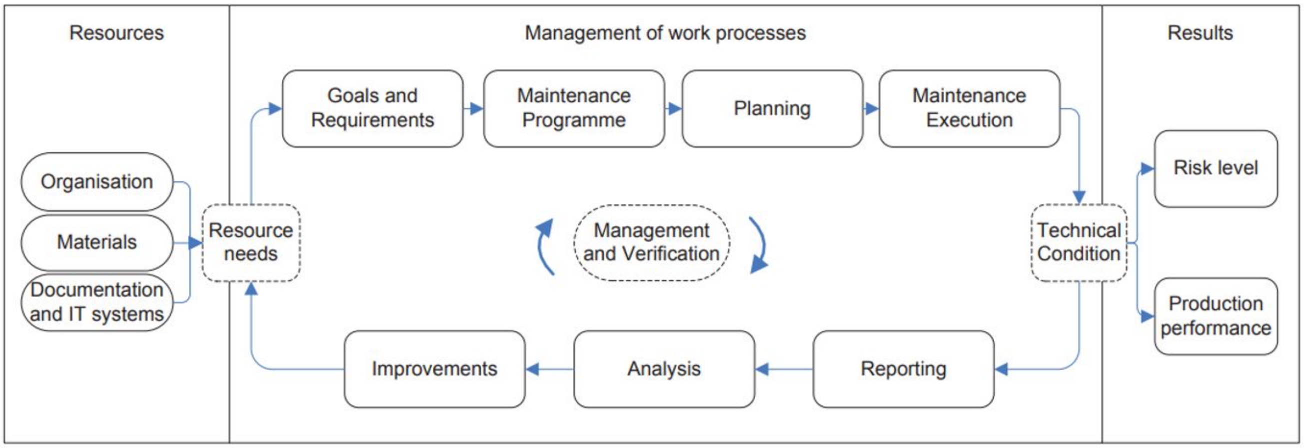

Figure 2.6: Maintenance Management Loop adapted from [NORSOK Z-008: 2017]

Choosing maintenance concepts depends on cost, maintainability, reliability, availability and safety. It also depends on system's operational and environmental condition.

a. Corrective maintenance or unplanned maintenance is when equipment is run to fail before fixing it.

b. Scheduled or planned maintenance is when you have hourly or time-based maintenance intervals.

c. Condition-based maintenance is done depending on the health condition of the equipment as operators think it is cost-effective to do maintenance based on equipment condition. Some operators believe that maintenance can only be done when necessary.

d. Reliability centered maintenance focuses on equipment to achieve acceptable reliability.

There is a connection between condition-based maintenance or condition monitoring and predictive maintenance. Condition monitoring is usually done first to have a piece of knowledge about the RUL estimates of an asset which is followed by maintenance planning.

2.6 Smart Maintenance planning in Asset Management

Industry 4.0 is used in the manufacturing industry in Europe to describe the 4th industrial revolution. Similar descriptive words could be used in a different part of the world but provided it represents the introduction of cyber-physical systems (CPS) and machine learning. Industry 4.0 is creating a big wave today as many industrial companies transform their systems to Industry

4.0 compliance. One of the essential aspects of Industry 4.0 is full automation to a large extent that entire production processes in a production plant will be highly autonomous without human intervention. Industry 4.0 can highly achieve fully autonomous systems through CPS, which is enabling. With the evolution of Industry 4.0, maintenance has also become a focal point towards attaining the apex of efficiency and productivity. The technology necessary for Industry 4.0 is one step forward, but optimizing intelligent maintenance techniques to achieve total plant equipment efficiency and productivity remains the primary goal. Depending on the criticality of an asset, some assets require real-time condition monitoring to ensure they will not fail, causing availability losses which trigger other forms of wastes during corrective maintenance [Verl et al., 2009]. Critical equipment should have a risk profile that tells if the consequences of failure are severe or not. Condition monitoring, diagnostics, and distance access to assets need an intelligent system to deliver collectively the vast amount of data and analysis that is required for this next level of digitalized maintenance [Chukwuekwe, 2016]. It combines Big Data and IIoTs, collecting data related to historical events, the asset health, performance of machines and machine parts thereby, effectively reducing the operational and maintenance costs which severely contribute to the “hidden factory”. The gathering of data, storage, analysis, and decision-making for smart maintenance is called an intelligent maintenance system (IMS) [Raza and Liyanage, 2009]. Monitoring and analyzing the behaviour of equipment and components of machines has become possible by employing advanced sensors, IoT, AI, ML, Cyber-physical Systems, and other intelligent technologies. An advanced intelligent maintenance system can process the collected data, provide insights in behaviour, trigger alarms and give instructions for preventive maintenance [Eveliene, 2019]. With the correct data acquired from monitoring assets, companies can obtain a competitive advantage by gaining relevant insights into equipment’s performance and usage levels of machinery. By IMS, criticality, planning, processes, production, use of resources, maintenance, etc., can be optimized. With the implementation of smart maintenance, unplanned downtime can be eliminated by automatic scheduling of maintenance before equipment failure, thereby increasing total availability and equipment performance which are part of the objectives of TPM.

2.6.1 Predictive Maintenance (PDM 4.0)

The NS-EN 13306:2010 defines predictive maintenance as “condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item.” Many researchers have investigated condition monitoring as a key maintenance activity necessary for implementing predictive maintenance on production assets. Condition monitoring could effectively achieve this concept with the application of digitalized technology.

Predictive maintenance is a branch of Industry 4.0 that can be defined as a set of activities that monitors changes of condition of processes or equipment or asset to make a correct and quick maintenance decision for maximizing the service life of equipment [Wang et al., 2016]. The predictive maintenance functions utilize a set of data generated by a cyber-physical system (CPS), transmitted by the Internet of Things (IoT), which is used to monitor machine and process conditions. This function will enable an automatic analysis to pick up any rules or patterns that include a positive fault through a data mining system for decision making [Wang et al., 2016]. The main objective of Predictive Maintenance 4.0 (PDM 4.0) is to improve the Remaining Useful Life (RUL) of machines and at the same time avoid unplanned downtime and also decrease planned downtime.

PDM 4.0 does not only monitor or help in predicting the health condition of an asset, but it also enhances the reduction in time losses during preventive maintenance. It is expensive to carry out Corrective Maintenance (maintenance activity carried out due to equipment breakdown) on production plants. For example, the breakdown of Critical Assets such as Gas Turbines, Compressors, or Pumps requires maintenance activities, including dismantling of subsystem and system components for repair, disassembling, and reassembling, etc. Such breakdown results in loss of production due to downtime, increase in corrective maintenance man-hour, increase in maintenance cost, increase in risk exposure of both equipment and maintenance operators, with a corresponding increase in the probability of environmental degradation due to safety losses.

2.7 The Deep Digital Maintenance (DDM) management concept

The main goal of DDM is to implement a smart maintenance concept from data capture to a work order and execution. The smart maintenance DDM model aims to support asset management in the realization of organizational values. Such values include risk management, cost efficiency, plant/ equipment availability, and performance. These targets can be achieved if PLI data is combined with data-driven prognostics via CPS for smart maintenance planning and execution. Through data analysis obtained from PLI estimates and RUL estimates of equipment, real-time maintenance planning can be achieved where the maintenance planner uses analytical support from a risk matrix performed with AI for smart decision making. The DDM concept will enable planning with its predictive maintenance capability for the optimization of assets in a digitalized maintenance system. This idea will enhance more recovery of values from physical assets through the optimization of smart maintenance. As AI remains the center of Industry 4.0 and offers data-driven methods, it is technically sound to determine the planning module of a digitalized system by determining the Remaining Useful Life (RUL) of failing equipment and the PLI of ignoring any failure. Through AI with ML method, RUL can be obtained from data-driven on equipment (historical vs. operational), which will be combined with PLI for intelligence maintenance planning. Where the PLI will be a consequence of ignoring any failure, and RUL of am equipment at any given time will be the probability of an equipment failure. The DDM model combines the principles of predictive maintenance, risk-based maintenance, and condition-based maintenance. The figure below illustrates the behaviour of DMM in terms of work process [Rødseth et al., 2017]. However, the objectives of DDM comprises several maintenance functions, which includes:

a. To increase plant/equipment availability and performance.
b. To increase man-hour for preventive maintenance.
c. To reduce maintenance cost.
d. To reduce operational risk.

2.7.1 The DDM's management loop

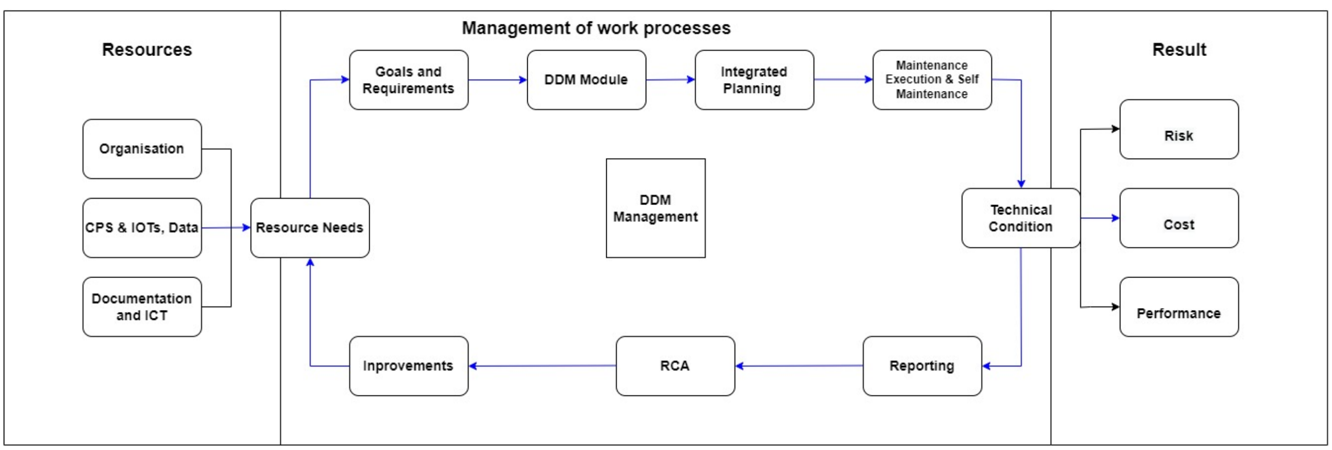

Figure 2.7: DDM Management Loop [Deming, 2018, Rødseth et al., 2017]

Figure 2.7 above shows the work processes for DDM as explained below.

a. Resource requirement: The resources required in establishing a DDM concept will include an already established smart maintenance platform with cyber-physical systems and its peripherals, organization, documentation, and ICT.

b. Goals requirements: The objectives of establishing the concept DDM has been highlighted in the previous section.

c. Deep Digital Maintenance modules: At this stage, the technical personnel should install and apply the DDM modules. RUL is estimated with the degradation model and ML algorithm, PLI values will be estimated by operators, and the planning module will control the maintenance functions.

d. Integrated Planning: To ensure that future maintenance works are effectively executed with efficient maintenance backlog management, production and maintenance must reconcile at various stages for integrated planning.

e. Maintenance execution self-maintenance: At this stage, the DDM will execute its maintenance functions. The physical system automatically conducts self-maintenance with the effort of CPS without human effort. Based on set-up rules for AI, the system will adjust the production to automatically perform standard maintenance of the physical asset.

f. Technical condition: After achieving maintenance execution self-maintenance, the physical system should have been upgraded in health condition. Hence, risk management, cost efficiency, and high equipment performance are the results.

g: Reporting: At this stage, the DDM reports the result of the maintenance already executed at the previous stage. Here, the CMMS saves the information for the future.

h: Root cause analysis: At this stage, the report is being investigated and based on the findings, it is followed with a root cause analysis RCA. Conventional RCA methods, including the Isikawa diagram and 5-why analysis, will be used for RCA. In addition, the analytics from data-driven methods will be able to cluster the information into different cause categories [Rødseth et al., 2017]. Also, the PLI cube is calculated for RCA.

i: Improvements: Haven found out the root causes, improvements will be performed.Improvement could be methods of waste avoidance.

j: Deep Digital Maintenance management: This is the management stage that ensures that the work process in DDM is effectively executed. The DDM management is centered at the loop. The DDM management will also audit the system when necessary.

2.8 Main purpose of Asset Management

In the industry today, asset management has been an important concern and have always been debated due to some events in the past decades which involved some major losses, such as, PiperAlpha-NorthSea [1988] , TexasCityRefinery–Texas [2005], DeepWaterHorizon–GulfofMexico [2010], AmuayRefinery–Venezuela [2012] etc. The common subject matters about these incidents are lack of risk evaluation and lack of performance functions [Petri et al., 2017]. Thus, asset management became an important science field because it integrates an aim of activities like maintenance, risk, processes, systems, resources, management, etc., and health safety and environment [Petri et al., 2017].

In NS-ISO 55000: 2014, it was pointed that one of the fundamentals of asset management is value. It was also highlighted that asset management does not focus on the asset itself, but on the value, the asset can provide to the organization. NS-ISO 55000: 2014 emphasized that value can be tangible or intangible, financial or non-financial, and due to this, the acceptance of what a value is or not must be determined by the organization and its stakeholders. For example, value can be a need to directly generate profit from an asset. Value could also be a need to deliver a low operating cost or safety from an asset. It is also clear that it was never stated in NS-ISO 55000: 2014 that an organization must have the most reliable physical assets to deliver value to the organization. Therefore, asset management needs to be noticeably clear on what and what they are trying to achieve to deliver value to the organization. For example, in a situation where a company's values become cost efficiency and safety in production, maintenance owes to make equipment deliver the required value, irrespective of the state of the physical assets. According to NS-ISO 55000: 2014, values can also be changed during the life cycle of an asset, and in such a situation, management of risks and liabilities must be up and doing throughout the asset's lifecycle.

Chapter 3

Methodology

The method of performance measurement used in this thesis came from the theories of TPM, asset management, and smart maintenance. Lots of literature were reviewed on the "hidden factory," OEE, and smart maintenance to address the problem formulation and the theoretical background of this thesis. The topic "Performance measurement using DDM concept: A Technique for Measuring Hidden Factory" was chosen as a result of the fact that production industries are vastly diverging into smart maintenance, and there was also a need for real-time condition monitoring and government of performance of production asset so as to ensure that physical asset maintains a high-level operational availability and performance throughout its life cycle. This does not only have to do with real-time condition monitoring of equipment but also real-time decisions making in planning. The real-time decision-making in planning will involve good knowledge of the principles of asset management, DDM, and PLI. PLI will be applied in smart maintenance to measure and estimate the "hidden factory" in physical assets. Terminologies from background and theories which were derived from literature reviews were used to interpret the result in a theoretical approach.

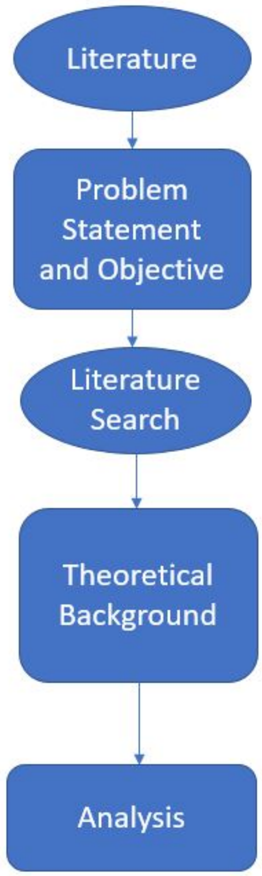

Figure 3.1: Overview of Research Methodology

3.1 Literature search for problem statement and objectives

A literature search was done to formulate a problem statement. In-depth research was carried out on "hidden factory" and how it has reduced the OEE values of several production companies. Literature from the Japanese Institute of Plant Maintenance (JIPM) and various OEE materials was perused at this stage. The Blond standard, various papers from the EU Taxonomy, Petroleum Safety Authority Norway (PSA), Norwegian Petroleum Directorate (NPD), ISO 5500 of asset management, and the German Industrie 4.0 all enhanced the possibility of formulating the problem statement.

3.2 Literature search for theoretical background

Literature was sourced from various databases for scientific literature, which includes Oria, Science Direct, Scopus, Google Scholar, NTNU's Library. Earlier literature was reviewed in exploring the contents of the metaphor "hidden factory" and how it was described by various authors. JIPM also helped in the structuring of production losses which was where the inspiration came for the introduction of safety losses. State of the art of several subject matters like OEE, smart maintenance, and performance measurement was previewed in order to write the background chapter. Performance measurement systems based on "hidden factory" were reviewed, and it was seen that several industrial measurement tools varied as some industries preferred customized performance measurement systems adapted from OEE. For this reason, OEE controlled the background of this thesis, but while trying to balance the current industrial operations with respect to technological advancements, production requirements, and other organizational visions, it became necessary to focus on the performance measurement for the future. This was why smart maintenance came into this master thesis. While performing searches, smart maintenance was always included. Other key search words include Digital Maintenance, Digitalized Maintenance System, Intelligent Maintenance Systems, Cyber-Physical Systems, Industry 4.0, Predictive Maintenance 4.0, Smart Maintenance in Asset Management, Improving Equipment's Effectiveness with Smart Maintenance, Improving Equipment Performance with Smart Maintenance Application, etc. These search words were both combined and sometimes filtered with a different query like dates, and with logical operators and, or, not. The searches on smart maintenance were narrowed within five years to date. In addition to the online literature searches, my supervisors sent some papers to me which supported my work. Those papers were related to state of the art on OEE, smart maintenance, and smart maintenance planning in asset management and were highly inspiring. Also, for each of the papers presented, references and cited papers were investigated to ensure validity before the citation.

3.3 Selection of method

After a thorough review of various literature: articles, journals, lecture notes on TPK4140 [2019], TPK4450 [2020], [TMR4260, 2020], with relevant books. There was a need to make a choice on the performance measurement of asset. The whole idea was focused on how to minimize "hidden factory". Initially, there was a thought of using one of the OEE models but my supervisor emphasised that OEE is a way old and there was a need for the use of a smarter and a more sustainable method with respect to day to day advancements in technology. However, after a further research and investigations, two stages of performance measurement were carried out on the physical asset.

a. Smart Maintenance planning with criticality assessment of the machine, which was briefed as a theory in section 2.6.

b. Performance measurement using the PLI cube: After criticality assessment, the PLI cube was used to trace and measure other elements of wastes on the machine. RCA was also obtained after PLI cube calculation for continuous improvements. The PLI cube was calculated on the machine (equipment level), as explained in Figure 2.4. PLI cube was used to measure OEE time losses and wastes on the machine.

3.3.1 Smart Maintenance planning with criticality assessment of the machine

The choice of the DDM concept came after reading a paper where it was applied. The DDM concept uses the principles of asset management and the cyber-physical system of Industry 4.0 in the maintenance and government of physical assets. Inspirations came after reading the DDM work processes and how it was applied in the criticality assessment of physical asset. The DDM modules include RUL, PLI, and Planning. As emphasized in section 2.2 of the theory aspect of this thesis, it is obvious that planning could contribute to a high equipment's performance and productivity. And in the other way round, inadequate planning could induce a "hidden factory" in production. Therefore, it was important to do real-time planning. This means that planning should be made smartly with data collection and analysis from condition monitoring of equipment. This will ensure that the right decision is made at the right time based on maintenance planning and execution. During the studies on the standard NS-ISO 55000: 2014 of asset management, values became significant importance of assets. But for organizations to realize more value from their assets, costs efficiency, risk management, and equipment availability and performance must be optimized. This will meet the TPM's objectives of zero breakdown, zero accident, and zero defect. It was also stated in the introductory part of this report that maintenance saves cost by increasing equipment's uptime which makes it possible to increase the quantity and quality of finished products for sale through its equipment's availability, performance, and safety. And of course, this is because preventive maintenance reduces the cost and risk due to equipment failures and unplanned repairs. It is also understandable that preventive maintenance could only be optimized if planning is optimized. And for this reason, I became highly inspired after reading a paper where the DDM model as planning was also included in its modules. Inclusion of CPS where AI was used for self-maintenance when estimated RUL became shorter was applied for data analysis, real-time prediction, and prescription of maintenance (preventive). This made me develop an interest in the DDM concept.

3.3.2 PLI Cube

The choice of selecting PLI came because of its smartness and flexibility in measuring and tracing time (OEE) losses and various categories of wastes in production. Although OEE has been modeled to fit many industrial purposes, the PLI cube is more generic in the sense that it can also be applied to fit various industrial measurement purposes irrespective of their objectives. Its smartness made it compactable with a smart maintenance application. It is quite obvious that time losses can be categorized into the 3 OEE losses, but some other wastes may not be able to be categorized. PLI will categorize such wastes in one of its four (4) waste categories. The forth category of waste (Other Waste) will enable the calculation of other PLI elements (wastes) that are unable to fit into Utilization, Raw Material, and Resource Consumption. For example, injury on personnel, under-utilization of employee etc. This will ensure that all lost profits in business are accounted for. But the other OEE models do not follow such a principle. PLI can also be used for cost estimation in smart maintenance planning. These are reason why PLI Cube was selected. Essential parameters in PLI Cube are formulated below:

The time losses due to equipment's unavailability, poor performance, and or poor quality of products are formulated below (see Figure 2.4):

Profit Loss = Turnover Loss + Extra costs
OEEavailability = OEE.A,T + OEE.A,C
OEEperformance = OEE.P,T + OEE.P,C
OEEquality = OEE.Q,T + OEE.Q,C

Where OEE.A,T = OEE's Availability (Time) loss due to Turnover loss in production

and,

OEE.A,C = OEE's Availability (Time) loss due to Extra Cost incurred during downtime

Also,

The calculation of profit loss due to the 4 categories of wastes are formulated below:

Profit Loss = Turnover Loss + Extra costs
U = W.U,T + W.U,C
RM = W.RM,T + W.RM,C
RC = W.RC,T + W.RC,C

OW = W.OW,T + W.OW,C

Where W.U,T = Time loss during overproduction (excess products)

and,

W.U,C = Extra Cost due to overproduction (excess products)

The same method is also applied for the rest of the parameters.

3.4 Performance Measurement Using DDM concept (First Stage Performance Measurement)

The performance measurement was carried out using the DDM concept, where smart maintenance planning was done in real-time after criticality assessment of physical assets. The two main analytic tools which enable machine data to create insights that drives performance measurement are KPI PLI and KPI RUL of PDM 4.0. Data collected from these tools were used to analyze physical assets. Physical assets consist of both static and rotating equipment in a production plant. Given that the performance of an industrial cutting machine is to be measured, the two KPIs to be used are PLI and RUL. With the principles of predictive maintenance (PDM. 4.0) technique, condition monitoring and the data-driven prognosis were used to determine RUL estimation of the cutting machine. The RUL of the machine is the estimated number of hours the machine will function with respect to its performance degradation degree at a given time before malfunction/breakdown. Imagine that this cutting machine requires to run 20 hours daily. It is obvious that the machine will begin to degrade due to internal wear and tear during normal operations or due to other operational factors. It is also important to understand that a sudden breakdown of this machine will result in an availability loss which will stop the production line with a risk of injury on operators. But with this RUL estimation principle, the diagnostic system will detect the performance degradation of the machine, and a real-time prediction of failures in parallel with a prescription for preventive maintenance will be made due to the deployment of intelligence maintenance system (IMS). This can be achieved with the DDM modules. The work process of DDM, as highlighted in subsection 2.7.1, describes more about this method of performance measurement.

3.4.1 PLI Estimation

The KPI PLI is used to analyze the consequences of a potential failure caused by performance degradation of the physical asset. This consequence or penalty is usually a cost. PLI estimation data can be decided by a plant manager or a cost engineer who has sound technical knowledge on a particular asset or assets and their operating and environmental conditions. PLI values are estimated just the same way Failure Mode Effects and Critical Analysis (FMECA) is used to analyze the effects (consequences) of failure modes of equipment. Further analysis in chapter 4 will show how KPI PLI is applied in the criticality assessment of physical assets. The calculation of PLI was also illustrated in chapter 4.

3.4.2 RUL Estimation

A technical system or machine normally work with a high performance level after installation but tends to degrade with time. Prognostics is used to evaluate the RUL estimation of the equipment. Prognostic system for RUL estimation is developed using data-driven approach. Prognostics system is operated to perform the RUL estimation at subsequent prediction point which are determined. Historical data of performance and operational parameters would be used to create a model that matches parameters for the machine's degradation. The historical data will be obtained from similar machines which are run in both functional mode and during malfunctions. These data are used to create models. Creation of the models are enhanced with ML algorithms. Different failure modes and failure mechanisms are used to build different models. One of the models that should be created in this approach is multi variate data for noise data so as to detect anomaly with unusual sound pattern in a cutting machine. In the beginning, the machine is assumed to be in a healthy condition. But when degradation begins, there will be some triggers on the prognostics system. This unusual sound from machine will indicate that the machine is in a degradation state. Prognostic data will automatically be generated and sorted and would be used to perform further analysis in parallel with the PLI estimated data.

3.4.3 Planning

Measurement of "hidden factory" is a critical element of maintenance planning. Identification and measurement of "hidden factory" will enhance effective decisions regarding maintenance techniques for maintenance planning functions. To achieve the highest level of asset performance, an intelligent maintenance system (IMS) must bring together technology, data, analysis, prognosis, and resources [Rødseth, 2017]. Just like Muchiri et al. [2011] said equipment performance measurement is very important in managing maintenance functions. This will improve the maintenance planning function where real-time data supports the planner. The smart maintenance planning with criticality assessment will enable maintenance planners to make decisions on the prioritization of work order based on the view in balancing costs, risks, and performance. This technique is a smart planning method that would help in saving time losses due to unplanned and frequent maintenance activities. Thus, this technique will enhance sustainable production, and the success of asset management will be accomplished. Criticality assessment of equipment will be an important input in smart maintenance planning. This will enable maintenance planners to make decisions based on data received from the equipment. In order to access the criticality of any equipment, the criticality assessment should evaluate both the probability and consequences for failure of that equipment [Rødseth et al., 2020].

3.5 Performance Measurement using the PLI Cube (Second Stage Performance Measurement)

PLI Cube is used as a second stage performance measurement because the DDM model can only measure the performance of physical assets within the capacity of smart maintenance through criticality assessment of equipment where real-time data are collected directly from equipment for further analysis and decision making. On the other way round, the PLI cube will be used for calculating PLI values because it's difficult to know the actual lost profit after sales of products which is the actual result of asset's performance. This is why PLI is a true performance measurement tool for business. The lost profit in business cannot be automated. Apart from this, after performance measurement of equipment, preventive maintenance will be carried out. But preventive maintenance attracts its own "hidden costs," which may include:

a. Costs of physical resources, for example, cost of man-hours and spare parts.
b. The risk for maintenance personnel.
c. The risk of another item failing due to functional dependence.
d. In some cases, constraints due to limited resources available for other tasks.
e. In some other cases, production losses and equipment unavailability.

These are all wastes in production and are categorized as "Other Wastes" and Time losses in the PLI cube. For these reasons, the PLI cube will calculate those time losses and wastes. This will unveil other elements of lost profits in production and will also create room for future improvements. This is why the PLI cube is regarded as a performance measurement tool. Therefore, it is very smart to use PLI cube for further performance measurement in the work processes of DDM model.

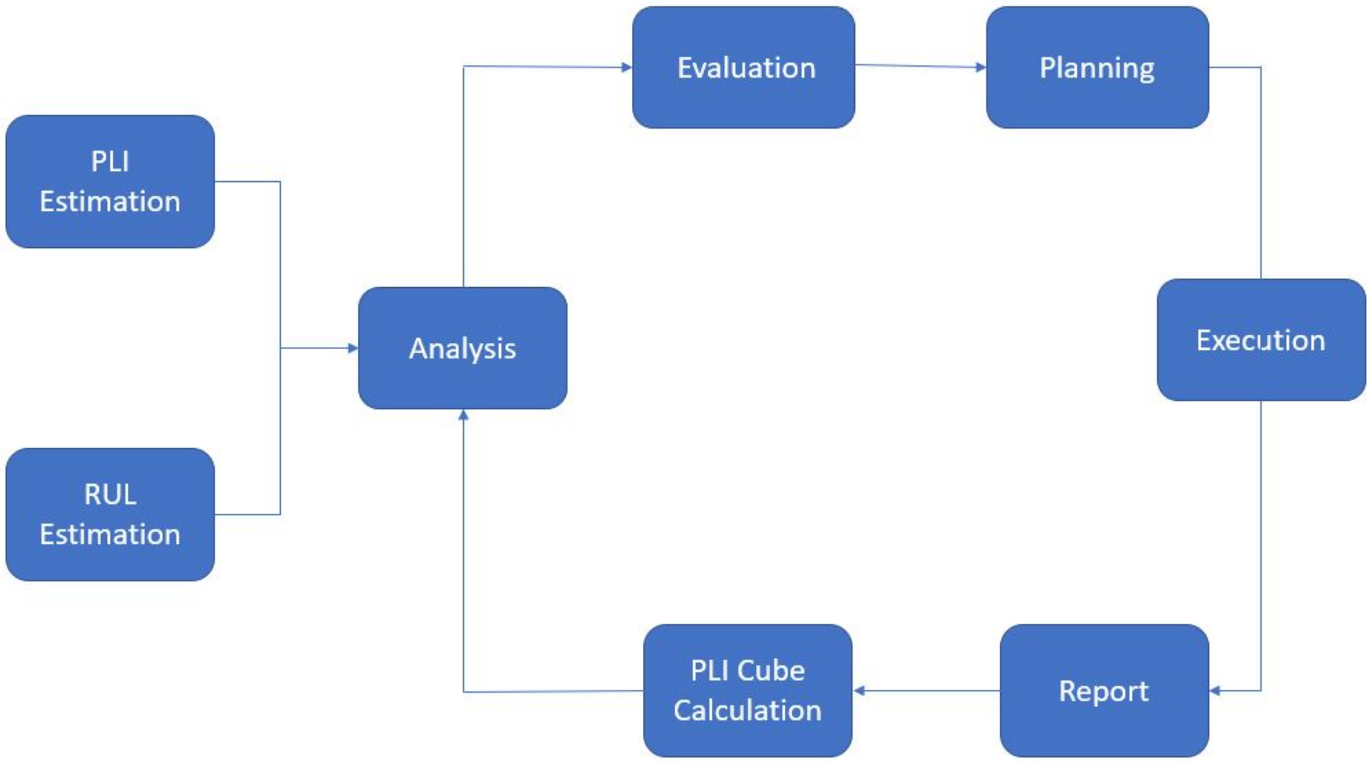

Figure 3.2: Overview of Performance Measurement of physical asset using the DDM modules

Figure 3.2 illustrates the work processes on performance measurement system of physical asset in a digitalized maintenance system. RUL and PLI are estimated based on the probability of an equipment malfunction and consequence of ignoring equipment failure, respectively. Analysis is done based on algorthm with ML method and, with AI, matrix is analyzed. Based on cost and risk, evaluation is ranked and planning is done. After planning, preventive maintenance is executed (self maintenance with CPS and, or maintenance by personnel) which is reported digitally. After the report, maintenance management will calculate the PLI cube.

Chapter 4

Analysis

4.1 Performance Measurement using the DDM concept

Performance measurement is a concept that ensures that maintenance activities are planned and executed to actualize organizational values. Performance measurement uses rigorously defined key performance indicators (KPI) to measure important aspects of equipment performance and determine maintenance functions. The objectives of maintenance management and its concepts usually determine the KPI types to be used. The effective use of a chosen KPI will enhance decision support and performance improvement. A well-defined performance indicator can potentially support the identification of performance gaps between current and desired performance and indicate progress towards closing the gaps. For this reason, maintenance planning must issue the right maintenance work order at the right time. Maintenance planning can use the measurement of "hidden factory" for decision-making regarding the correct work order. For asset management to realize more value from an asset, risks, and costs must be balanced. This idea can be actualized using the DDM concept of smart maintenance planning with criticality assessment of physical assets.

4.1.1 Performance measurement using Smart Maintenance Planning with Criticality Assessment of a Physical Asset

With the DDM concept, criticality assessment of a cutting machine was carried out using both the PLI estimated data and the RUL estimated data. With AI, a model was built for a risk matrix. The risk matrix PLI VS RUL was analysed, and was used for a criticality assessment of the machine, where PLI estimates represent the consequence or penalty of ignoring potential failure of different parts of the machine. And RUL is the probability that the machine will fail given the RUL of different parts of the machine at any given time. To apply this concept on a single asset, it is very important that FMECA is carried out to determine the parts to be monitored and for the installation of smart sensors. Each failure mode attracts different consequences. For example, an anomaly detected due to excess vibration could be a loss in lubrication and might result in shaft damage. Anomaly detected due to variation in sound (noisy machine) might be as a result of rubbing internal rotating surfaces, which might result in wear and tear of parts. These various part degradations will attract different financial consequences during maintenance. Real-time analysis of the risk matrix will enable the maintenance planner to understand the effect based on risks and costs behind any failure mode. This enabled the planner to establish a prioritized work order for maintenance. This criticality assessment was carried out on an equipment level, which assesses various consequences of potentially failed parts, and to prioritize preventive maintenance by parts. Criticality assessment can also be carried out on various equipment in a plant (plant level) so as to prioritize maintenance by equipment.

4.1.2 Measurement Tools

In this chapter the two KPIs to be used are PLI and RUL.

PLI Estimation

PLI module was used for estimating the financial consequences or penalty given there were performance or availability losses due to performance deterioration of the cutting machine. Assuming that the loading time for the cutting machine is 20 hours per day. And a total of 2000 pieces of pipe length are produced per day. Given that there was a machine breakdown for 5hours and that 3hours before the downtime, the machine cut 100 pieces which were considered as scraps due to short lengths (poor quality pipes) as a result of performance degradation, and the cost of production for per hour is NOK5000. If the cost of hiring maintenance personnel and restoration of the machine is NOK1500 and NOK2500 respectively. The PLI module will be used in making some estimations which are as follows:

Profitloss = turnover loss + extra cost

The Time Losses (OEE:availability, OEE:performance, OEE:quality) are calculated below using the PLI cube:

availability loss (OEE:availability) = (production cost) + (restoration cost)
= (no. of hours loss x cost per hour) + (personnel cost + restoration cost)
= (5 x NOK5000) + (NOK1500 + NOK2500) = NOK25000 + NOK4000
=NOK29000

Quality (OEE:Quality) loss is also calculated as follow:
No of pieces produced per hour = 100pcs Since 100pcs where found as scrap 3hours before downtime, then number of hours loss due to the scraps will be 1hour
Therefore, Quality (OEE:Quality) loss = cost of production per hour
= NOK5000

Performance (OEE:performance) loss can also be calculated as follow:
Performance (OEE:performance) = (No. of hours due to performance loss x cost of producing 100 scraps)
= (3hrs x NOK5000)
= (NOK15000) Assuming that scraps cannot be reused

To be able to capture all the lost profit due to this scenario, PLI cube is best used for calculations. This calculation is done at equipment level (cutting machine) of the physical assets using PLI cube:

Profit loss = Turnover loss + Extra cost
OEE.A,C which is extra cost which was introduced due to corrective maintenance and hiring of maintenance personnel. OEE:AvailabilityC OEE.A,T + OEE.A,C
=NOK25000 + NOK4000
=NOK29000

PLI estimation usually depends on the operational and environmental context. If there were some other additional cost such as injury on personnel or any other cost due to safety losses, PLI estimate those consequences in financial value. For these reasons, there is no generic data as individual companies should make available data for their estimations. This is the weakness about PLI.

RUL Estimation

After estimating the consequence of failures (PLI values) or costs due to potential machine parts failure, the next step is to also estimate the RUL of various parts. This is done with the machine learning method. One of the goals of predictive maintenance is to estimate the RUL of the asset or RUL of various parts of the asset. RUL is computed as the time between the current condition and failure condition, as shown in Table 4.1 below. Depending on the system, this time period can be represented in terms of days, miles, cycles, or any other quantity like long, medium, short, etc. RUL is estimated using the Degradation model in this report. The data captured for the degradation model should have a safety threshold where the algorithm should differentiate data between a healthy state and a failed state since we assume that no failure data is available from a similar machine. Therefore, the operator should have a piece of good knowledge of the safety threshold. A degradation model will be fit to the condition indicator, which uses past information from the same machine parts to predict how the condition indicator will fail in the future. With this approach, we can statistically estimate how long there are until the condition indicator crosses the threshold, which will help to estimate the RUL.

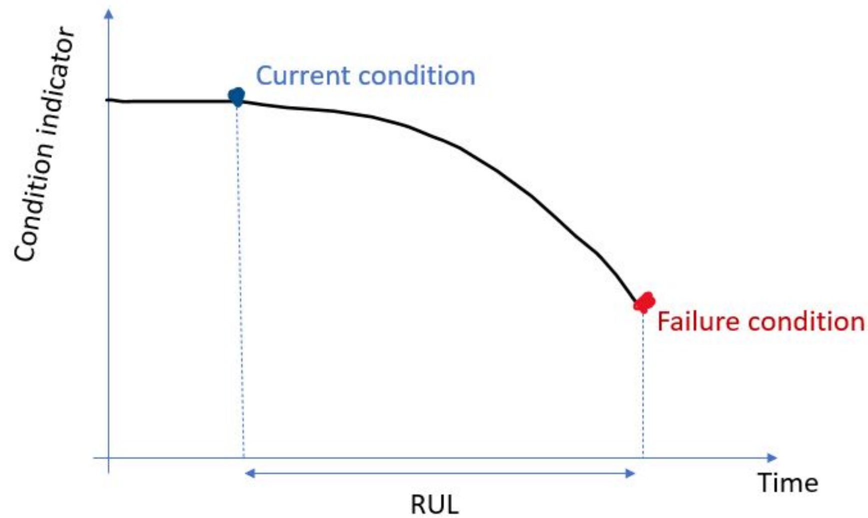

Table 4.1: Performance degradation of a technical system over period of time

A predictive maintenance algorithm will be designed to timely detect faults and also identify fault types, as this will help figure out what part should be fixed or replaced in DDM. The figure below shows the steps in condition monitoring of asset parts.

a. Acquire data. Data is collected from the machine based on what is to be monitored. Smart sensors can be installed on a rotor for instance, for vibration monitoring.

b.The aim of reprocessing it is for a clean-up.

c. The next step is to extract features from the data with which ML models can be trained. With this step, different fault types can be classified. Therefore ML model will be trained with features. The features will be extracted diagnostically. A lot of features are always revealed, and it is important that useful features are correctly selected. If useful features are not selected, it may hurt the performance of the ML model in making correct predictions.

d. Train Model. After extracting features to train a model, then different types of features will be tried to see which sets works best for classifying fault types.

e. Deploy and integrate. After training the model, the next is to deploy and integrate the model.

Figure 4.1: Steps to design predictive maintenance algorithm Failure prediction adapted from [Li, 2018]

Linking performance deterioration of asset to maintenance cost

An increase in degradation mechanism will result in performance deterioration of asset (see Table 4.2), which will cause an increase in cost over a period of time. This degradation will tend to increase over time, hence, reducing the RUL of an asset till the breakdown (availability loss). Performance and cost will be affected when considering long-term degradation. Degradation identification and quantification with RUL enables the evaluation of the performance of assets more conveniently. This will add as an input to the elements of decision-making in smart maintenance planning. Hence, the risk of asset failure will be managed, and maintenance costs will be optimized. Two types of degradation include :

a. Recoverable: Examples include clogges, scalings, etc. An asset with recoverable degradation can be recovered or maintained during system operations. This means that preventive maintenance costs will be extremely low.

b. Non-recoverable: Non-recoverable degradation includes tear, wear, corrosion, erosion, etc. This degradation can not be recovered during the system's operations. Therefore the system must be shut down for preventive maintenance (part replacement); hence, this will attract more cost due to production losses and increase in the risk of "16 big losses" and "4 safety losses".

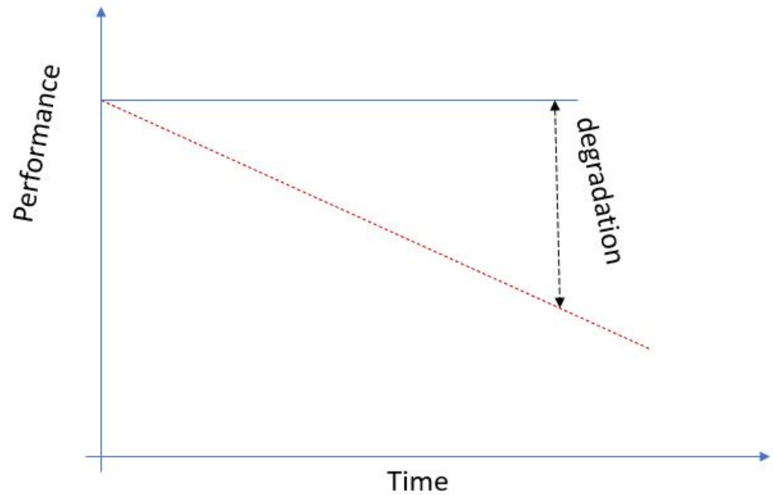

Table 4.2: Degradation of asset over time

The Table 4.3 below shows how degradation increase operational and maintenance cost over time. As degradation increases, RUL reduces and operating cost increases from time T1 to T3. At T4, there was a warning, and preventative maintenance was implemented. At T5, the operating cost drops as the system becomes as good as new. At T6, degradation continues till T8, where there is another warning and preventive maintenance was implemented. This will continue to increase the life cycle cost of the asset. Also, as illustrated in the Table 4.4, income will continue decreasing due to loss in investment and operating costs.

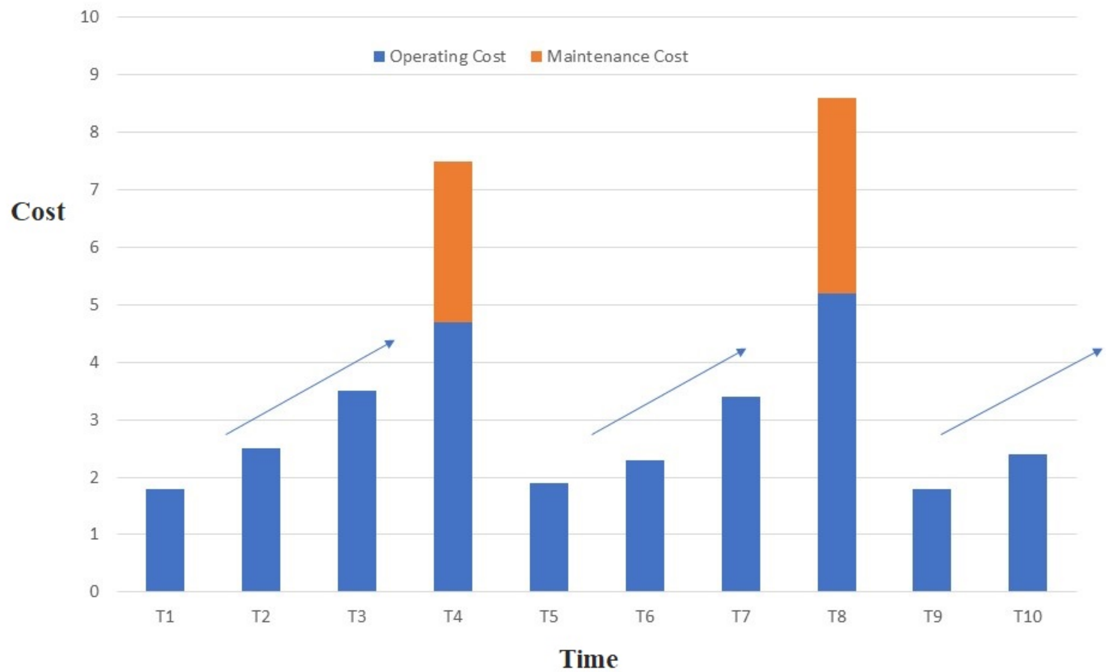

Table 4.3: Increase in costs due to performance degradation of physical asset over time

The chart below also shows the lost profit due to performance degradation and preventive maintenance cost of the asset during a period of time. These losses are due to planned maintenance, but it would contribute to the life cycle cost of the asset through maintenance cost. Other contributing factors like waste generated during preventive maintenance costs can be minimized if PLI is deployed and all PLI elements are identified and measured.

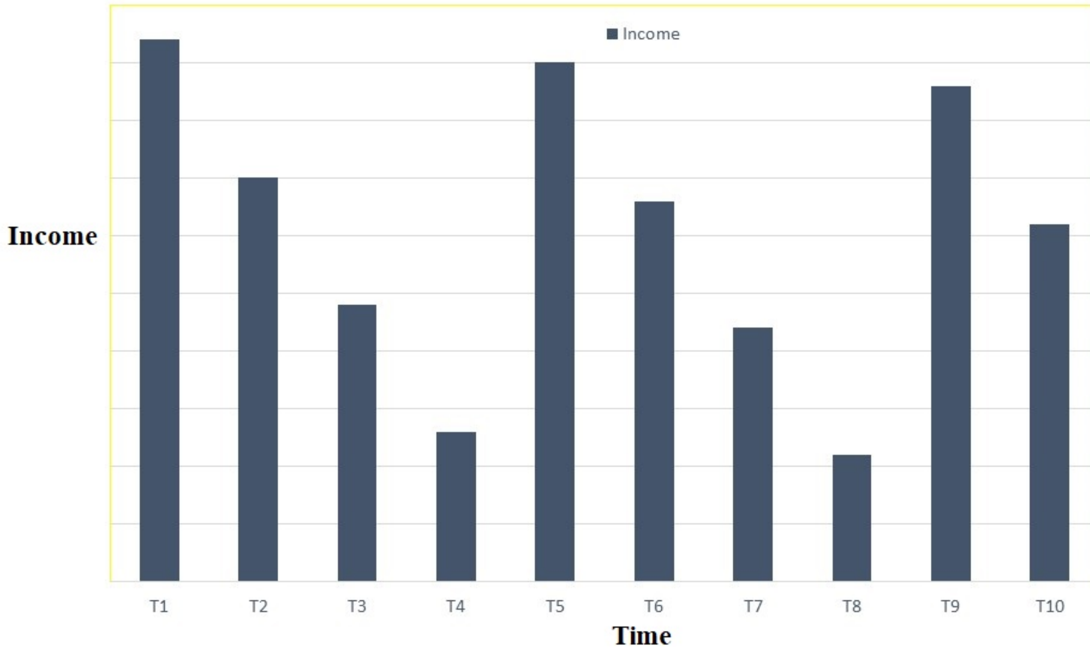

Table 4.4: Lost income due to performance degradation of asset over time

4.1.3 Criticality Assessment of physical asset

Haven evaluated both the probability and the consequence, i.e., the RUL and PLI; the criticality assessment of a physical asset can be performed in a risk matrix evaluated for both the probability and the consequence for a potential malfunction of an asset in the plant or parts of equipment. This action will help in prioritizing the preventive maintenance work order, and this is because higher-risk conditions versus high maintenance costs of assets require urgent action. Criticality assessment will enhance maintenance planning in optimizing maintenance. This would also help in ensuring reduced accidents, reduced production losses, and safety losses which are the objectives of TPM.

Risk

In risk analysis, risk can be defined as the probability of occurrence of a negative event, but in this thesis, risk will be defined as the probability of loss in business. The consequence of loss is usually cost, which is defined as the "hidden factory." In smart maintenance with criticality assessment of physical assets, various asset risks will be exposed with the DDM modules, and the equipment vulnerable to most severe risks and costs will be prioritized in maintenance. The criticality of an asset is best described by the operator, and severity ranking is usually validated for decision making.

Risk = Probability (P) x Consequence (C)

where P is defined as the probability that a machine will malfunction due to its RUL, and C is defined as the Consequence or penalty costs due to malfunction of asset. Cost is also a function of PLI. The consequence of asset malfunction could trigger the "16 big losses" or "4 safety losses" as highlighted in chapter 2. These will impede the sustainability of production.

Risk = P1C1 + P2C2 + P3C3 + PkCk = Sigma PiCi

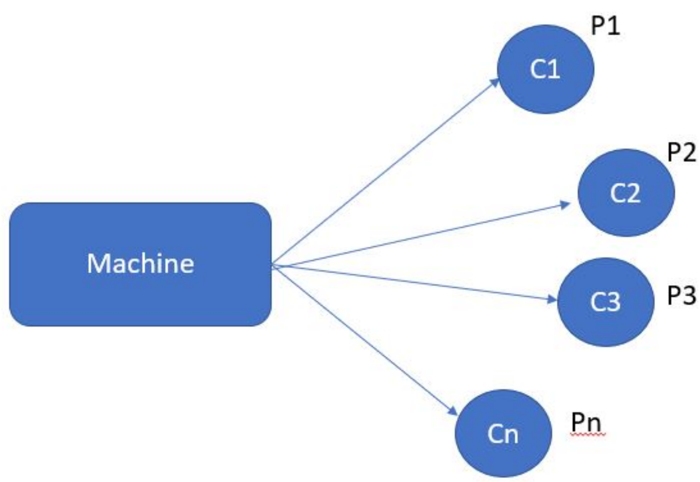

Figure 4.2: Risk analysis

Furthermore, it is important to prepare some data to support PLI during the criticality assessment of assets. PLI values which are functions of costs, will be the consequence of asset malfunction or failure. It is also important to rank various assets according to severity classes with corresponding PLI values for decision making.

Rank	Class	PLI	Description
1	Minor	NOK	Failure does not result production stops but results in a minor system damage.
2	Major	NOK	Failure results production stops with minor injury on personnel. Alarm should be activated.
3	Critical	NOK	Failure results production stops, serious injury on personnel, release of chemical to the environment.
4	Catastrophic	NOK	Failure results production stops, Death of personnel, release of chemical to the environment.

Table 4.5: Risk ranking

Table 4.6 below also illustrates a proposed model of risk matrix in DDM that supports the planning of preventive work orders. In the consequence category, the PLI is established for the physical asset and classified as "low, medium, or high." The probability category is evaluated with RUL of asset and is classified as "short or long." By trending RUL in the risk matrix, it is possible to evaluate when a preventive maintenance work order should be issued and the possible costs and consequences of ignoring any potential failure.

Also, the color code follows a traffic-light logic. Just as it is in risk analysis, if the equipment is in the green zone, no further actions are necessary. If the equipment is in a yellow zone, it is an early warning where maintenance actions should be executed. If the equipment is in the red zone, it is an alarm where immediate maintenance actions should be executed order wise this could result in a consequential event such as performances losses or availability losses (catastrophic failure resulting in a hazardous event).

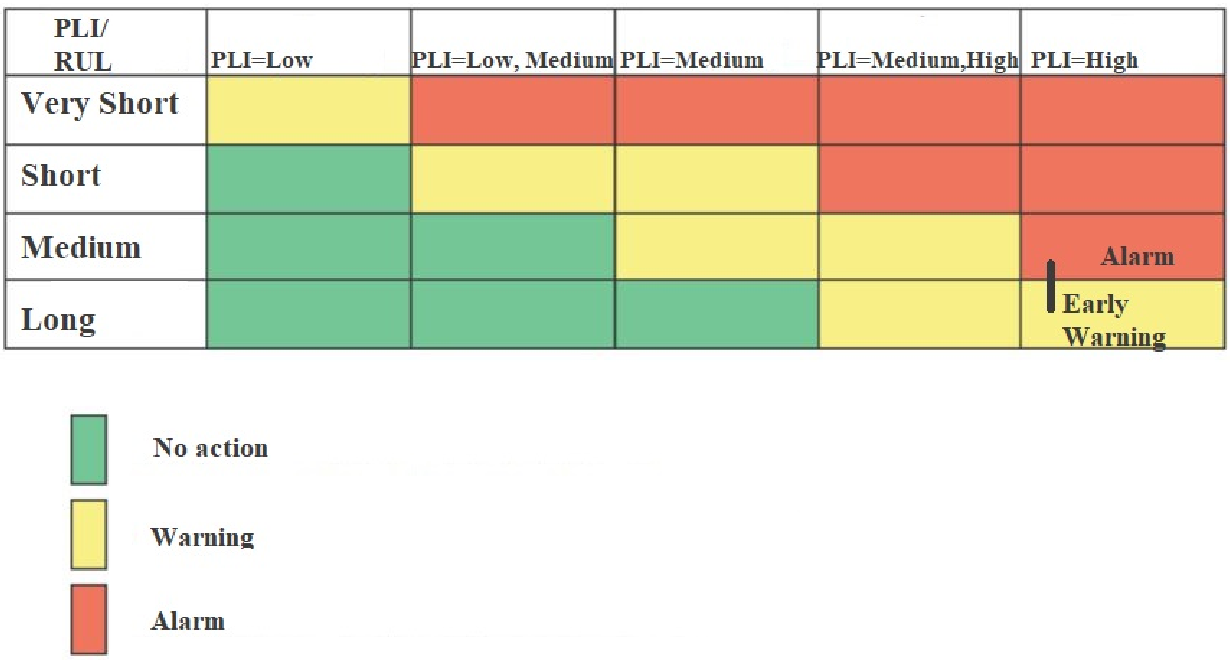

Table 4.6: Risk matrix

When applying DDM concept, it is very important to understand different ways in which equipment could fail. This can be achieved with FMECA. FMECA identifies all the failure modes of the various parts of a system and analysis the effects these failures may have on the entire system. This will help in estimating PLI (costs). FEMCA will also help in deciding what part of the machine to collect data based on condition monitoring for estimating RUL. FMECA is very generally important in preventive maintenance (planning module) as it helps in reducing non-value operations thereby, reducing wastes.

4.2 Performance Measurement using PLI Cube

Following the DDM management loop as shown in chapter 2, "Technical Condition" should succeed "Reporting," followed with "RCA". So, after preventive maintenance execution and reporting in performance measurement stage 1 (smart maintenance planning with criticality assessment of machine), management should calculate the PLI cube to unveil the "hidden factory" in the machine at the equipment level. Then, all the elements of PLI cube, including various time losses and wastes generated during the preventive maintenance, should be calculated. With this approach, all the profit loss in connections with the machine will be accounted for. Various fault tree analyses (FTA) have been constructed to support the management in identifying and tracing the different elements of time losses and wastes and their causes in production.

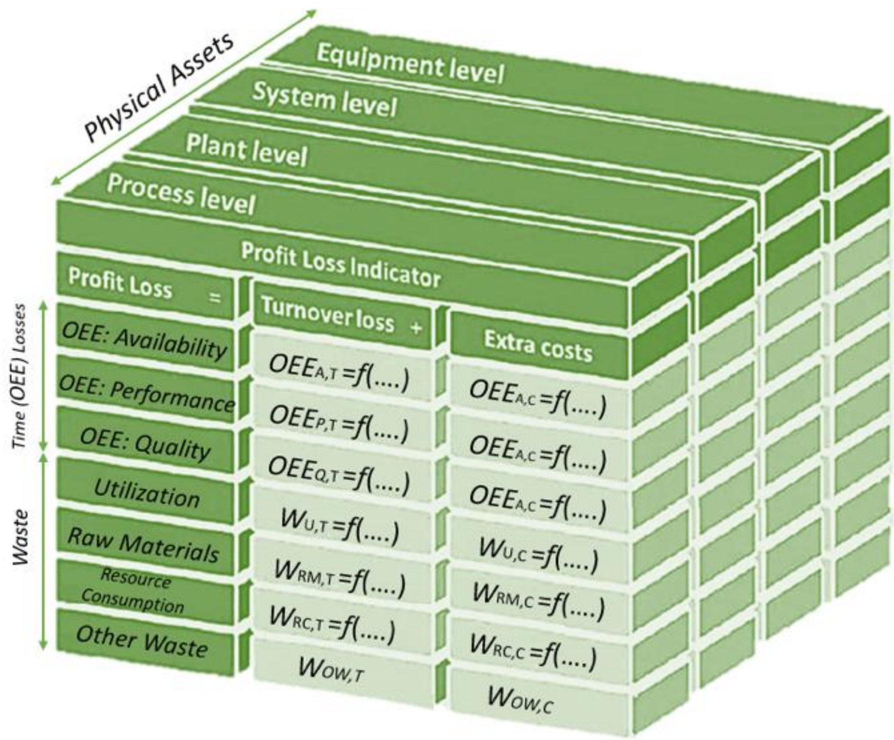

Figure 4.3: The PLI cube adapted from [Rødseth et al., 2015]

The FT in Figure 4.4 analyses the elements of profit loss in production. The FT will support management in investigating the top event, "Profitloss." The boolean logic combines a series of lower-level events, and it is a top-down approach to PLI elements (basic events) that causes profit loss (top event). The FTA is used to understand how profit can be lost and identify the best ways to reduce the risk of losses for continuous improvement. Profit loss can occur due to either turnover loss or extra cost. Turnover loss can occur if there are time losses due to OEE, or waste. Time (OEE) losses due to turnover loss will occur if there is availability, performance, or quality losses. Waste due to turnover loss will occur if there is utilization, raw material, resource consumption, or other wastes. Similar procedure is done for the extra cost. But the idea is to trace it down to the basic events. 14 basic events were listed as elements of PLI. Profit losses of each of these time losses and wastes in production can be calculated to a financial number.

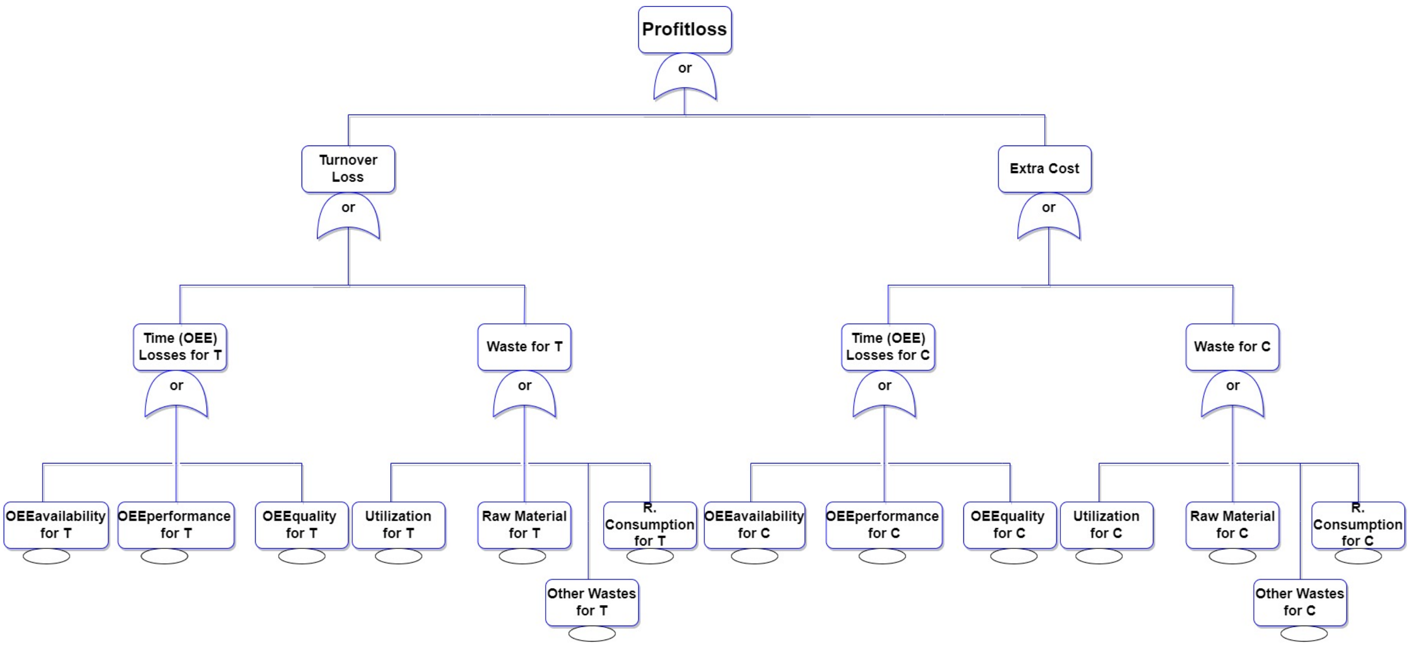

Figure 4.4: Fault Tree Analysis on Profit Loss in Production

Furthermore, the fault tree in Figure 4.5 describes the causes of time losses and waste in production which are all elements of "hidden factory". From the FT, it is shown that turnover losses can occur if there is either "reduced price of products" or "reduced quantity of products". Extra cost can be inccured due to cost of raw materia or CAPEX. Further step top-down, list the 11 basic event (causes) of profit losses in production.

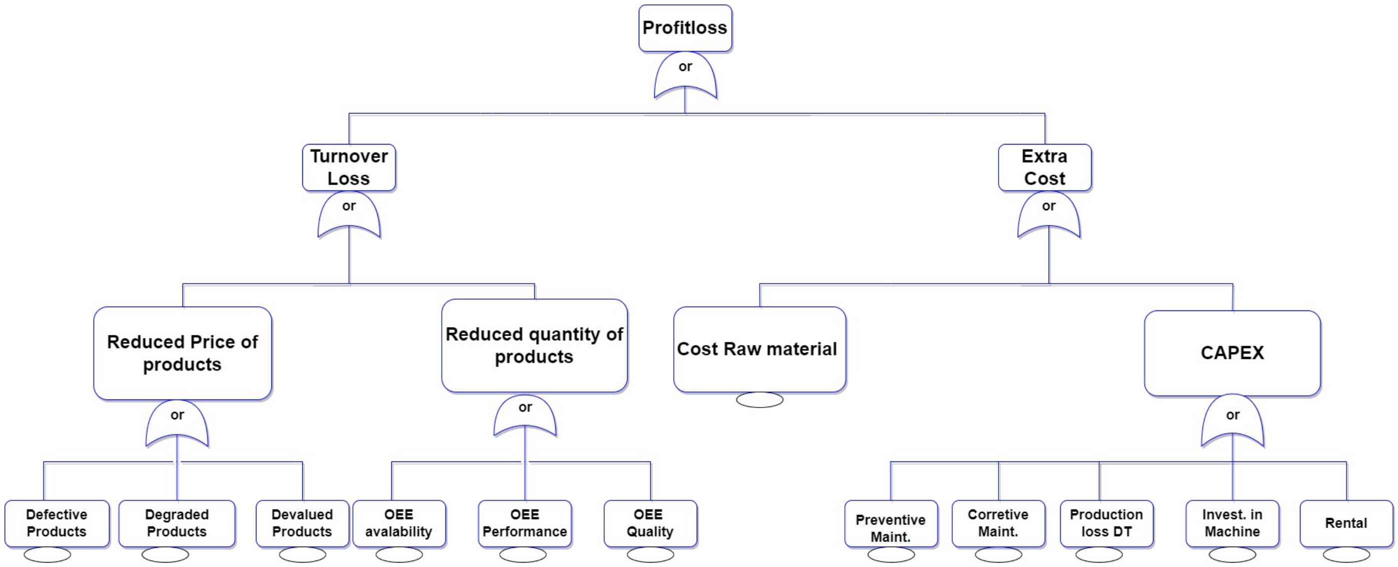

Figure 4.5: Fault Tree Analysis on the causes Profit Loss in Production

Figure 4.6 below also shows the causes of time losses in production. The time losses occur due to availability or performance losses of equipment or quality losses due to scrap. The basic events are also listed as it is in the "6 Big Losses".

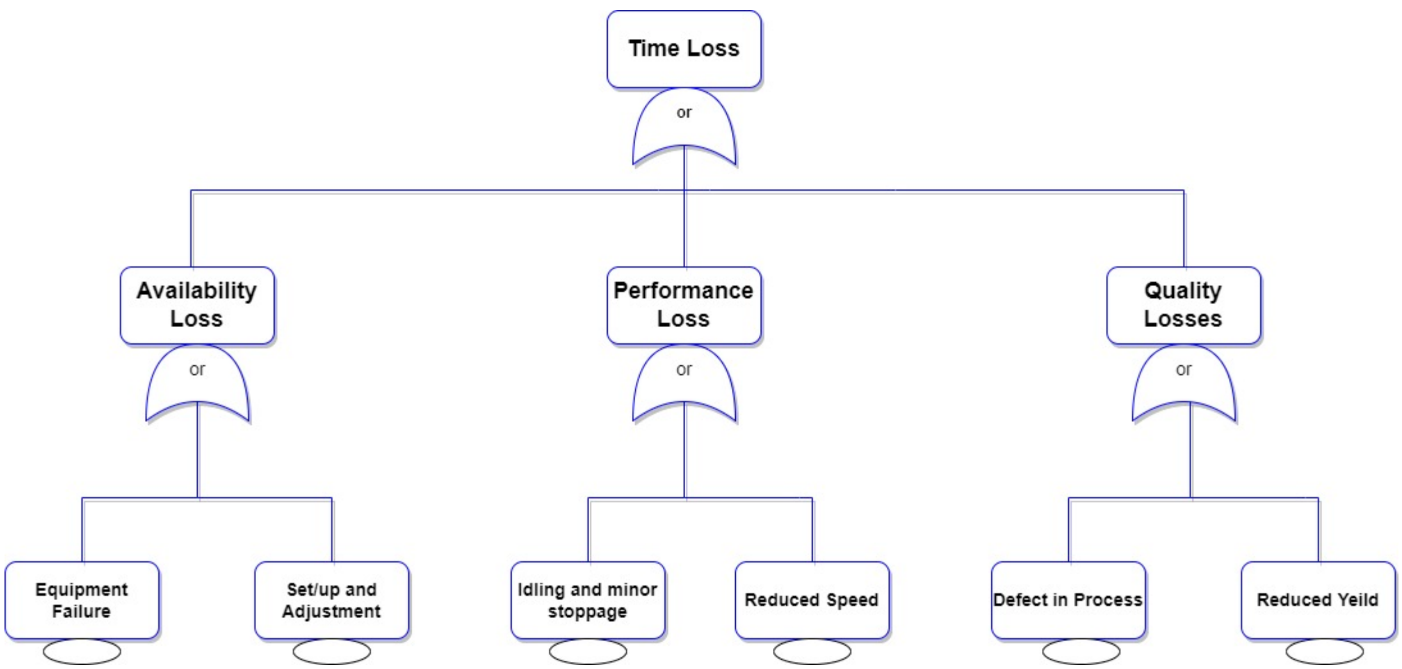

Figure 4.6: Fault tree Analysis on Time Losses in Production

The PLI Cube was used as a second stage performance measurement because the DDM model can only measure the performance of physical assets within the capacity of smart maintenance through criticality assessment of equipment where real-time data are collected directly from equipment for further analysis and decision making. On the other way round, the PLI cube will be used for calculating PLI values because it's difficult to know the actually lost profit after sales of products which is also the actual result of asset's performance. The PLI will reveal these profit losses in monetary values, which is the language that management will understand. This is why PLI is a true performance measurement tool for business. The lost profit in business cannot be automated. Apart from this, after performance measurement of equipment with criticality assessment of physical assets, preventive maintenance will be carried out. But preventive maintenance attracts its own "hidden costs," which may include:

a. Costs of physical resources, for example, cost of man-hours and spare parts.
b. The risk for maintenance personnel.
c. The risk of another item failing due to functional dependence.
d. In some cases, constraints due to limited resources available for other tasks.
e. In some other cases, production losses, and equipment unavailability.

These are all wastes in production and are categorized as "Other Wastes" and Time losses in the PLI cube. For these reasons, the PLI cube will calculate those time losses and wastes. This will unveil other elements of lost profits in production and will also create room for future improvements. Because of this, the PLI cube is regarded as a performance measurement tool. Therefore, it is very smart to use PLI cube for further performance measurement in the work processes of the DDM model.

4.3 Decision processes in DDM

Figure 4.7 illustrates the decision processes in DDM. During the smart maintenance planning with criticality assessment of physical assets or asset parts, a model is built for matrix analysis; afterward, equipment (at plant level) or parts of the equipment (at equipment level) will run in yellow or red boxes, which indicates warning signs or alarm respectively. The real-time decision is made by AI based on work order which is prioritized based on the criticality (warning or alarm). Afterward, alarming equipment will be prioritized for preventive maintenance after evaluations. After preventive maintenance, reporting will be done based on the technical condition, which will be followed with PLI cube calculations to identify the root causes of wastes during preventive maintenance. Then improvements would be made based on the root causes.

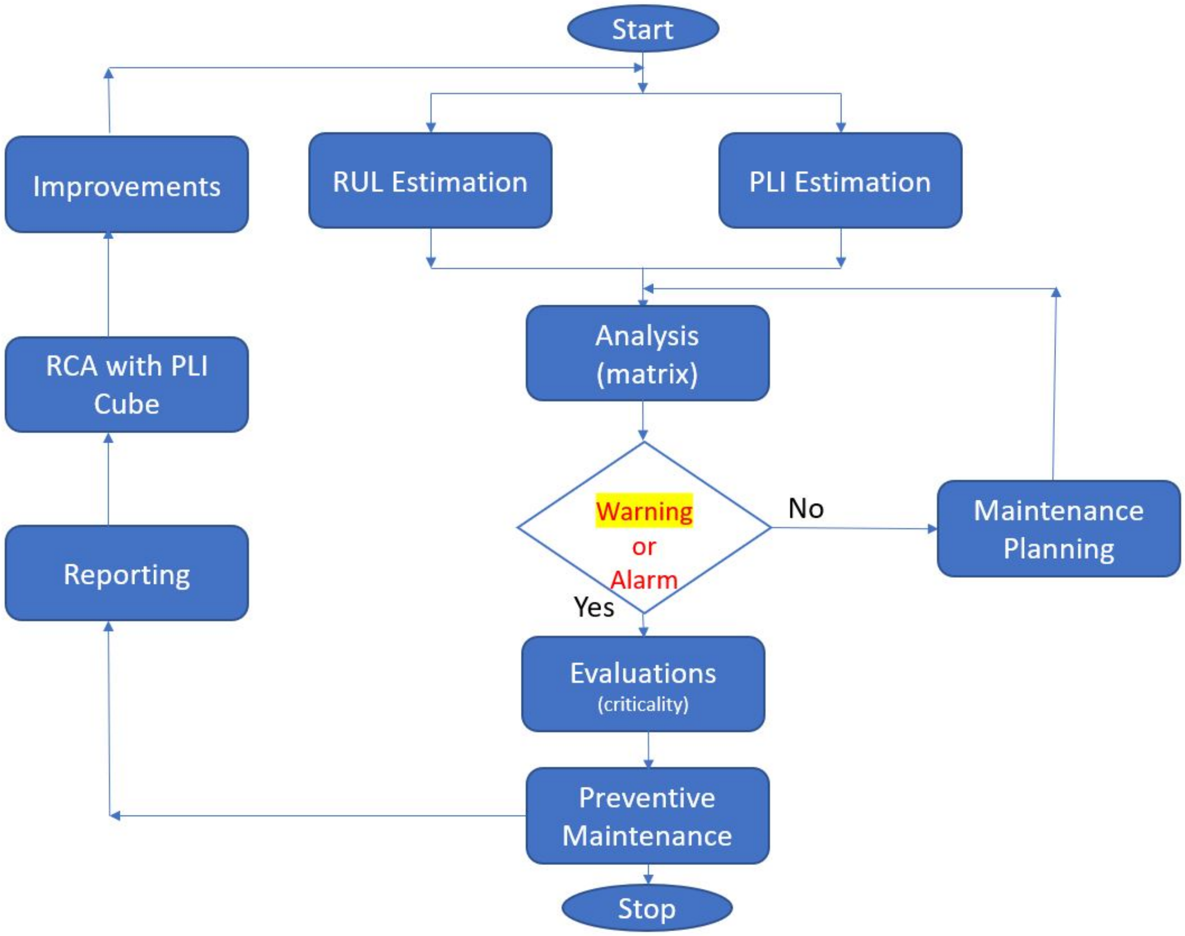

Figure 4.7: Decision processes in DDM

4.4 Risk Calculation using probabilities and consequences in criticality assessment of physical asset

According to NS-ISO 55000: 2014, asset management is more interested in the value realized from asset instead the asset itself. Therefore, in order to optimize DDM, the need to balance cost, risk and performance of assets must be prioritized when executing maintenance planning. It is very important that the maintenance planning makes proper audit and ensure that all required data are available before making criticality assessment of physical assets. The criticality assessment of physical asset has shown that RUL is the probability of failure of an equipment. Decrease in the length of RUL will cause an increase in the probability of equipment breakdown. In other words, this can be interpreted that an decrements in RUL of an equipment will result to the likelihood of the equipment failure.

Therefore, Probability of failure Pf(t) = RUL

Also, in the criticality assessment, the PLI is used to estimate and quantify the consequences in terms of costs implications of equipment failures if preventive measures were not taken on time. Such consequences may not be restricted only on the equipment but might cause hazardous event which triggers different forms of production and safety losses. For example, if a safety critical equipment like a Separator is in red zone, and no immediate action is taken, a hazardous event such as explosion might occur which will not only result loss of the Separator as a single equipment, but explosion of entire plant and, or oil spillages on the environment (safety losses). And so, the PLI should be able to estimate all these consequences and round them up in a financial number.

Therefore, PLI = Consequences of potential failure of an equipment C(F)

Then, the calculation of risk can be determined as a function of time by combining probability of failure and the consequence of failure, as shown in Equation below: (inspired from API 581)

Risk, R(t) = Pf(t)x C(F)

Risk = RULvalue x PLIvalue

Note that the probability of failure Pf(t), is a function of time since RULvalues decreases with time i.e., time when equipment jumps from Green -Yellow -Red – Malfunctioning/Failure. Whereas the consequences of failure PLIvalue, are assumed to be invariant with time. Failure in this context could be either malfunctioning of the equipment, or breakdown.

But Probability of failure RULvalue could be influenced by some factors which include:
Damage Factor DF, which is exact fault detected prognostically, Generic Failure Frequency GFF which are fault generated as OEM failure data, and Management Factor which has to do with the methods equipment had been operated by users. The DF can be occurred due to aging effect, damage type/rate, or inspection effectiveness (see Figure 4.8 below).

The consequences of failure PLIvalue, are also estimated as costs due to the “16 Big Losses” and or “4 Safety Losses” such as injuries incurred by personnel, cost of purchasing new equipment, equipment repair, cost of business intelligence, cost due to environment pollution etc.

4.5 How to determine PLIvalue in consequence calculation

To calculate consequence PLIvalue due to potential failure event, three main costs factors derived from "16 Big Losses" and "4 Safety Losses" should be considered:

1. Business Interruption Costs: The costs include cost of production losses which also includes cost for not meeting customer's satisfaction.

2. Equipment Damage Costs: Equipment damage costs may attract procurement costs, repair cost, and cost of man hour.

3. Safety Costs: Safety costs include cost due to the "4 safety losses" as explained in chapter 2.

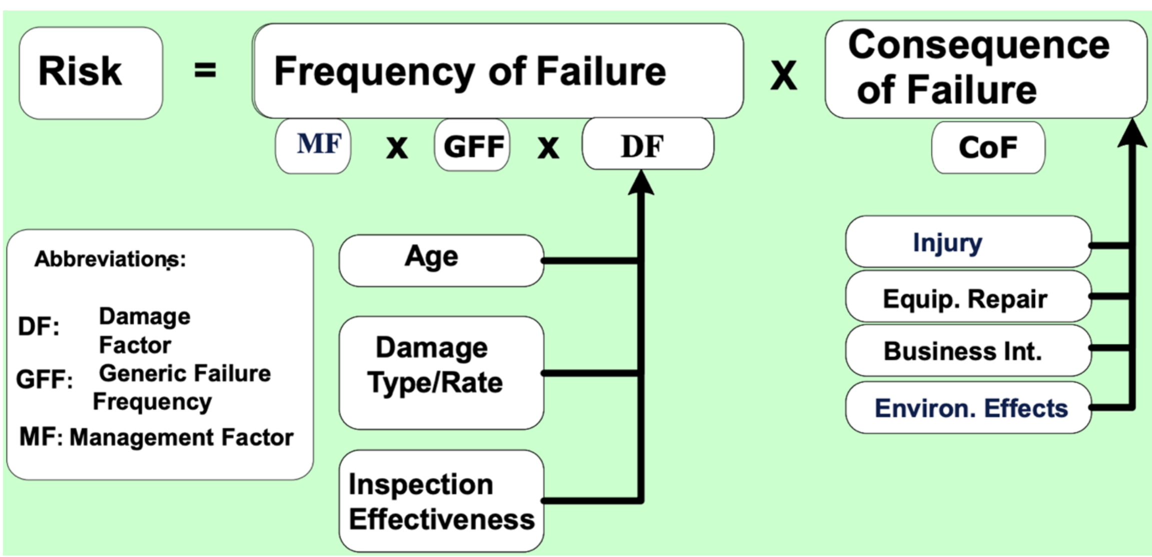

Figure 4.8: Equipment risk calculation in detailed analysis as inspired from [API RP 581]

4.6 Benefits of applying Criticality Assessment of Physical Assets in maintenance planning

The key purpose of a criticality assessment of physical assets is to drastically eliminate unplanned downtime (time losses) due to frequent maintenance activities that can lead to financial losses. This will help in minimizing "hidden factory" in production. From investigations so far, most wastes in production have something in common with equipment malfunction or breakdown. Therefore, there is a need to focus on ensuring that equipment does not breakdown at all. Except in a situation where run-to-failure becomes cost-effective without interrupting safety. Hence, other benefits of criticality assessment of assets include:

4.6.1 Identify the high-risk equipment

High-risk items may not necessarily mean expensive equipment. Any equipment which is vulnerable to both production and safety losses is high-risk equipment. For example, Oil and Gas Separator, High Pressure Pipeline etc. Such equipment will not breakdown if smart planning with criticality assessment technique is implemented. And this action must proceed with the execution of work order/preventive maintenance.

4.6.2 Understand the risk drivers and develop mitigation plans

Criticality assessment creates the basis of making a decision relating to the choice of arrangements and measures, including maintenance action and strategies. They are especially suitable for identifying equipment and activities that significantly affect risk and for analyzing the effect of risk-reducing activities. Through smart data analytics, early signs can be revealed, and mitigation plans (preventive measures) can be executed.

4.7 Maintenance Functions

To deliver high performance of asset, the maintenance function must optimize all invested maintenance resources. For this reason, the need to improve production system performance has brought maintenance function to the point of attention. Deterioration of plant equipment begins as soon as systems are installed. Apart from wear and deterioration, some other failures may occur due to the way equipment is operated beyond its design limits or due to operational errors. As a result of this, equipment downtime, speed losses, safety hazards, or environmental pollution becomes the next problem. These problems have the potentials to negatively impact operating cost, profitability, customer demand satisfaction, productivity, safety, and other important performance requirements. But in order to ensure that the plant operates at a required condition while meeting production targets at optimal cost, and risks at ALARP, maintenance functions must be established.

4.7.1 Establishing Maintenance Work Order from criticality assessment of physical asset

Decision-making on DDM using criticality assessment of physical assets is very sensitive and important in maintenance planning. Maintenance, production, and safety are the three major departments working closely together in a production plant. Therefore, maintenance planners should make work orders depending on the risks which are vulnerable to maintenance, production, or safety losses. This is why PLI is promising, as it is used as a financial indicator. In most cases, safety losses attract higher PLI due to the consequential cost of environmental degradation (oil spills, GHG Emission, Fire Outbreak) or loss of reputation of the production company. In a situation when RUL is Long, and PLI is High (Early Warning), planning should issue a work order ASAP before Alarm. This is because high PLI positioning of equipment could be very disastrous, and such position is usually associated with potential safety losses. This will impede the sustainability of a production company.

4.7.2 Main objective of the maintenance function

Generally, it is obvious that maintenance impacts a company's entire economy and profitability, and hence it is a competitive force in the future. Therefore, it is necessary to perform the DDM concept, which focuses on strategies and actions that prevent damages and losses of equipment availability and performance, and the maintenance (preventive) that contributes to keeping the system efficiency as close to the design intent as possible.

Figure 4.9 below shows the main elements constituting the main objective of the maintenance functions. Internal and external requirements and regulations normally determine the need for maintenance concerning safety. When it comes to the influence on availability and efficiency, maintenance cost optimization is considered since more efficient maintenance contributes to improved production and uptime of the equipment. However, such an increase in the maintenance effort or strategy may increase the maintenance cost. The task of the maintenance function in a company should therefore be to optimize this relationship and, in addition, perform the maintenance as efficiently as possible to the lowest possible cost and with risks at ALARP. Therefore, the maintenance function should compare the cost, risk, and performance to make decisions while prioritizing preventive maintenance work orders after the criticality assessment of physical assets.

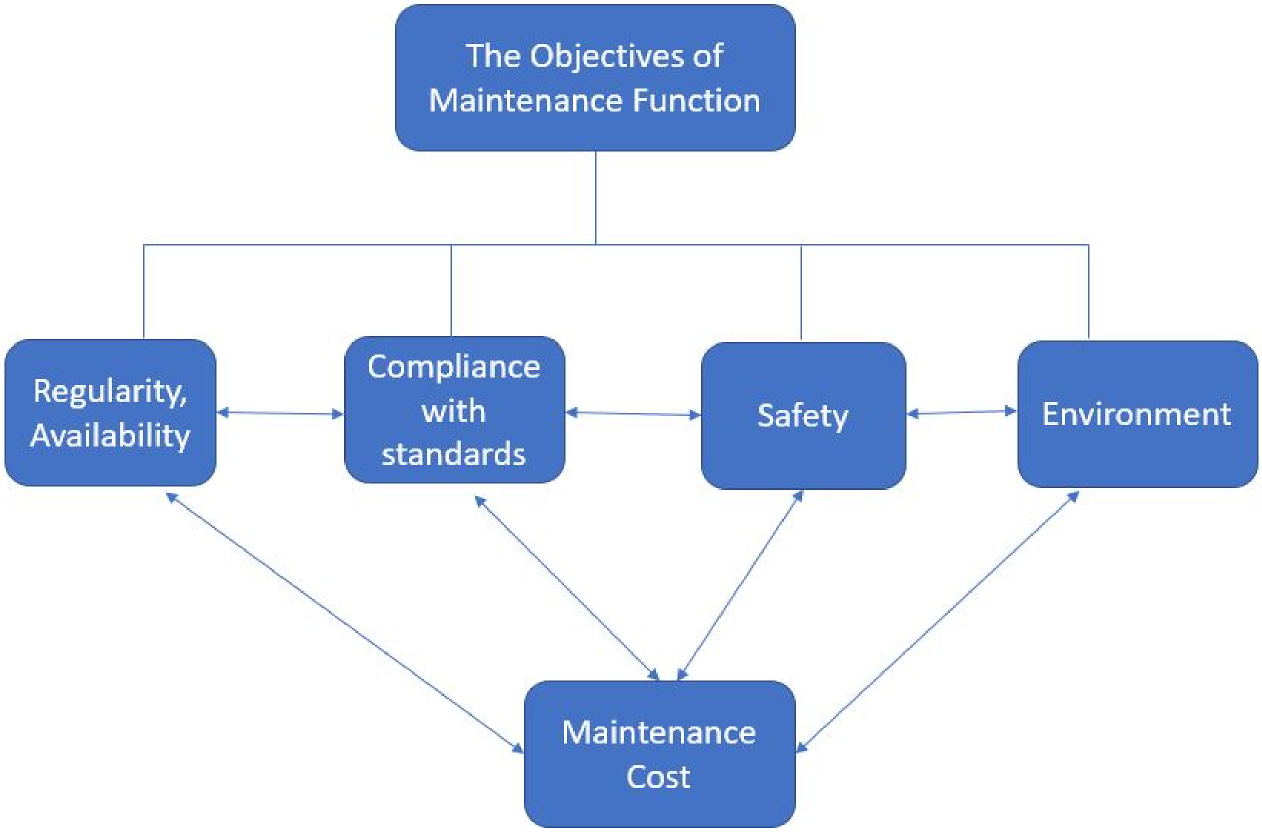

Figure 4.9: Elements constituting the main objective of the maintenance function adapted from TMR4260 Compendium

Safety of personnel, environment, and physical assets means more demanding requirements and control both from the authorities and from society as a whole. Safety aspects are, therefore, an important element of the maintenance objective. For these reasons, the effective monitoring of physical assets with the DDM concept will become a proactive barrier that controls the systems and prevents undesired incidents, as well as an escalation from the less serious events into accidents.

4.8 Smart Maintenance with DDM concept and the future of a production company

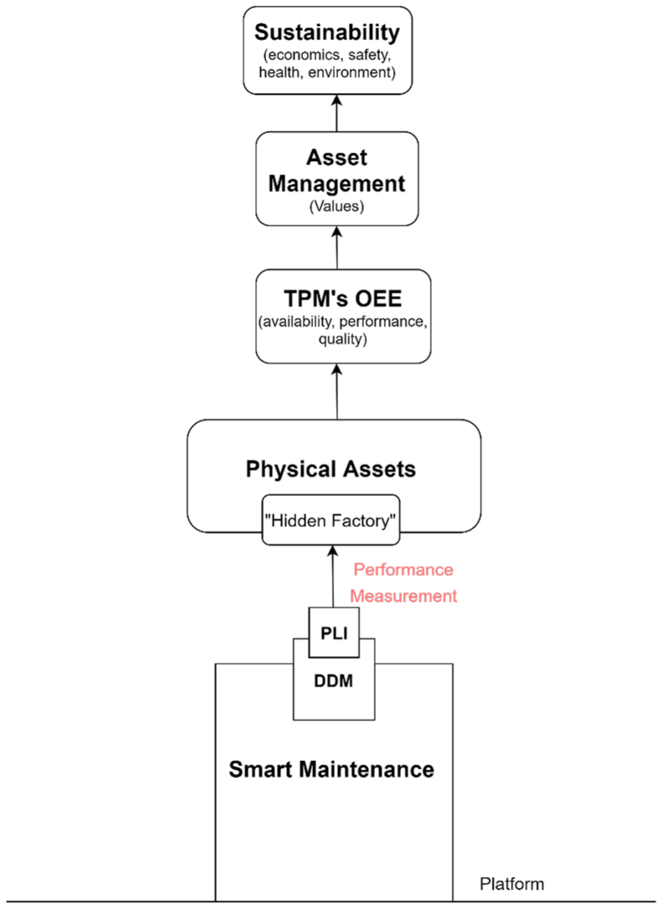

Figure 4.10: A framework to illustrate the influence of Smart Maintenance and its DDM model in minimization of "hidden factory" ("16 Big Losses and "4 Safety Losses"); how smart maintenance increases OEE value, and how OEE improves the Asset Management and future of a production company.

TPM is an achievement after making better use of available resources in enhancing plant/equipment performance. After a deep investigation into the production and maintenance losses ("hidden factory"), it is left with no doubt that the "16 Big Losses" propagates into "4 Safety Losses". However, an intelligent maintenance technology (DDM) is not coming in to mitigate the effects of these losses but to minimize them by predicting failures before they occur, followed by preventive maintenance planning and execution. In this regard, the DDM modules (PLI, RUL, Planning) are regarded as the performance measurement tools for the future. Maintenance management planning should also be smart enough when deciding about the work order system. In the smart maintenance platform with DDM and PLI, as shown in Figure 4.10, criticality assessment measures the performance capability of a physical asset with consideration of risk and costs to determine the performance requirement of maintenance functions. The maintenance function is usually a preventive maintenance work order followed by execution. With the aid of CPS, the system itself automatically performs this action with relevant information updated after activities. However, maintenance personnel is deployed to the site for other maintenance activities that CPS could not automate. With the DDM technique, TPM will achieve its main objectives through equipment's availability, performance, and quality of products which will meet the customer's satisfaction. Also, the organizational values of a production company, which include cost efficiency, safety, availability, and performance, will be actualized by asset management. This will enable a production company to remain competitive by making more profit, abiding by the environmental law, and achieving organizational objectives: economic growth, safety, health, and environment for sustainability.

Chapter 5

Discussion

The background aspect of this report was a litany of the consequences of time losses and wastes in production and how it has eaten cankerworm into the economy of several production companies. These wastes and losses could be initiated from production operators, maintenance personnel, process, tooling problems, unavailability of spare parts in the required time, etc. Wastes could also occur in idle machines, idle personnel, lack of cooperation between maintenance and production personnel (Integrated planning issues), breakdown of machines, etc. An increase in performance deterioration will affect the productive capability of physical assets, hence, reducing output, increasing operational costs, and interring with customers' services. All the wastes and losses mentioned above are elements of the "hidden factory" in the production. Investigations have also revealed "16 Big Losses" in a production plant linked to "4 Safety Losses". The"4 Safety Losses" can be eliminated or minimized if the "16 Big Losses" are eliminated or minimized. An equipment breakdown will increase the risks of accident events during corrective maintenance. The "4 Safety Losses" are very disastrous and can impede the sustainability of a production company. The TPM'OEE factored the "hidden factory" into availability, performance, and quality losses to enhance its measurement and elimination. Industrial companies have also modeled OEE to improve performance in various companies. Despite these efforts, cases of "hidden factory" have never persisted as it seems to be beyond human control. "Hidden Factory" is regarded as "evil," which tends to deprive an organization of the achievement of its organizational values.

5.1 PLI

To unleash a "hidden factory," the first step must be identifying and measuring time losses and wastes. PLI cube is smart and capable of measuring OEE time losses, tracing any waste, including raw materials, resource consumption, utilization, and other wastes, and presenting them in financial measure. OEE is a performance measuring tool that can be satisfactory if a business becomes revenue or profit after-sales of products. In this situation, management will assume that OEE is high. But one of the advantages of PLI is that even if there is gross profit or income after-sales of products, PLI will also calculate the lost income. Hence, this will help to sustain the business. Another advantage of PLI is its genericity. OEE tools are only concerned with equipment effectiveness, but PLI is concerned about the business as a whole. PLI's generic advantage makes it possible to trace and measure time losses and various sources of wastes from any facet of an industrial company, e.g., wastes from logistics, wastes from the supply chain, and wastes from the Human Resources department, etc. This is why "Other Wastes" was included in the PLI cube to support this idea. From an accounting point of view, a "business loss" occurs when a business has more expenses than earnings during an accounting period, and vice versa is "business profit." The "loss" means spending more than the amount of revenue. But the PLI does not only focus on the "business loss" but also investigates the expenses or costs even if there is "business profit." PLI will explore other sources where the business would have made more profit by examining the costs. To trace profit loss, some fault trees have also been analyzed to support the identification of time losses and wastes in business (not only in production). With FTA, the top event "profit loss" can be traced, and the basic events will become the root causes or the initiating causes of the profit loss in business. All the basic events are all denoted with "OR" gate, which means that all basic events are minimal cutsets. Therefore all cutsets (basic events) are critical. This means that any occurrences of any basic event will trigger the top event, which is "profitloss" in business. Management can also do further PLI calculations to see how much profit was lost due to each basic event. In this report, time losses occurred due to OEE losses in production/maintenance. Still, generically, time losses can also occur in other business aspects, such as unproductive meetings, general interruptions in workflow, etc. These losses are not profitable in business. As illustrated in chapter 2, the PLI can also calculate both the turnover losses and extra costs in every wastes and time losses. This will enhance minimization of "hidden factory". Another characteristic of PLI is its ability to make cost estimations of failure consequences and present them in a financial number. PLI estimation usually depends on the operational and environmental context of the physical asset. This means that PLI will vary in different operational fields based on process, equipment, and environmental context. For this reason, its weakness remains the fact that there is no generic data as individual companies should make up data for their estimations. The whole essence of PLI analysis is to identify, measure, and minimize "hidden factory" for the minimization of costs. The PLI cube will help unveil "hidden" areas affected by wastes and time losses in business. This is a more straightforward approach to identifying and measuring "hidden factory"; thus, PLI is regarded as a performance measurement tool for the future.

5.2 DDM

The most outstanding achievement of DDM is to implement a smart maintenance concept from data capture to a work order and preventive maintenance execution. From the DDM work processes in Figure 2.7, it was shown that an organization would invest CPS, IOTs, Data, and documentation, and ICT into their system to result a reduced risk, cost efficiency, and high plant/equipment performance. This will be possible if DDM modules are deployed to minimize unplanned maintenance by increasing man-hour for predictive maintenance, which will enhance the minimization of "hidden factory." The essence of minimizing "hidden factory" is to reduce costs. Unlike the conventional predictive maintenance approach, one of the technological advancements in DDM is that the self-maintenance execution, which the CPS enhances, also reduces man-hours for labour. This will reduce the frequencies of preventive maintenance activities by personnel onsite, reducing the risk of "16 Big Losses" and "4 Safety Losses". Furthermore, in DDM, RCA is done with the PLI cube after reporting. This will reveal areas where wastes and time losses are felt during preventive maintenance for improvement. The main targets of smart maintenance's DDM model are to reduce performance losses and downtime, increase man-hour for predictive maintenance and reduce maintenance costs to achieve organizational values, which are also the objectives of NS-ISO 55000: 2014. DDM's target is to improve productivity by maximizing output while minimizing input which constitutes a "hidden factory" in production. Input includes labour, equipment, and material, while output includes production, quality, performance, cost, safety, health, and environment. In order words, its goal is to minimize "hidden factory" and increase the OEE values (equipment's availability and performance, and quality of products). The IOTs involve connections of devices, collection of data, transforming it to information, and distributing it through the organization via internet (cloud) technology. But the question is, "how can we link machines, technology, and humans together to create an intelligent maintenance system that would minimize the "hidden factory" in production?" The Remaining Useful Life and Anomaly detection models are fundamental concepts of smart maintenance. An important metric in predictive maintenance, RUL, is used in obtaining the time remaining for a component to perform its functional capabilities before failure. RUL is used to predict the lifespan of components to minimize catastrophic failure events in production. Its purpose is to identify failure mechanisms and emphasize the failure events prediction approaches that can effectively reduce uncertainties. For example, failure prognosis, which involves predicting the remaining useful life of a failing pump, enables the maintenance operators to effectively plan preventive maintenance on the pump, thereby avoiding losses due to breakdown and corresponding safety losses.

On the other hand, Anomaly Detection (AD) identifies rare occurrences, items, or events of concern due to their deferring characteristics of the processed data. An anomaly could be structural defects, quality defects, etc. Machine learning uses algorithms to parse earlier data, read from it, and predict the health status of equipment. These algorithms can read from experience and build models without explicit programming. Deep learning is a subset of machine learning, in which artificial intelligence (AI) has channels capable of learning unsupervised from unstructured or unlabeled data. Image classification, object detection, and recognition are all driven by deep learning. These all attribute AI, which is one of the enablers of DDM. To meet the objectives of the DDM, RUL estimates must link PLI estimates in other to make a criticality assessment of equipment. This will enhance performance measurement of equipment where the analysis and evaluations would be made in real-time to provide useful information for making an effective decision based on preventive maintenance planning and execution, thereby minimizing time losses and wastes in production, which are all elements of a "hidden factory." Through a criticality assessment of equipment, more technical knowledge based on the criticality (production or safety) of equipment can be obtained, hence creating room for designing independent protection layers. During criticality assessment of equipment, it was also found that the "4 safety Losses" will always attract higher PLI values due to the consequences and penalties of safety losses such as oil spillages, plant explosion, fatality, etc. But this must be based on operational and environmental context.

5.3 Maintenance Functions

To deliver high performance of asset, the maintenance function must optimize all invested maintenance resources. There is a close relationship between quality and performance. From the PLI calculation in chapter 4, it was evident that when equipment performance is low for a given period, defective products are expected to increase; hence extra costs will keep increasing. It was also illustrated that increase in the degradation mechanism would result in performance deterioration of assets, which will cause an increase in cost over a while. This degradation will tend to increase over time, reducing the RUL of an asset until the breakdown. In as much as we want to increase predictive maintenance man-hour, it is also essential that we keep track of the costs incurred during preventive maintenance activities; otherwise, the company will not realize more value from assets. Some preventive maintenance can accumulate huge costs if its frequency increases in the life cycle of assets. The cost of providing maintenance service to businesses can indeed represent a considerable proportion of the total operating cost of a company. In chapter 4, Table 4.3 shows how the degradation of asset increases operational and maintenance costs over time. These costs considerably contribute to the LCC of assets. Fortunately, these costs can be reduced if "hidden factory" is minimized during preventive maintenance. This can be achieved starting with identifying and measuring the "hidden factory" with the PLI cube. In addition to the PLI cube, it is also important that FTA goes alongside. This will enhance the tracing and identification of time losses and wastes. Therefore, the maintenance function should keep track of preventive maintenance records and be conscious of LCC. This is why one of the advantages of criticality assessment physical assets is to identify high-risk equipment. In this context, the criticality of an asset is a function of cost. If equipment will generate high costs, then it is critical, and management should do the needful based on their maintenance strategies.

Chapter 6

Conclusions and Recommendations for further work

6.1 Conclusions

The whole essence of the performance measurement in this report is to realize more value from business by eliminating or drastically minimizing the "hidden factory." It was emphasized in this thesis that equipment breakdown will tend to increase production, maintenance, and safety losses in business. This report has demonstrated how PLI translated time (OEE) losses to financial values in NOK. This translation is a business language that management will understand irrespective of their disciplines. The report has also illustrated that increase in degradation mechanism of assets will increase the performance deterioration of that asset for periods, hence, contributing to the LCC. However, calculating the PLI cube will reveal the contributing factors such as wastes and time losses in maintenance, thereby creating room for performance improvements through the minimization of "hidden factory.". The PLI has also been modeled to fit into other performance measurement objectives of various business aspects. For example, the "Other Wastes," portrayed in this report, can capture any other forms of wastes induced by the business. This is because business wastes could vary by companies, but the aim is to reduce profit loss. The FTA, as introduced in the PLI model, will enable management to trace "hidden factory" from the TOP event "profitloss" to the BASIC events, which are the root causes of profit loss in business.

Also, it was clearly stated that identifying and structuring the "hidden factory" does not eliminate the "hidden factory" but is just a step forward. However, the application of Smart Maintenance with the DDM concept reduces availability and performance losses by increasing manhour for predictive maintenance, which reduces maintenance and operational costs that contributes to LCC through "hidden factory". On the other side, reducing performance losses will also reduce quality losses. Furthermore, the DDM concept will minimize "hidden factory" through real-time performance measurement where preventive maintenance is also planned and executed in real-time, increasing the company's OEE level, which results in sustainability and achievement of organizational values.

6.2 Recommendations for Further Work

Based on the discussions and conclusions presented, the following recommendations are made:

1. More investigations with case studies should be done regarding the performance measurement and development of maintenance functions on all rotating equipment that can be data-driven in a production plant e.g pumps, compressors, gas turbines etc. This investigation can be actualized if adequate PLI estimated data for various equipment malfunction are established and if RUL estimations on those equipment are also established. The PLI cube should be used to trace and measure various wastes and time losses associated with those critical equipment, which triggers both safety and production losses. Criticality assessment of those equipment will enhance the prioritisation of maintenance work order at plant level. Functional safety can also consider this idea during the design phase of safety protection layers.

2. A case study where PLI cube would be used to calculate time losses and wastes should be applied in the performance measurement of other industrial aspects such as accounting and finance, human resource management, marketing, logistics, supply chain etc., should be carried out. The generality of the PLI cube should unveil the time losses and wastes in those departments, thus, minimizing profit loss in business.

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