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Abstract

Industry 4.0 is among related terms a buzzword in today's industry. It is clear that several technologies aim to enable operators to obtain better control of their production operations, avoid non/added value events e.g. failures, stoppages, cut the operating and maintenance cost, and extend the asset lifetime. All these benefits are achieved by collecting and analyzing data in a smart i.e. automated manner. However, there are four main challenges to achieve such transformation (lack of standards, work processes, product availability and new business models). Therefore, industrial companies as organizations are struggling to navigate through the hype of Industry 4.0 to make digitalisation initiatives successful and beneficial for their purposes.

This thesis is in line with the above addressed challenge where it tries to answer the following research question: "*How* can a *predictive maintenance* programme be *developed and implemented* in fish feed *processing industry* in a *cost-effective* manner that *complies with the Industry 4.0 vision*". Thus, the purpose of this thesis is to propose and demonstrate a model i.e. set of procedures to develop predictive maintenance programmes that are compatible to the needs of the fish feed processing industry and their organizational resources. Moreover, the developed model shall be compliant to Industry 4.0 vision.

In order to achieve such purpose, the developed model is demonstrated at two levels i.e. machine and organizational level through a purposefully selected case study. The selected industrial case study is related to the extruder as one of the most critical equipment in Skretting's production plant (Hillevåg Plant).

This thesis, based on the case study, proposes a model to develop and implement predictive maintenance programmes through four phases; systems analysis of the physical assets, programme development based on Industry 4.0 architecture, cost-benefit analysis, and roadmap development for programme implementation at organizational level.

The systems analysis is a core phase to develop an intelligent system with a purpose (develop smart asset and operations to the required level and not over/implementation to just follow the buzzword hype or wave). Systems analysis was an effective methodology to identify the critical assets that have priority to be transformed into smarter state to gain the potential benefits of the enabling technologies of Industry 4.0.

The systems analysis highlights that the wear and fatigue crack faults are the most critical failure causes within the selected critical system i.e. the extruder. The wear fault can be monitored by detecting the natural frequency shift as the main fault symptom, and the fatigue fault can be monitored by detecting the amplitude values at the crack frequency as a main fault symptom.

The development model illustrates how the proposed seven layers (from data into decision) can be used to allocate the technical requirements needed to build the predictive health monitoring system in an effective and traceable manner. It clarifies the requirements of the system for each layer which is useful to compare against service provider solutions.

The cost benefit analysis shows that the cost of implementing and running the proposed predictive health monitoring system for ten years is lower than the value gained by the potential mitigation of the several failure events related to the two faults from the optimal baseline maintenance schedule.

The implementation model at organizational level concludes that five steps are required to successfully implement a PdM strategy that complies with Industry 4.0 vision. The five steps are self/assessment, strategy development, roadmap creation, capability and competence building and finally take action i.e. piloting the change.

Preface

This project is a collaboration between the University of Stavanger and Skretting AS in the spring semester of 2018. The thesis is submitted for a MSc degree.

The issue was submitted by Industrial Supervisor Lars Tomren and the research question was formulated together with Academic Supervisor Idriss El-Thalji.

I would like to thank Idriss El-Thalji for his guidance. I have learned a lot from his feedback and been inspired by his unique way of teaching.

I want to thank Skretting AS, and especially Lars Tomren for giving me the opportunity to be a part of this collaboration. Being able to focus on a real application has given me motivation and made the thesis enjoyable to write.

I also want to thank Geir Bremnes for letting me spend two weeks observing and discussing with everyone in the technical department in Skretting, Hillevåg. The time and knowledge shared has been crucial for the project.

Lastly I would like to thank Denis Komoza from SKF for providing valuable insights into vibration analytics from the training day given at the University of Stavanger related to the vibration monitoring lab.

Kristian Førland Steinsland,

University of Stavanger – 14.06.2018

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SKRETTING
a Nutreco company

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Abbreviations

AI	Artificial Intelligence
CC	Cloud Computing
CM	Corrective Maintenance
CMMS	Computerized Maintenance Management System
CPS	Cyber-Physical System
FFT	Fast-Fourier Transform
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
HSE	Health, Safety, and Environment
IOT	Internet of Things
ISO	International Organization for Standardization
ML	Machine Learning
MTBF	Mean Time Between Failures
PdM	Predictive Maintenance
PHM	Predictive Health Monitoring
PM	Preventive Maintenance
RCM	Reliability-Centered Maintenance
RPM	Revolutions Per Minute
RPN	Risk Priority Number
RUL	Remaining Useful Life
SME	Specific Mechanical Energy

1 Introduction

1.1 Project description and problem formulation.

The problem has been formulated based on the requirements given by the industrial and academic supervisors and influenced by personal interest. The intention with the formulated problem is to provide Skretting with the information they desire, while also fulfilling the requirements of the thesis by answering it. The problem formulation template given in Appendix A was used to develop a research question.

1.1.1 Project description

Skretting is the global leader in aquaculture feed [1]. In Norway there are 3 factories with a total of 8 production lines. In each production line there are many assets that need to function in order to produce the feed. Skretting's current maintenance strategy focus on Corrective Maintenance (CM) and Preventive Maintenance (PM) with the purpose of reducing downtime and increasing reliability. Skretting has noticed compelling drivers in the market and wishes to explore the opportunity to implement Predictive Maintenance (PdM) as a part of their maintenance concept. They have reached out to the University of Stavanger to help evaluate if they can add any value to their current systems.

PdM is becoming more popular and accessible due to development of cheaper sensors and monitoring equipment [2]. When looking at the trends and driving forces of today's industry, we discover that this is one of the trends which act as a main driver for many rapidly developing areas within a paradigm which has been coined as "Industry 4.0".

1.1.2 Challenge

The motivation behind this project is related to exploring new technologies. For a company to be able to adopt new technologies to get to the next level in their maintenance strategy, they need a method to follow. The lack of Industry 4.0 standards makes this a challenge [3]. Furthermore, for there to be any value for the company, the proposed maintenance system needs to be cost-effective. The focus of the thesis can be presented as a two-fold:

1) How can a predictive maintenance strategy be implemented?
2) Will such a predictive maintenance system be cost-effective?

1.1.3 Research question

To answer these two questions, we formulate a research question. The answer to the research question will provide Skretting with the desired knowledge:

> "*How* can a *predictive maintenance* programme be *developed and implemented* in fish feed *processing industry* in a *cost-effective* manner that *complies with the Industry 4.0 vision".*

1.1.4 Approach

The approach to answering the research question is to analyze Skretting's production lines and find a relevant case study that can be used to illustrate how a PdM strategy can be developed on machine level. The case study is based on two weeks of observation and interviews of experts with many years of experience with the production lines at Skretting's facilities in Hillevåg, Stavanger. Then, a literature study on Industry 4.0 and intelligent maintenance is performed to give some insights on how a PdM strategy can be implemented on organizational level.

An illustration of the project progress is given below:

- January: Literature study and project planning.
- February: Practice period at Skretting, Hillevåg. Starting the case study report.
- March: Formulating specific problems, delimitation of project scope and design of work methodology.
- April: Finalizing the case study. Writing of introduction, and background chapters.
- May: Results, reporting and reviewing. Writing of the theory and finalizing the models.
- June: Evaluation and spelling/ citation checks. Delivery.

1.2 Scope

Most of the critical equipment in Skretting's production lines is rotating machinery. Among identified critical equipment are mixers, hammer mills, extruders, pumps, and transportation equipment. The case study will be limited to the BC160 extruder application. The data used to produce the models in the case study are simulated based on the knowledge of the symptoms of the faults.

Specific aspects that Skretting wants to have covered in the thesis include:

- Generic assessments on pros/cons with PdM.
- How the data can be analyzed/utilized
- What types of conditional monitoring is suitable for equipment at Skretting.
- Economical, both the investments needed and potential savings.
- Need for competencies or organizational changes

1.3 Structure

The following is an overview of the contents of each of the chapters in this report. A more detailed content list is given in the start of each chapter.

- Chapter 1: Concludes with this an introduction, problem, method, scope, and structure.
- Chapter 2: Provides theory related to maintenance, Industry 4.0, condition monitoring and systems thinking
- Chapter 3: Presents case study data
- Chapter 4: Analysis chapter
- Chapter 5: Results, discussion, and further recommendations
- Chapter 6: Conclusion with the answer of the research question

2 Theory

The scope of the thesis is PdM in feed processing industry in the era of Industry 4.0. This chapter serves the purpose of providing the reader with insights in the background and developments within these areas and provide supplementary theory for the case study. The structure of this chapter is the following:

1) Maintenance philosophies

- Corrective
- Preventive
- Predictive

2) Industry 4.0 paradigm

- Short summary of the various industrial revolutions
- Trends, driving forces, rapidly developing areas
- Intelligent maintenance
- Smart machines

3) Condition monitoring implementation

- Failure analysis
- Vibration analysis

4) Systems thinking

- Idef
- Pugh matrix

2.1 Maintenance philosophies

Maintenance is defined as the "*combination of all technical, administrative and managerial actions, including supervision actions, during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function*" [4]. Proper maintenance helps to keep the life cycle cost down and ensures proper operations. In most industries, a variety of maintenance philosophies are utilized in specific maintenance concepts. The maintenance concept is defined as "*the set of various maintenance interventions and the general structure in which these interventions are foreseen*" [5]. We have many names for the things we love, it is therefore natural that various sources use different names for each of these philosophies [6] [7] [8] [9] [10]. An effort to give an overview of the maintenance philosophies and some related concepts is given in Table 1:

Table 1 Overview of maintenance philosophies.

Philosophy	**Related/ Synonyms**
Corrective maintenance (CM)	• No maintenance • Reactive maintenance • Run-to failure maintenance • Breakdown maintenance • Shutdown maintenance
Preventive maintenance (PM)	• Periodic maintenance • Time Based maintenance • Risk Based maintenance • Automobile maintenance
Predictive maintenance (PdM)	• Condition-based maintenance • Just-in-time maintenance • Proactive maintenance • Prescriptive • Self-maintenance

The process of determining the most effective maintenance approach for each asset is called Reliability-Centered Maintenance (RCM) [9]. RCM is together with the complementary Total Productive Maintenance a philosophy that aims to change the organizational culture and establish a process for continuous improvement of the maintenance concept [11].

In the following, a definition of the various maintenance philosophies used in this thesis is given, and an evaluation of the pros and cons for each of them based on the sources identified in the introduction of this chapter.

2.1.1 Corrective

The CM approach is used when the failure of the equipment does not have a critical consequence related to Health, Safety, and Environment (HSE), or operations. It is based on the belief that the costs related to downtime and repair of the asset is lower than the investment required for a maintenance program. The asset is allowed to operate until the parts wear down to the extent that the machine is no longer operational. The parts are then replaced. An evaluation of the pros and cons of CM is given in Table 2:

Table 2 Evaluation of pros and cons of corrective maintenance.

Corrective maintenance evaluation	
Pros	**Cons**
• No planning: Appointments for replacement of parts do not need to be scheduled in advance • Complete wear and tear: All components are used until they are completely worn down	• Financial loss: Unplanned downtime is the same as loss of production • Customer dissatisfaction: Unplanned downtime can lead to increased lead times which can be frustrating for the customer. Unhappy customers at the end of the supply chain can lead to loss of profit • Missed learning experience: Spontaneous problems need to be fixed immediately which can mean that there is no time to implement measures to avoid similar problems in the future

2.1.2 Preventive

The PM approach is used when the breakdown of an asset is assumed to be costlier than the prevention. It is an approach that utilizes knowledge of the machine regarding how the components break down. Time-based and risk-based approaches are utilized to schedule inspections and maintenance of the equipment to increase the components life-cycle. Time intervals are estimated from breakdown history, or from supplier recommendations. An evaluation of the pros and cons of PM is given in Table 3:

Table 3 Evaluation of pros and cons of preventive maintenance.

<table>
<tr><th colspan="2">Preventive maintenance evaluation</th></tr>
<tr><th>Pros</th><th>Cons</th></tr>
<tr><td>Minimized downtime: When spare parts are replaced before failure there is no unplanned downtime
Efficient scheduling: Spare parts and service technicians are available
Increased life expectancy of machines: By replacing parts before they are damaged; the general function is not compromised.
Predictable maintenance costs</td><td>Financial loss: Parts are often replaced before they are completely worn down
Increased maintenance scheduling costs
Maintenance timing: Implementing inspections based on time-intervals does not always consider the machine operational time
Risk related to sudden change in equipment operating state / part degradation</td></tr>
</table>

2.1.3 Predictive

The PdM approach is used when the failure of the equipment has a critical consequence related to HSE or operations. One can say that where PM has a goal to minimize downtime, PdM aims to maximize uptime. In general, we can say that the condition of the asset is assessed and compared to healthy operating state. Maintenance is carried out when certain indicators signals that the equipment is deteriorating and the failure probability is increasing. PdM is realized with the use of various condition monitoring techniques. There exist a large variety of offline and online monitoring techniques, depending on the application. Other than visual inspections, the most used condition monitoring techniques are: Vibration monitoring, oil-debris monitoring, process parameter monitoring, acoustic emission monitoring, and thermography. A taxonomy for PdM solutions is given in Figure 1.

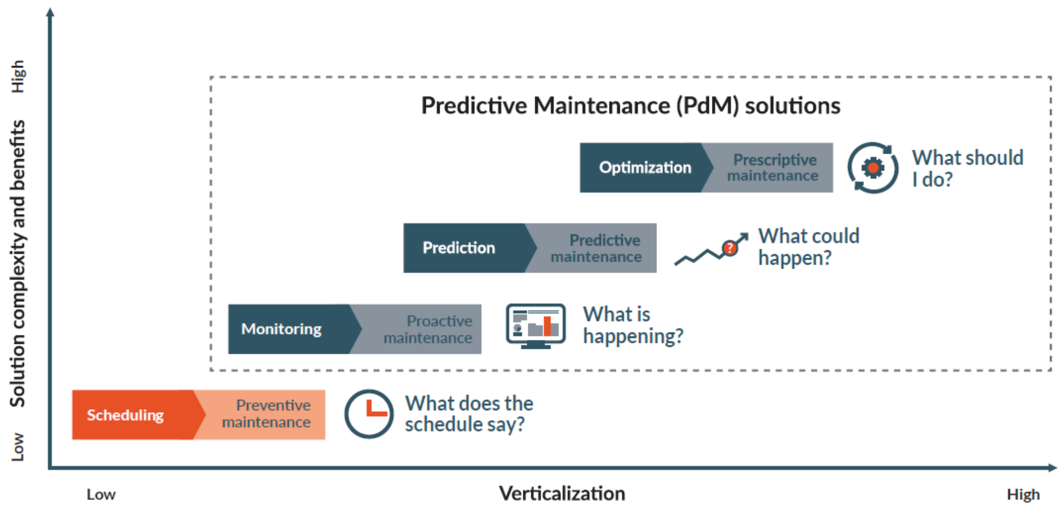


Figure 1 A taxonomy for predictive maintenance analytics [12].

It is assumed that the increasing availability of data and computing will allow operators to evolve beyond condition monitoring to anticipate problems before they happen, making PdM a lucrative and potentially game-changing possibility [12]. In this thesis, we define three levels of PdM with increasing complexity; proactive, predictive, and prescriptive. Proactive maintenance is the utilization of condition monitoring tools to diagnose what is happening. The overall vibration levels are usually compared to vibration levels defined in International Organization for Standardization (ISO) standards such as ISO 7919 series and ISO 10816 for rotating and non-rotating parts respectively [13]. We define PdM as the utilization of a Remaining Useful Lifetime (RUL) model to evaluate the state of the machine and predict the RUL of the components [14]. Prescriptive maintenance is when machines utilize Big data analytics, Machine Learning (ML) and Artificial Intelligence (AI) to gain a cognitive level that enables the machine to not only provide maintenance decision support, but also act on the recommendations [15]. In this paper we are concerned with PdM as defined here. An evaluation of the pros and cons of PdM is given in Table 4:

Table 4 Evaluation of pros and cons of predictive maintenance.

Predictive maintenance evaluation	
Pros	**Cons**
• Maximum uptime: With knowledge of the health of the asset, failures can be avoided completely • Flexible scheduling: Spare parts and service technicians can be scheduled based on need • Optimal use of parts: All machine parts are used until shortly before they are no longer operational • Minimized expenses: Cost of downtime and unnecessarily replacing parts disappear • Increased life expectancy of machines: By replacing parts before they are damaged; the general function is not compromised	• Maintenance costs: High capital and operational expenditures. • Short-term costs: Need-based repairs give less maintenance cost predictability • Increased need for flexibility: Need to adapt to real-time services and solutions

2.2 Industry 4.0 paradigm

In this chapter we will look at the evolution of the various industrial revolutions. Then, we will look at the various factors that constitute the emergence of Industry 4.0. We will cover the trends and driving forces of Industry 4.0, and which are the affected areas. Further, we will look at how this is related to maintenance and propose an intelligent maintenance model. Finally, we will look at what constitutes a smart machine.

2.2.1 First Industrial Revolution

The First Industrial (Mechanical) Revolution took place from 1760 to 1850 [16]. The invention of the steam engine is considered to be the main driver of this revolution. The main areas affected were agriculture production and manufacturing industry. Work in all industries were still highly labor-intensive.

2.2.2 Second Industrial Revolution

The Second Industrial (Technological) Revolution lasted from 1850-1970 [17]. The invention of electricity can be considered as the main driver for this period. Conveyer belts gave manufacturing plants moving assembly lines laying out the infrastructure and processes for the mass production of products. New innovations in steel production, petroleum and electricity led to the introduction of public automobiles and airplanes.

2.2.3 Third Industrial Revolution

The Third Industrial (Digital) Revolution started around 1970 [18]. The invention of the internet and the Programmable Logic Controller (PLC) has been the main drivers for improving computational and data analysis technologies. The innovations from computer and automation has improved all industries and are the basis of the world we live in today.

2.2.4 Fourth Industrial Revolution

The Fourth Industrial (Cyber-Physical) Revolution started when Professor Wolfgang Wahlster, Director and CEO of the German Research Center for AI, addressed the opening ceremony audience of the Hannover Messe in 2011 [19]. Here, he stated that we must be in shape for the Fourth Industrial Revolution that is being driven by the internet. After this, several countries have adapted the term in various ways in their strategic plans. In this section, we introduce the concept and define the various factors that constitute the emergence of Industry 4.0. The World Economic Forum characterizes the Fourth Industrial Revolution to be fundamentally different than the first three [20]. Quoting Klaus Schwab:

> *"Previous industrial revolutions liberated humankind from animal power, made mass production possible and brought digital capabilities to billions of people. This Fourth Industrial Revolution is, however, fundamentally different.* ***It is characterized by a range of new technologies that are fusing the physical, digital and biological worlds, impacting all disciplines, economies and industries, and even challenging ideas about what it means to be human****".*

McKinsey has evaluated a set of technologies, both in terms of potential economic impact and capacity to disrupt [21]. They propose a list of twelve potentially disruptive technologies, which is here illustrated in Figure 2. The largest estimated economic impact is assumed to be within; mobile internet, automation of knowledge work, Internet of Things (IoT), cloud, and advanced robotics.

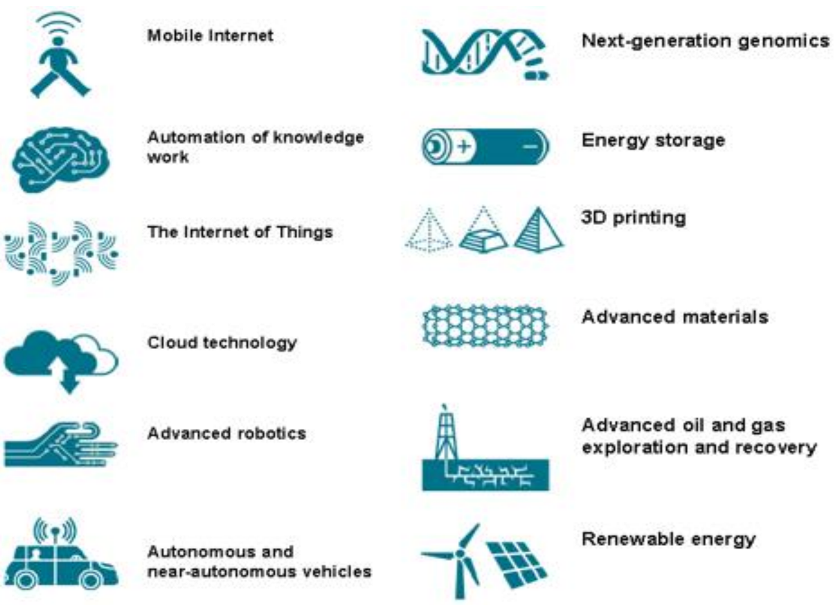


Figure 2 McKinsey's twelve disruptive technologies [21].

2.2.4.1 *Trends & driving forces and rapidly developing areas of Industry 4.0*

Industry 4.0 is symbolized with the real-time smartness exhibited by machines. Sensors are becoming smaller, cheaper, and are able to be embed in all sorts of devices. The increasing intelligence of sensors in various types of devices is the key enabler of Industry 4.0 [22]. With the use of more sensors a huge volume of data is being generated, which bring with it challenges and opportunities. The advancements of Big data, Cloud Computing (CC), data collection and transmission devices, software, and increasingly connected societies are driving Industry 4.0 [23]. An overview inspired by Prof. Eric Tsui [24] of the major trends and driving forces, and the rapidly developing areas of Industry 4.0, is illustrated in Figure 3.

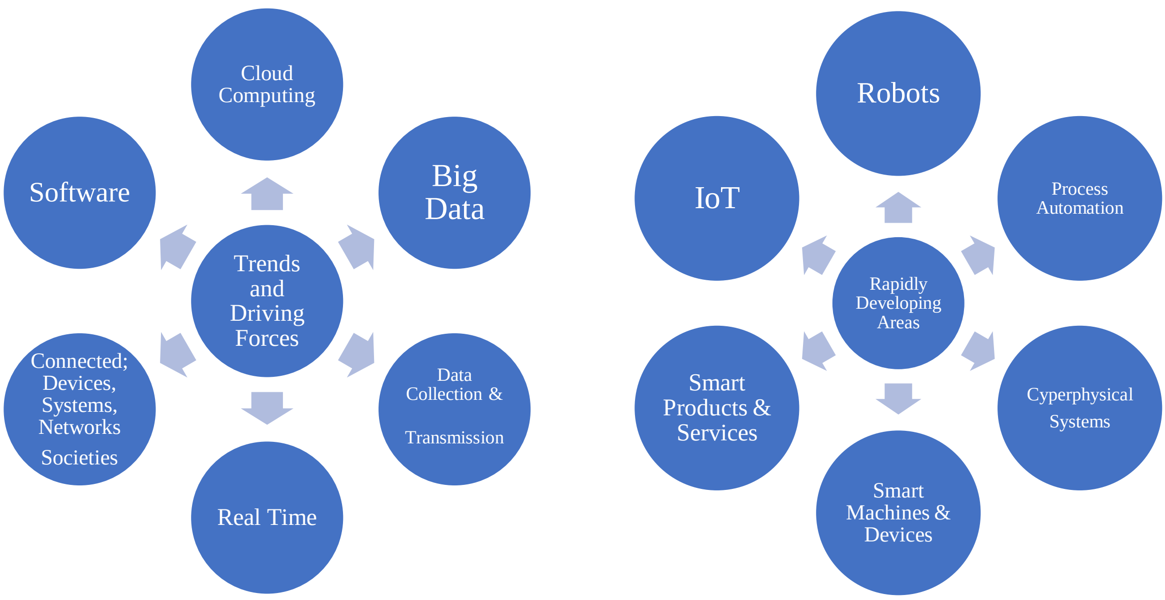


Figure 3 Trends and driving forces and rapidly developing areas of Industry 4.0 [24].

2.2.5 ***Industry 4.0 and intelligent maintenance***

In this chapter, we look at how maintenance fits into Industry 4.0. The World Economic Forum identifies PdM as one of the applicable technologies in the "New Era of Automation" digital initiative in a white paper on digital transformation in oil and gas industry [25].

One of the main challenges of Industry 4.0 is the lack of an international standard for implementation. DIN has, with a new standardization deliverable with less stringent requirements to stakeholder acceptance, produced the DIN SPEC 91345:2016-04 standard [26]. It describes a standard Reference Architecture Model for Industry 4.0 called "RAMI 4.0" which can remedy this problem. The next challenges are now, according to "Plattform

Industrie 4.0”; the creation of sub models for individual processes, creation of a common language, and specific recommendations for implementation. The RAMI 4.0 reference architecture is illustrated in Figure 4 [27].

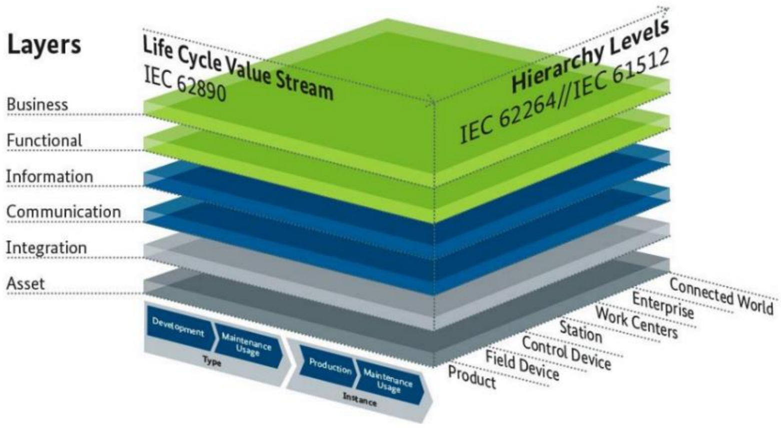


Figure 4 RAMI 4.0 Reference architecture for Industry 4.0 [27].

The model breaks down complex processes into understandable packages, ensuring that all participants involved in Industry 4.0 discussions understand each other. In the first axis, there is the factory hierarchy. The second axis is the architecture showing the layers from physical assets in the asset layer, to information being enabled into the organization in the business layer. The third axis illustrates the product life cycle from development to Operations and Maintenance. Placing this thesis within the RAMI4.0 reference architecture, we can say that we are concerned with raising a field device in the maintenance instance from the asset layer to the digital layers. We wish to provide recommendations for development and implementation of an administration shell.

According to a recent review of essential standards relevant for Industry 4.0, several models are identified using five to nine layers [28]. Jay lee proposes the 5C architecture model for implementation of Cyber-Physical-Systems (CPS) [29] illustrated in Figure 5.

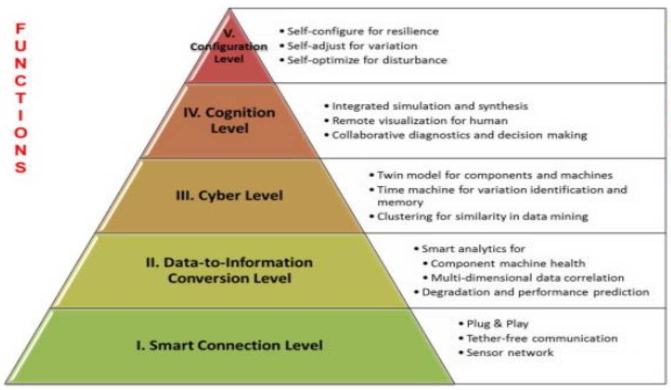


Figure 5 5C architecture for implementing CPS [29].

Since there is no standard for implementing PdM in the Industry 4.0 frame, we will in this paper propose an intelligent maintenance model influenced by this layer architecture to develop the PdM programme in compliance with Industry 4.0.

To develop a smart factory/process (according to Industry 4.0), you need to develop that process based on seven layers:

1) Application layer: A physical thing (asset / machine / system) must be chosen.
2) Perception layer: Each thing e.g. machine can generate data about itself, so we must choose between various types of sensors.
3) Connection layer: The data can be transferred into a specific cyber space.
4) Conversion layer: The collected data are of high volume, variety, velocity and veracity and needs pre-processing to reduce the resources needed for computation.
5) Computation layer: Signal analytics using software and algorithms.
6) Cognition layer: Creation of maintenance decision support with specific diagnostics and prediction of machine health.
7) Configuration layer: Movement from cyber to physical space where intelligence is transformed into action looped back to the application.

We will use this 7-layer intelligent maintenance model to develop the PHM programme in the case study.

2.2.6 Smart machines

The goal of Industry 4.0 is essentially to integrate physical assets with cyber technology in the factories and make the equipment internet enabled. We can say it is the creation of CPS connecting to each other through an IoT. The University of Berkeley defines the concept of CPS when introducing their CPS concept map [30]:

> *"Cyber-Physical Systems (CPS) are integrations of computation, networking, and physical processes. Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa"*

IoT is the main enabler for Industry 4.0. By embedding sensors and actuators in machines and giving them unique IP addresses, each thing is connected. There are currently many smart products, services, and devices that are developing within various industries.

When focusing on smart machines, it is desirable to understand what lies in this term. Just how smart are smart machines? A review paper from Michigan Institute of Technology (MIT) proposes a framework for managers to assess the extent to which a task or process can be performed autonomously by which type of machine [31]. They define a machine’s level of cognition with four levels of intelligence; support for humans, repetitive task automation, context awareness and learning, and self-awareness. They further define four task types that the machine can handle; analyze numbers, analyze words and images, perform digital tasks, and perform physical tasks. An evaluation of what today’s cognitive technologies can and can’t do is given in Figure 6.

	LEVELS OF INTELLIGENCE			
TASK TYPE	SUPPORT FOR HUMANS	REPETITIVE TASK AUTOMATION	CONTEXT AWARENESS AND LEARNING	SELF-AWARENESS
Analyze Numbers	Business intelligence, data visualization, hypothesis-driven analytics	Operational analytics, scoring, model management	Machine learning, neural networks	Not yet
Analyze Words and Images	Character and speech recognition	Image recognition, machine vision	IBM Watson, natural language processing	Not yet
Perform Digital Tasks	Business process management	Rules engines, robotic process automation	Not yet	Not yet
Perform Physical Tasks	Remote operation of equipment	Industrial robotics, collaborative robotics	Autonomous robots, vehicles	Not yet

THE GREAT CONVERGENCE

Figure 6 What today's cognitive technologies can and can't do [27].

The matrix gives an overview of the developing areas that realizes each of the machine task types on the various levels of intelligence. We see from this that machine self-awareness still only exists on a theoretical stage.

2.3 Condition monitoring

The general guideline for implementation of (off-line) condition monitoring and diagnostics of machines is given in ISO 17359 [32]. A flowchart from page 3 is presented in Figure 7.

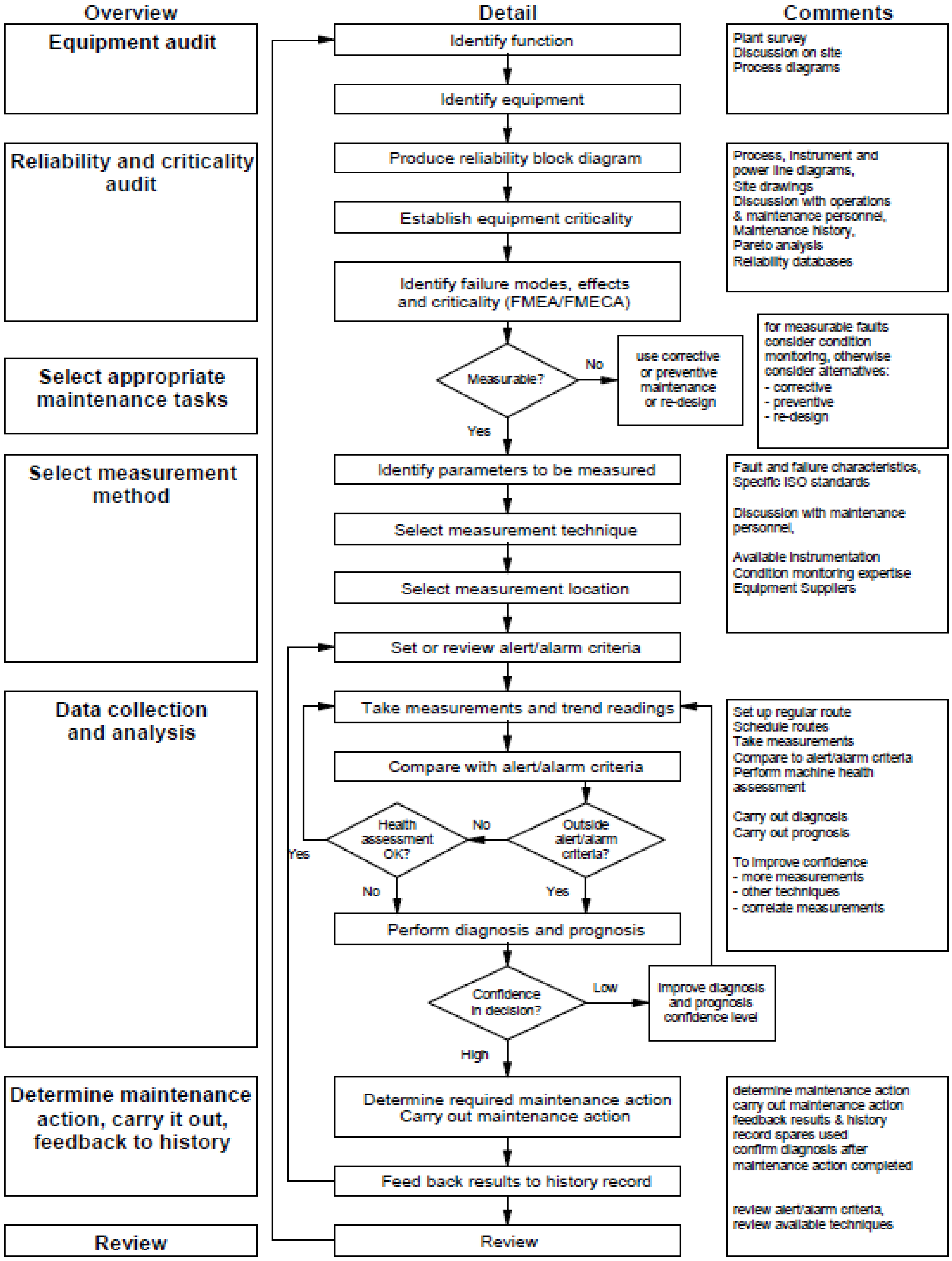


Figure 7 Condition monitoring procedure flowchart [32].

2.3.1 Failure analysis

After gaining an understanding of the chosen system by identifying and describing all the engineering aspects, we analyze potential failure risks within the system. In this report we use a qualitative Fault Tree Analysis (FTA) technique to identify possible failure events and evaluate the criticality of those using the Risk Priority Number (RPN) risk analysis tool.

2.3.1.1 Fault Tree Analysis

The FTA is a deductive analysis that begins with a general conclusion, then attempts to determine the specific causes of the conclusion by constructing a logic diagram called a fault tree. This is also known as taking a top-down approach [33]. A description of the analysis will be given based on the definitions in the international standard IEC 61025 [34]. Some terms and definitions used to describe the analysis is given in Table 5.

Table 5 Terms and definitions of FTA [34].

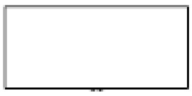
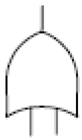
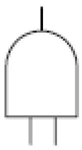
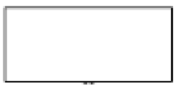
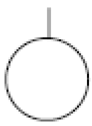
Term	Definition
3.1 Outcome	Result of an action or other input; a consequence of a cause.
3.2 Top event	Outcome of combinations of all input events.
3.5 Gate	Symbol which is used to establish symbolic link between the output event and the corresponding inputs.
3.6 Cut set	Group of events that, if all occur, would cause occurrence of the top event.
3.7 Minimal cut set	Minimum, or the smallest set of events needed to occur to cause the top event.
3.8 Event	Occurrence of a condition or an action
3.13 Single point failure	Failure which, if it occurs, would cause overall system failure or would, by itself regardless of other events or their combinations, cause the top unfavorable event (outcome)

In order to use FTA effectively as a method for system analysis, the procedure should consist of at least the following steps:

1) Definition of the scope of the analysis
2) Familiarization with the design, functions, and operation of the system
3) Definition of the top event
4) Construction of the fault tree
5) Analysis of the fault tree logic
6) Reporting on results of the analysis
7) Assessment of reliability improvements and trade-offs

On this page, a description of the most common symbols used in an FTA is given in Table 6, along with an illustration of a fault tree representation of what would be a series structure in a reliability block diagram in Figure 8. More symbol descriptions can be found in annex A.

Table 6 Description of symbols in FTA [34].

Symbol	Symbol name	Description	Reliability correlation
	Top event	The formulated failure scenario that is desired to be avoided.	Outcome of combinations of all input events
	OR gate	The output event occurs if any of the input events occur.	Failure occurs if any of the parts of that system fails – series system Reliability model when independent: i = 2 to n $F(t) = 1 - \prod_{i=2}^{n}[1 - F_i(t)]$
	AND gate	The output event occurs only if all the input events occur.	Parallel redundancy, one out of n equal or different branches. Reliability model $F(t) = \prod_{i=2}^{n} F_i(t)$
	Event	Occurrence of a condition or an action.	Input event
	Basic event	The lowest level event for which probability of occurrence or reliability information is available.	Component failure mode, or a failure mode cause.

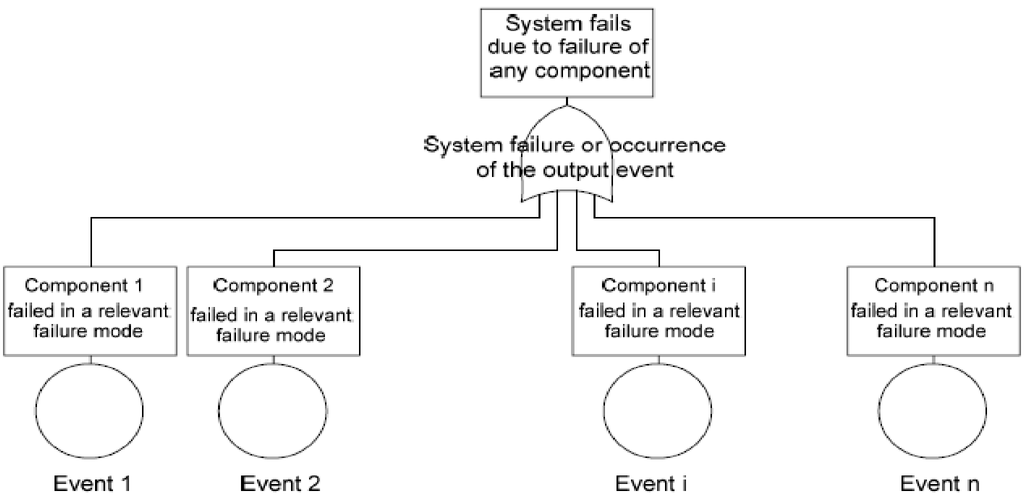


Figure 8 Fault tree representation of a series structure [34].

2.3.1.2 Risk priority number

The RPN is a risk analysis tool often used in the failure analysis to evaluate the criticality of the identified failure modes [36]. It involves evaluating failures according to severity, occurrence, and detectability on a scale from 1 to 10. The RPN is the product of these with a value ranging from 1 (absolute best) to 1000 (absolute worst). See equation (1):

$$RPN \;=\; Severity * Occurence * Detection \qquad (1)$$

Depending on the application, there are different ways to define the measure of criticality of each of these parameters. NORSOK standard z-008 gives guidelines for optimizing a maintenance program based on risk analysis and cost-benefit principles. In chapter 5.2, some necessary preconditions to start up a criticality analysis is given [4, p. 10]: In addition to a detailed technical description of the plant systems and relevant technical drawings, the consequence classes must be properly defined prior to performance of the criticality analysis. From the knowledge gained from the systems analysis we, can define the severity, occurrence, and detection based on downtime, Mean Time Between Failures (MTBF), and probability of detection. In the following we present some estimates.

The severity is a subjective estimate of how severe the effects of the failure event will be. An example of how the severity can be defined in terms of downtime is proposed in Table 7. The description of the ratings is given in the context of machinery Failure Mode and Effect Analysis (FMEA) [35].

Table 7 Severity rating description.

Rating	Meaning
1	Process parameter variability within specification limits; adjustment or other process controls can be taken during normal maintenance.
2	Process parameter variability not within specification limits; adjustment or other process controls need to be taken during production; no downtime / no production of defective parts.
3	Downtime of up to 10 minutes, but no production of defective parts
4	Downtime of 10 to 30 minutes, but no production of defective parts.
5	Downtime between 30 minutes and 1 hours or the production of defective parts for up to 1 hour.
6	Downtime of 1 to 4 hours or the production of defective parts for 1 to 2 hours.
7	Downtime between 4 and 8 hours or the production of defective parts for 2 to 4 hours.
8	Downtime greater than 8 hours or the production of defective parts for greater than 4 hours
9	Downtime greater than 24 hours or the production of defective parts for greater than 12 hours
10	Regulatory and / or Safety implications

The occurrence is a numerical subjective estimate of the likelihood that the cause of a failure mode will occur during production. It can be based on known data or lack of it. Similarly, we can define the criticality metric for the occurrence to be related to the Mean Time Between Failures (MTBF) of the equipment defined in Table 8.

Table 8 Occurrence rating description.

Rating	Meaning
1	MTBF greater than 20000 hours
2	MTBF from 10001 to 20000 hours
3	MTBF from 6001 to 10000 hours
4	MTBF from 3001 to 6000 hours
5	MTBF from 2001 to 3000 hours
6	MTBF from 1001 to 2000 hours
7	MTBF from 401 to 1000 hours
8	MTBF from 101 to 400 hours
9	MTBF from 11 to 100 hours
10	MTBF from 1 to 10 hours

Detection is a subjective numerical estimate of the effectiveness of the controls to prevent or detect the failure mechanism. An example is given in Table 9 where we define the detection rankings as follows:

Table 9 Detection rating description.

Rating	Meaning
1	Equipment control will almost certainly detect a potential mechanism and subsequent failure mode.
2	Very high chance that the equipment control will detect a potential mechanism and subsequent failure mode.
3	High chance that the equipment control will detect a potential mechanism and subsequent failure mode.
4	Moderately high chance that the equipment control will detect a potential mechanism and subsequent failure mode.
5	Moderate chance that the equipment control will detect a potential mechanism and subsequent failure mode.
6	Low chance that the equipment control will detect a potential mechanism and subsequent failure mode.
7	Very low chance that the equipment control will detect a potential mechanism and subsequent failure mode.
8	Remote chance that the equipment control will detect a potential mechanism and subsequent failure mode.
9	Very remote that the equipment control will detect a potential mechanism and subsequent failure mode.
10	Equipment control will not and cannot detect a potential mechanism or there is no equipment control.

2.3.2 Vibration analysis

2.3.2.1 Simple harmonic motion

In its simplest form, vibration can be considered the oscillation or repetitive motion of an object around an equilibrium position [36]. The vibratory motion of a whole body can be completely described by translation in the three orthogonal directions x, y, and z, and rotation around the x, y, and z axis. Together these make six degrees of freedom.

The rate and magnitude of the vibration of a given object is completely determined by the excitation force, direction, and frequency. The forces depend the machine condition, and a knowledge of their characteristics and interactions allows one to diagnose a machine problem.

The simplest possible vibratory motion that can exist is the movement in one direction of a mass controlled by a single spring, also known as "a single degree of freedom spring-mass system". If the mass is displaced a certain distance from the equilibrium point and then released, assuming that there is no friction, the mass will overshoot the rest position and deflect the spring an equal distance in the opposite direction. The illustration of a simple harmonic motion in Figure 9 shows a graph of the displacement of the mass plotted versus time.

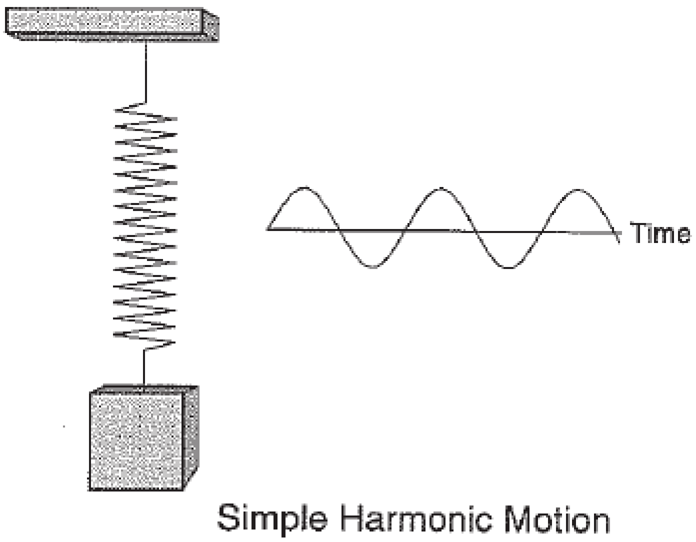


Figure 9 Simple harmonic motion of a single degree of freedom spring-mass system [36].

The period is the time required for one cycle from one zero crossing to the next zero crossing in the same direction measured in seconds. The frequency is the number of cycles that occur in one second. The following definitions apply to simple harmonic motion:

- $T = The\ Period\ of\ the\ wave$
- $F = The\ Frequency\ of\ the\ wave = \frac{1}{T}$

The following definitions apply to the measurement of mechanical vibration amplitude.

- Peak Amplitude (Pk) is the maximum excursion of the wave form from the zero or equilibrium point.
- Peak-to-Peak amplitude (Pk-Pk) is the distance from a negative peak to a positive peak.
- Root Mean Square Amplitude (RMS) is the square root of the average of the squared values of the wave form.

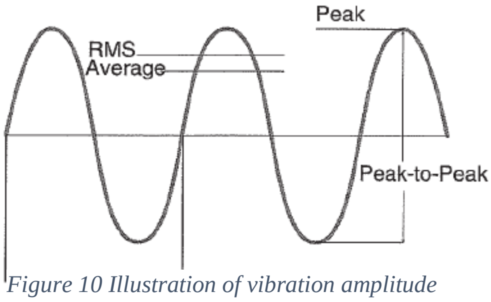
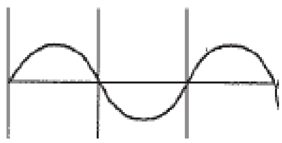
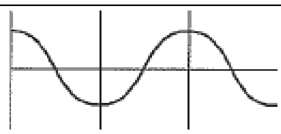
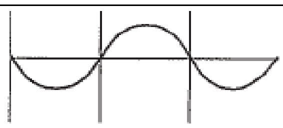


Figure 10 Illustration of vibration amplitude measurements [41].

There are three measures in which we can measure the vibration of an object: Displacement, velocity, and acceleration. Table 10 is given to describe each of them and how they correlate to each other.

Table 10 Displacement, velocity and acceleration vibration units [36].

Vibration unit	Equation of motion	Phase relationship
Displacement $[m]$ as a measure of vibration amplitude is the distance from equilibrium, which is measured in peak to peak.	$d = D\sin(\omega t)$, where d = instantaneous displacement, D = maximum, or peak, displacement ω = angular frequency, = 2πf	
Velocity $\left[\frac{m}{s}\right]$ is the rate of change of displacement, which is measured in peak.	$v = \frac{dD}{dt} = \omega D\cos(\omega t)$ where v = instantaneous velocity.	
Acceleration is the rate of change of velocity $\left[\frac{m}{s^2}\right]$, which is measured in rms.	$a = \frac{dv}{dt} = \frac{d^2D}{dt^2} = -\omega^2 D\sin(\omega t)$ where a = instantaneous acceleration.	

2.3.2.2 Complex vibration

If there are two forcing frequencies occurring at the same time, the resulting wave form of vibration will be more complex. Under these conditions, the high frequency and the low frequency vibration add together giving the resulting wave form of vibration illustrated in Figure 11.

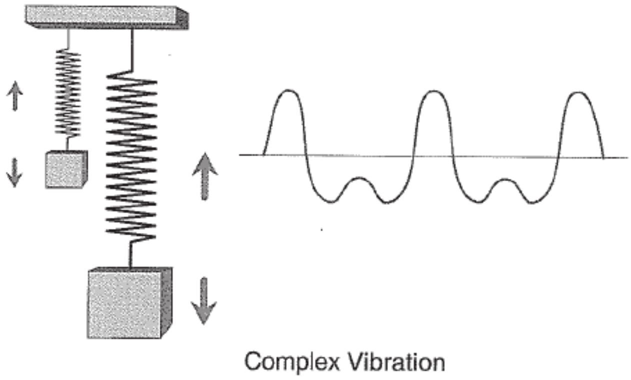


Figure 11 Vibration signal with more than one forcing frequency [36].

In real-world applications there will be several forcing frequencies occurring at the same time, and there will be friction which will cause the amplitude of vibration to gradually decrease as the energy is converted to heat. In a typical rotating machine, it is often hard to get information of the inner workings of the machine by looking at the vibration wave form, but in certain cases wave form analysis is a powerful tool.

2.3.2.3 Natural frequency

Any physical structure can be modeled as a number of springs, masses, and dampers. If energy is applied to a spring-mass system, it will vibrate at its natural frequency. The level of the vibration depends on the strength of the energy source as well as the absorption or damping in the system. The natural frequency of an undamped spring-mass system is given by the following equation (2) [36]:

$$F_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}, \text{ where} \qquad (2)$$

- F_n = the natural frequency
- k = the spring constant, or stiffness
- m = the mass

2.3.2.4 Frequency analysis

To get around the limitations in the analysis of the wave form, the common practice is to perform frequency analysis, also called spectrum analysis [36]. As previously stated, a vibration wave form from a machine will contain several responses. Some of the information is in very low-level components whose magnitude may be less than the width of the line of the wave form plot. Nevertheless, such very low-level components may be important if they indicate a developing problem. The essence of PdM is the early detection of incipient faults, which we are able to detect using spectrum analysis.

Spectrum analysis is defined as *"the transformation of a signal from a time-domain representation into a frequency-domain representation"* [36, p. 51]. The father of spectrum analysis is the engineer Jean Baptiste Fourier. He showed that a periodic time signal is equivalent to a collection of sine and cosine functions whose frequencies are multiples of the reciprocal of the period of the time signal. The most commonly used piece of signal analysis equipment in the vibration field is the Fast Fourier Transform (FFT). It is a computer algorithm for calculating the Discrete Fourier Transform which transforms a discrete periodic time signal into a discrete periodic frequency spectrum. The first step in performing an FFT analysis is the actual sampling process, which is illustrated in Figure 12.

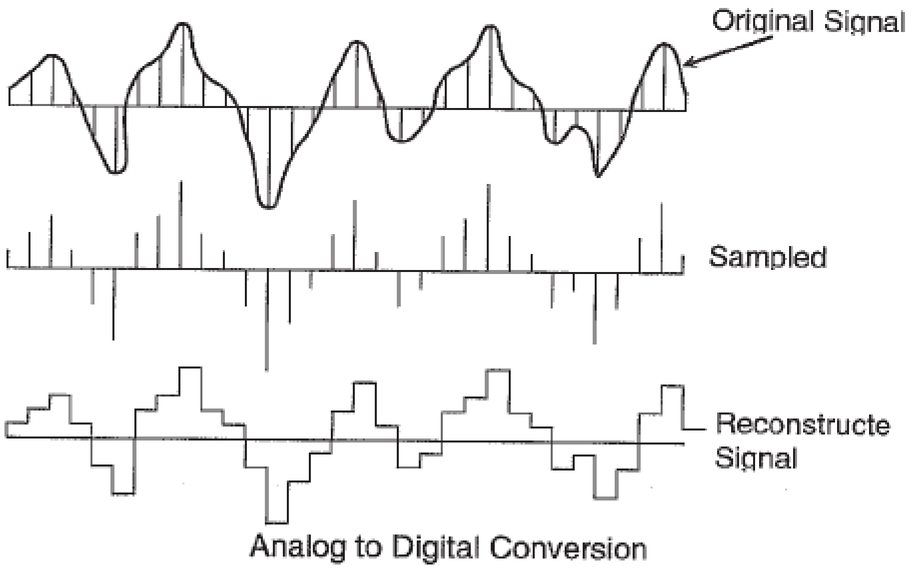


Figure 12 Analog to Digital Conversion process in Discrete Fourier Transform [36].

The sampling is an analog process accomplished by a sample and hold circuit which outputs a sequence of voltages which are fed into an analog to digital converter (ADC) which after some data processing gives the frequency spectrum data.

2.3.2.5 Machinery fault diagnosis using vibration analysis

SKF has produced a vibration diagnostic guide with methods used to detecting and analyzing machinery problems with examples of "typical" ways in which various machinery problems show themselves, and how these problems are "typically" analyzed [37]. A clear distinction is here made between detecting a machinery problem and analyzing the cause of a machinery problem, like we defined with the predictive maintenance taxonomy in Figure 1 as the difference between a "proactive" and a "predictive" approach. The proactive approach can be recognized by the "overall vibration" method. Here, one defines a stable operating state defined within the "stable zone" of a p-f curve [14], and monitor degradation characteristics due to degradation of a component into the failure zone. The health is defined by using trend readings and observing the increased level of overall vibration amplitude and comparing to vibration severity charts such as in ISO 10816 [13]. Further explained by SKF [37]:

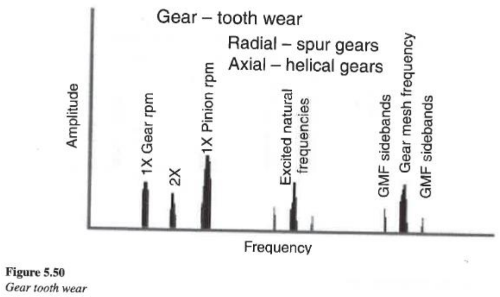
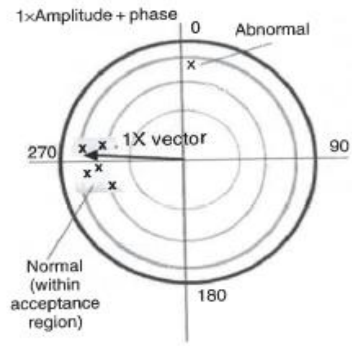
> *"Measuring the "overall" vibration of a machine or component, a rotor in relation to a machine, or the structure of a machine, and comparing the overall measurement to its normal value (norm) indicates the current health of the machine. A higher than normal overall vibration reading indicates that "something" is causing the machine or component to vibrate more".*

The first part of the analysis concerns collecting useful information about operating parameters. The analysis part is about identifying frequency ranges and suspected fault frequencies. FFT analysis is the single most powerful tool for vibration fault diagnosis of rotating machines [38, p. 88]. Some of the machinery defects detected using vibration analysis are:

- Unbalance
- Bent shaft
- Eccentricity
- Looseness
- Belt drive problems
- Gear defects
- Bearing defects
- Electrical faults
- Oil whip
- Cavitation
- Shaft cracks

Some relevant examples of machine faults and their frequency spectrum analysis are given in Table 11.

Table 11 Machine faults and frequency spectrum analysis [38].

Machine fault	Description	Spectrum
Gear tooth wear.	As the gear tooth wears down it will lose mass. "An important characteristic of gear tooth wear is that gear natural frequencies are excited with sidebands around them." [38, p. 116]	 Figure 5.50 Gear tooth wear
Shaft crack	During crack development the rotor will lose stiffness in the direction perpendicular to the crack direction. "In one revolution of the ruler we will see two big deflections which would cause a 2X RPM vibration frequency." [38, p. 131]	

The relationship between vibration diagnostics and prognostics is illustrated in Table 12. Once the diagnostics procedure has been performed (step 1-3), information is produced which can be utilized to build the prognostics model (step 4-5) [14].

Table 12 Diagnostic - prognostic relationship [14].

Diagnosis	Step 1	Fault detection	Detecting and reporting an abnormal operating condition.
	Step 2	Fault isolation	Determining which component (subsystem) is failing or has failed.
	Step 3	Fault identification	Estimating the nature and extent of the fault.
Prognosis	Step 4	RUL Prediction	Identify the lead time to failure.
	Step 5	Confidence interval estimation	Estimating the confidence interval associated with the RUL prediction.

Appropriate model selection for successful practical implementation requires both a mathematical understanding of each model type, and an appreciation of how a particular business intends to utilize the models and their outputs. We do not go into details on prognostics modelling in this paper, but models are provided for illustration purposes.

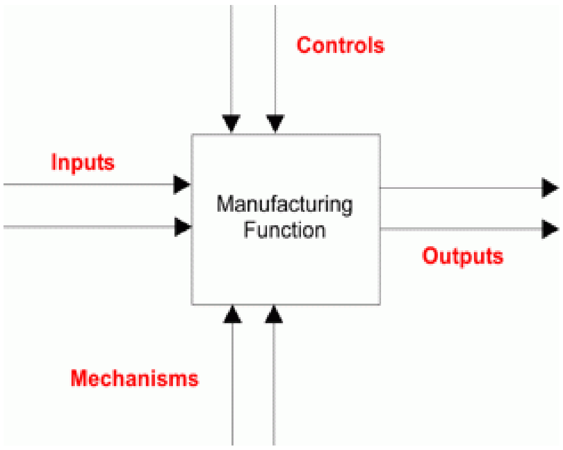
2.4 Systems thinking

The first step in developing a PHM programme is to gain an understanding of the engineering aspects of the selected system. To help understand how a system works, one can generate management models to explain the system in a logical manner.

The key enabler for system modelling is systems thinking. There are many definitions of systems thinking and even though it was coined by Barry Richmond in 1987, it seems like the term has not yet been clearly defined [39]. The originator of the term defines it as "the art and science of making reliable inferences about behavior by developing an increasingly deep understanding of underlying structure (1994)".

Our goal is to make a conceptual model for the processes and associated inspection and monitoring procedures for our selected system. We do this by utilizing the IDEFØ concept and breaking down manufacturing functions into system blocks and mapping the corresponding inputs, outputs, mechanisms, and controls and how they relate to each other. A description is quoted from the IDEF website in Table 13 [40]:

Table 13 Description of the idef analysis tool [40].

Illustration	Description
	*"As an analysis tool, IDEFØ assists the modeler in identifying what functions are performed, what is needed to perform those functions, what the current system does right, and what the current system does wrong. Thus, IDEFØ models are often created as one of the first tasks of a system development effort"* [40]

2.4.1 Pugh matrix

The Pugh matrix is a decision-making tool which can be used for comparison of a number of design candidates, leading ultimately to which best meets a set of criteria. It also permits a degree of qualitative optimization of the alternative concepts through the generation of hybrid candidates. The Pugh process is comprised of six steps [41]:

- Step 1: Identify and clearly define the criteria for selection.
- Step 2: Use one candidate design option as the baseline and score all criteria/requirements.
- Step 3: Compare each candidate design option against the baseline design, criteria by criteria.
- Step 4: Calculate the total score for each candidate design option.
- Step 5: Consider hybrid solutions by combining where possible the best from each alternative.
- Step 6: Make the decision.

3 Case study background (Data collection)

The aquaculture industry is responsible for over 22.700 Norwegian jobs that produce over twelve million meals a day, being delivered to 100 vastly different countries [42]. The feed processing industry in particular is facing challenges that make equipment maintenance of paramount importance. New products are entering the market at increased frequency. Nearly two-thirds of all feed processing plants are more than twenty years old. The industry is constantly in need to add or modify equipment. It is important for businesses to be innovative to excel in such a competitive industry [43].

3.1 Skretting - a nutreco company

Skretting was established in 1899 in Stavanger. Since then, it has grown from a small family business to be the world's leading company within the production and transport of feed for the aquaculture industry. The factory to the left with the distinctive white 80-ton silos in Figure 13 is the factory which this report is based upon [44].

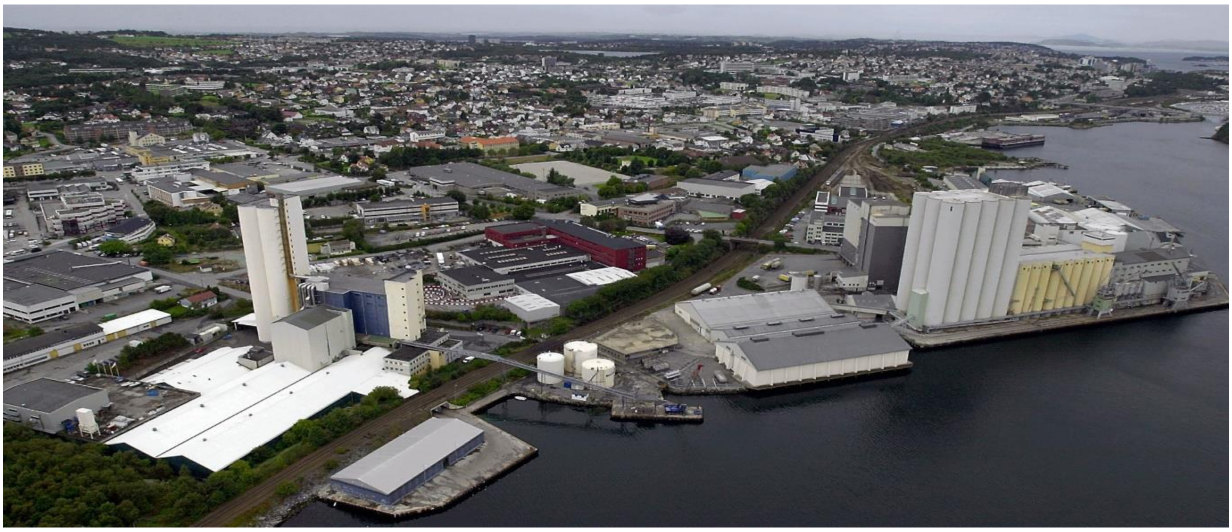


Figure 13 Skretting factory in Stavanger, Hillevåg [44].

3.2 Organization and values

Skretting is a company of Nutreco which is present in both agriculture and aquaculture industry [1]. The Skretting organization is world-leading within feed production for the aquaculture industry, producing over 2 million tons of feed each year. Operating out of 19 countries it has over 2900 employees, with over 300 of these being in Norway. Looking at Figure 14, we see one of the core values in Skretting is innovation, which has been one of the driving forces responsible for the company's success since the start.

Figure 14 Skretting's mission and core values [33].

The concept of feeding the future [45] is based on a prediction of the rise in the world's population to 9 billion people by the year 2050, as seen in Figure 15. Skretting's ambition is to contribute to meeting the rising food needs in a sustainable manner. They aim to do this by constantly seeking innovative ways to raise the efficiency and nutritional value of their products, the productivity of activities internally and with the customers, and to reduce the environmental impact of the value chains to ensure sustainability.

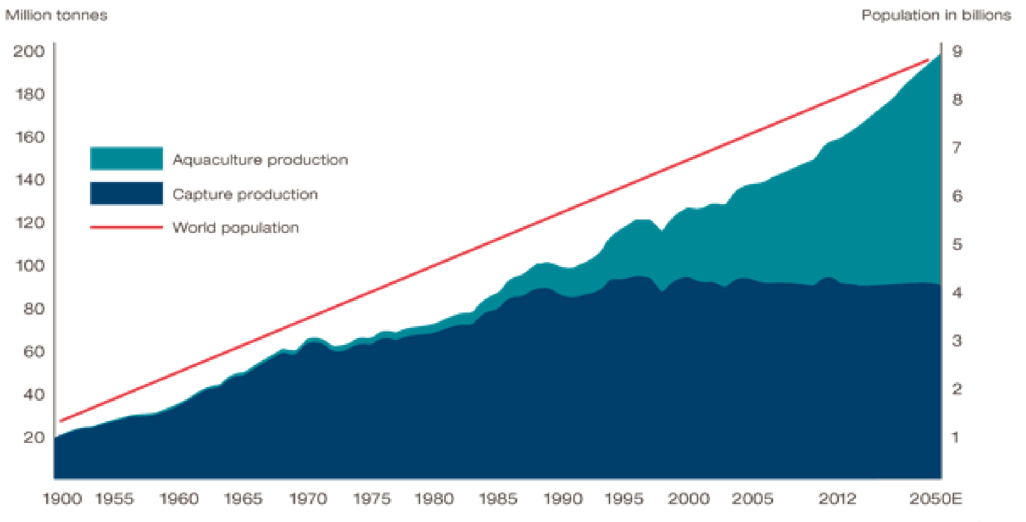


Figure 15 Increase in feed demand due to rise in population towards 2050 [33].

3.3 Process

The production lines can produce many different products. The raw material used in various products include Soy Protein Concentrate (SPC), fishmeal, wheat, wheat gluten, faba beans, sunflower meal, rework, fish oil, rapeseed oil, rapeseed lecithin and SPAR oil (Skretting documents). These are mainly transported to the facilities by boat and put in respective oil tanks and material silos by mechanical transport systems such as redlers, elevators and gravimetric transports.

For each product, the various raw materials needed for the recipe is weighed and transported from the on-site silos to enter the milling process. After being milled into low particle size, the mass enters the mixer where crucial vitamins and nutrients are added. This semi-finished product is called the meal mix, which is stored in pre-batch silos ready for on-demand production. This process can be considered as its own production line and include the two first critical phases of the production. Figure 16 shows the layout of this production line. The milling and mixing processes are shown to the right, the smaller nutrient silos are in the middle, and the meal mix silos are to the left.

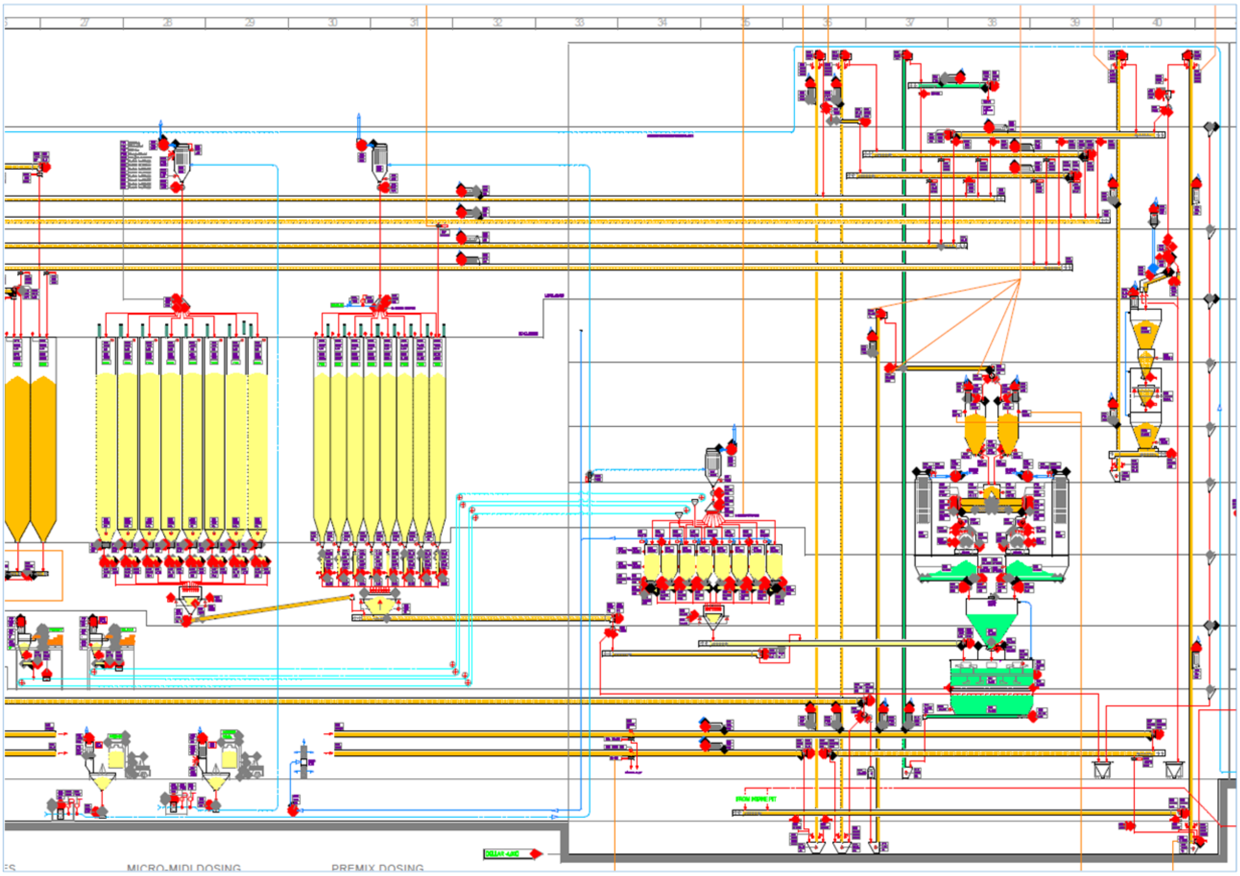


Figure 16 Milling and mixing production line.

The next step of the process is transforming the meal mix into a finished pellet product. At the Skretting facilities in Stavanger there are two production lines for this purpose which have the same layout. The two production lines differ because one of them is equipped with two smaller extruders working simultaneously and the other utilizes a single bigger extruder. The single extruder is the same type that is used in the other production facilities in Norway, Averøy and Stokmarknes, therefore we will focus on extruder line 1.

The meal mix enters the extruder process where it is first mixed with oil, hot water and steam in the preconditioner. It then enters the extruder where it is mixed and melted using mechanical energy produced by the twin co-rotating extruder screws. The output of the extruder is the processed mass which is cut to pellet size at the end of the machine. The pellets are transported to a dryer to extract the water in order to make place for the oil. The next step is a coater which uses vacuum to make the oil enter the pores of the dry pellet. After this process, the product is cooled, shaken to remove excess particles, weighed, and put into 750 kg bags to storage ready for transportation to the customer. The process layout is illustrated in Figure 17. Further explanation of the extruder process will follow in 4.1.3.

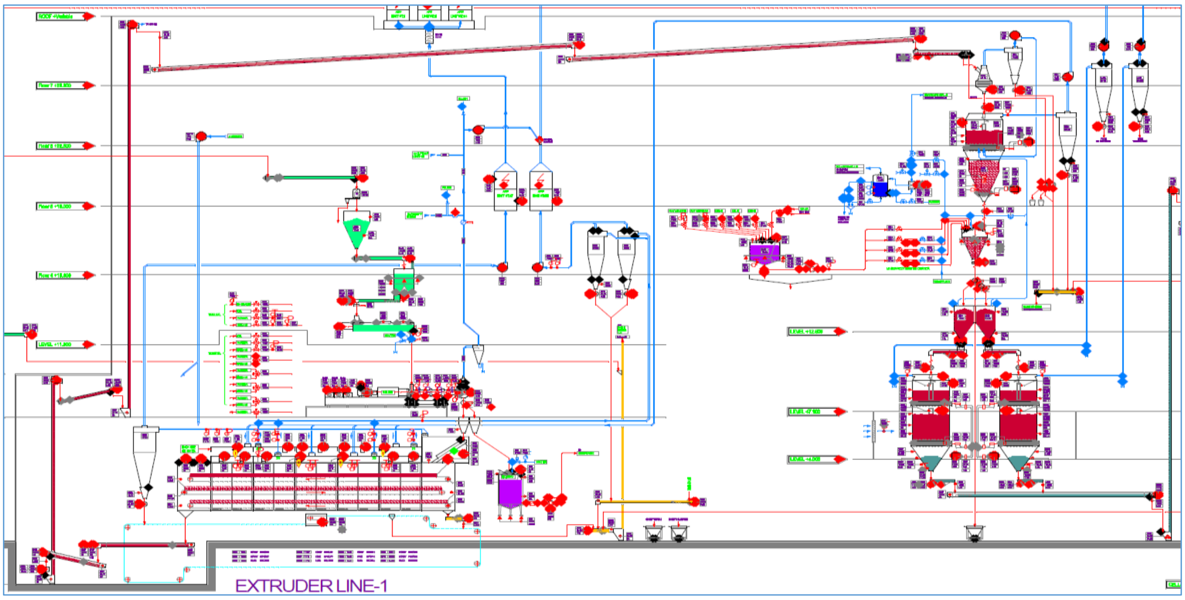


Figure 17 Extruder Line 1.

The main critical production steps are summarized in Figure 18.

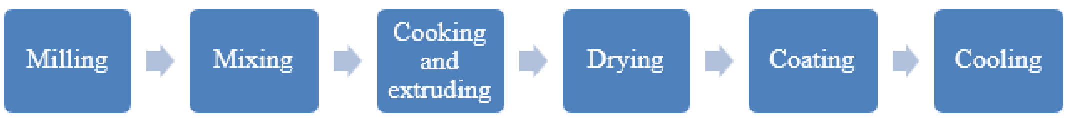


Figure 18 Critical production processes.

3.4 Current maintenance management

Of the 2405 systems that are registered in the Plania maintenance management system there are 1050 systems which are scheduled with periodic inspection and/ or maintenance tasks. The last ten years Skretting has experienced a large increase in the amount of systems equipped with such measures due to stricter demands of documentation and internal control in the industry regulations. A consequence of this evolution is an approximate increase in uptime of the system from 85% to 94% in a ten-year period. The frequency of the scheduled tasks is based on experiences from within the industry and within Skretting.

The technical department of Skretting in Stavanger consists of the technical manager, three automaticians/ electricians and two mechanics. They are responsible for following up on weekly, monthly, and bimonthly scheduled PM tasks as well as CM needs.

There are two main periods where production is shut down for a longer period to perform larger maintenance tasks. These are usually two 2-week periods approximately two months apart in the low season, which is in the spring semester. The high season of production is August to October, given that the production is fresh fish feed, and the fish eat more during this period. In this critical period, it is crucial to avoid any unplanned downtime. In the larger maintenance shutdowns, personnel are hired from outside.

There exists some instrumentation for monitoring the production line, but its purpose is to monitor the process parameters. It is not actively used in the maintenance strategy.

4 Analysis – Development and implementation of PdM

In this analysis, we will demonstrate how to develop and implement a PdM strategy on machine level and organizational level. We illustrate this through a case study where we develop a retrofit PHM programme of a critical asset in the production lines of Skretting AS in Hillevåg, Stavanger. Furthermore, we evaluate the cost-effectiveness of the program by comparing the cost with the benefit of mitigating the failure events from an optimal baseline maintenance schedule. A literature study is then performed to develop a model for how the case study can be utilized in an implementation roadmap. The data in this case study is based on internal documents in Skretting, interviews and direct observations.

The structure of this chapter is:

1) System analysis of physical assets
2) Development of PdM programme
3) Cost-benefit analysis
4) Implementation of PdM strategy

4.1 System analysis of the physical assets

The production line is evaluated as whole, and critical systems which could be suitable candidates for implementing condition monitoring are identified. For the purpose of this case-study, the extruder is identified as the heart of the production process and serves as our chosen asset to analyze. The extruder is a complex system consisting of many components. These kinds of machines are widely used in the feed industry and comes in different sizes and configurations. We look at its context and functions and the needs of the relevant stakeholders of the system. Once we gain an understanding of how the system functions and the key acceptance criteria for its operation and maintenance, we identify failure modes that can make the system not perform as desired. Figure 19 illustrates the extrusion process with the feeder system, preconditioner, and extruder.

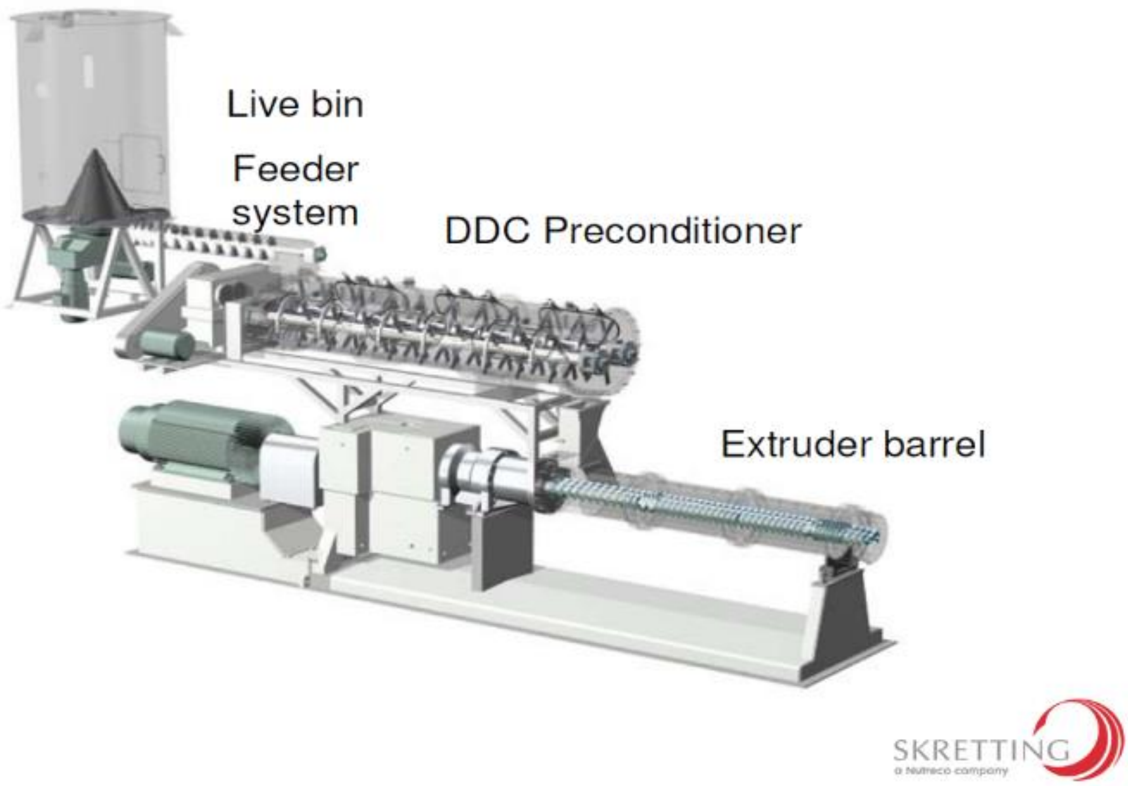


Figure 19 Illustration of feeder, preconditioner, and extruder systems.

4.1.1 System boundary

First, we define the boundary of the selected system. We are concerned with the functions related to the cooking and mixing of the product. We define our system boundaries to be the input from where the mass exits the preconditioner and enters the bypass chute, up until where the product exits the dieplate and enters the cutting box. The system boundary "cooking and mixing" is illustrated in the Systems of Systems chart in Figure 20.

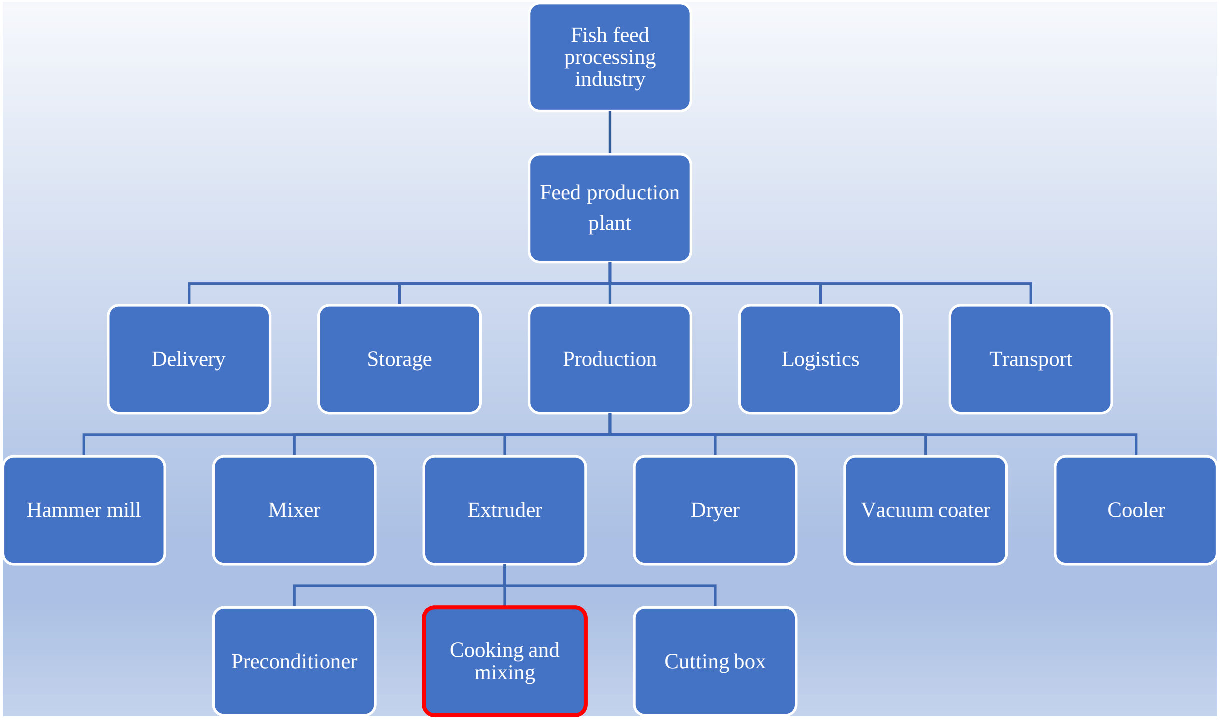


Figure 20 Systems of systems chart.

4.1.2 Physical architecture

We focus on the Clextral BC160 extruder used in extruder line 1. This is the machine type used for making the product with the highest fat percentage. This product needs more expansion properties and therefore higher Specific Mechanical Energy (SME) input. In Figure 21 an illustration is given of the physical architecture of the extruder with the corresponding critical parts.

1) Frame
2) Screw motor
3) Coupling torque limiter
4) Drive unit
5) Lantern
6) Barrel
7) Electrical boxes
8) Adj. supporting feet
9) Barrel rail
10) Barrel support

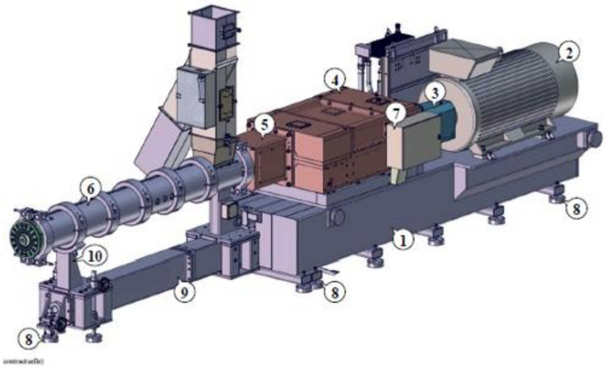


Figure 21 Physical architecture of BC160 Extruder.

The essential accesses for operation and maintenance is given in Figure 22. The figures are taken from the extruder instructions note from Clextral.

1) Supply materials, bypass chute
2) Extruder, lantern
3) Extruder, torque limiter (reducer)
4) Extruder, barrel
5) Extruder, hydraulic unit
6) Output product

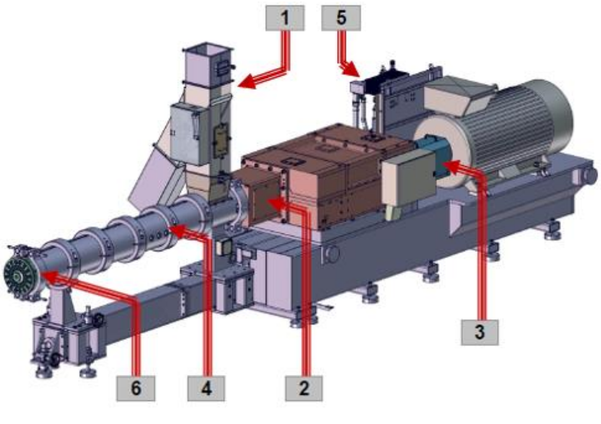


Figure 22 Essential accesses for operation and maintenance.

4.1.3 Functional architecture

We have identified the physical architecture of the system. We now need to know the operating conditions of the system. We therefore look at the extrusion process in more depth. An illustration of the functional architecture in relation to the critical parts performing the functions is given in Figure 23. We break down the extrusion process into the following four steps:

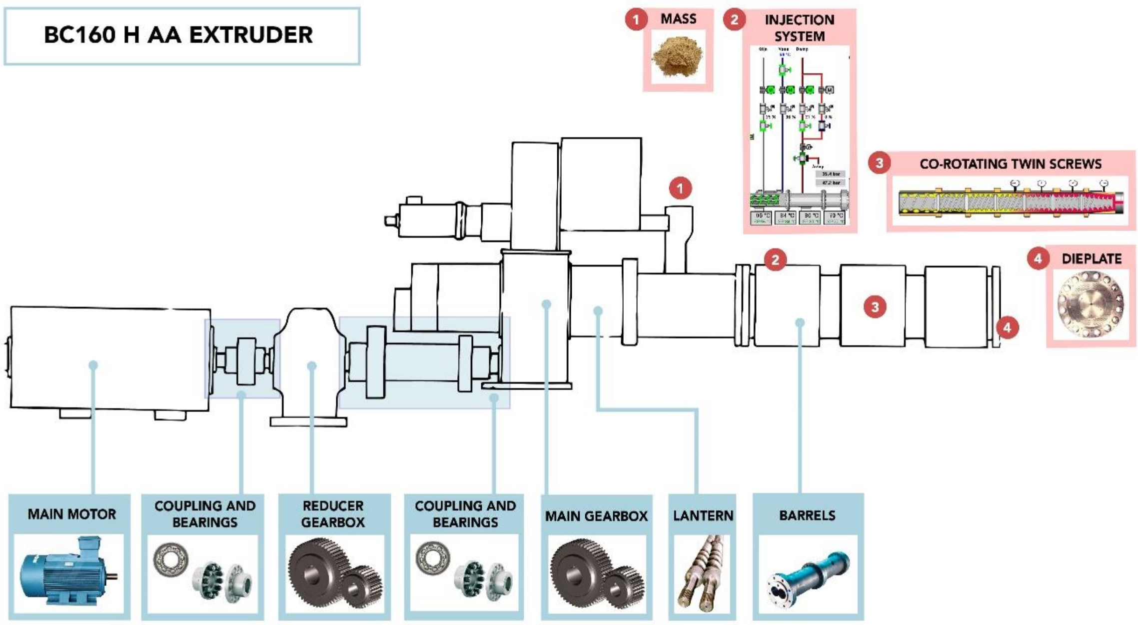


Figure 23 Functional architecture and critical parts.

1. The preconditioned mass enters the bypass chute of the extruder.
2. The mass is transported into the barrel module and mixed with water, steam, and oil.
3. The saturated mass is mixed into correct quality based on time, temperature, pressure, liquid and oil content percentages, and the SME produced by the twin co-rotating screw elements inside the barrels.
4. The mass reaches the end of the barrel, where the highest pressure-profile exists. Here, the product is pressed through the dieplate, exiting our system boundary, and making the product expand and enter the cutting box that cuts the product into pellet size.

By breaking down the functions of the extruder into a system view, we can create an idef diagram to illustrate the inputs, the processes, and the controls of each step of the extrusion process. See Figure 24.

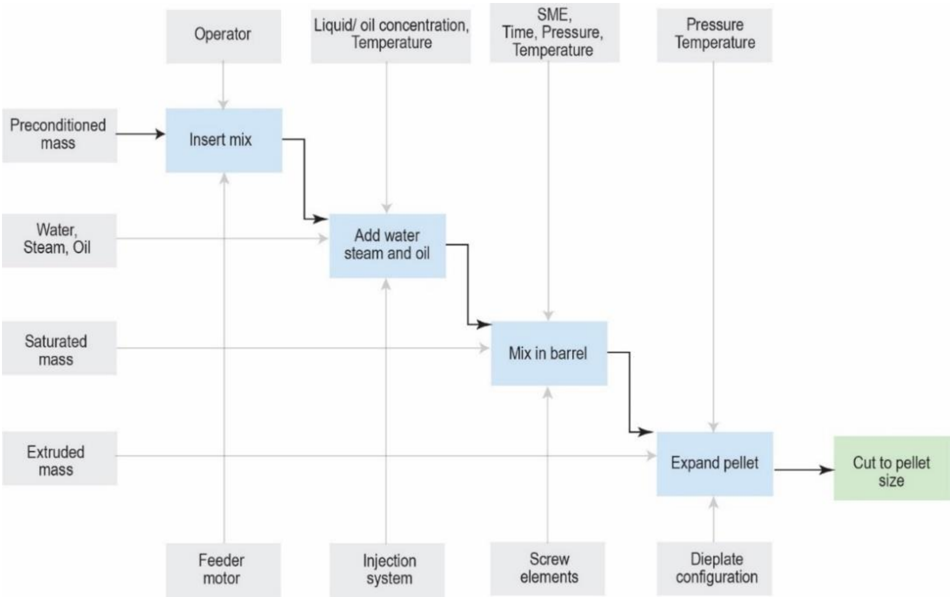


Figure 24 Idef of extrusion process.

4.1.4 Monitoring scenarios

The entire production line is closely monitored in real time by skilled operators with years of experience. A screenshot of the process monitoring display from an extruder line at Averøy is given in Figure 25. The picture is taken from an educational document in Skretting.

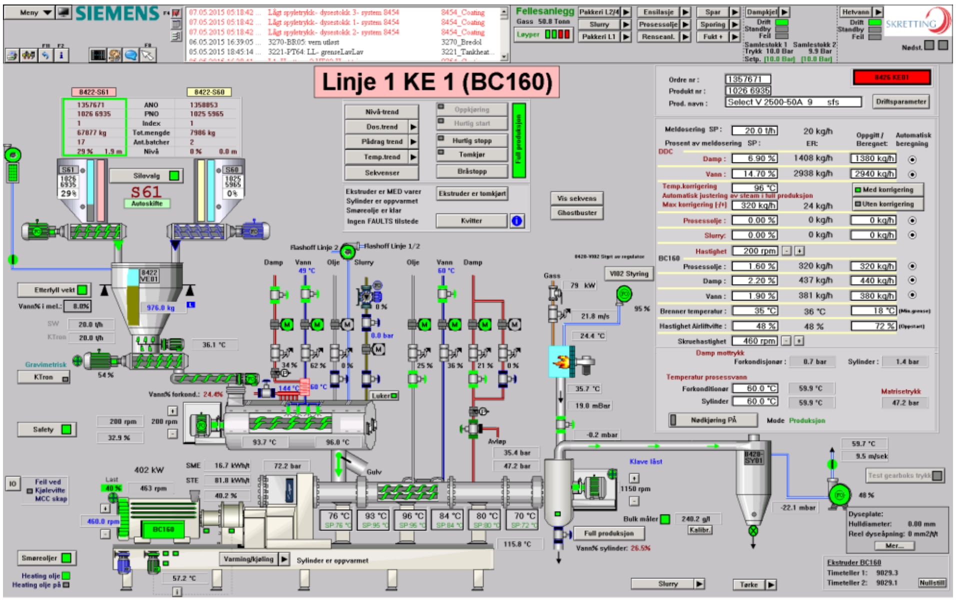


Figure 25 Monitoring of extruder line.

4.1.4.1 Process monitoring

There is one operator for each extruder line who is in charge of operating the extruder. In the operating room he has a real-time view of all the parameters that he needs to control in order to produce the product in the desired quality.

4.1.4.2 Quality monitoring

Quality monitoring is crucial. All the parameters of the production are closely monitored in order to take advantage of the starch in the product and obtain the desired expansion of the pellet so that the correct fat quantity and water percentage is reached. Key performance indicators for fish feed pellets are; bulk density, durability, fat leakage, hardness, water stability [46].

Real time monitoring includes personnel performing visual inspection of the pellets. Also, the DORIS test is performed to test the durability of the pellet. The DORIS machine is a piece of equipment with plastic paddles. The test is performed by putting pellets inside the machine where the plastic paddles impact the pellet and the pellet loses some mass. The mass loss is measured, and the resulting value should be somewhere in the range of 1-2%. If the mass loss is higher, e.g. in the range 3-5%, then glossiness will occur in the feeding system of the costumer which is not desirable.

4.1.4.3 Machine health monitoring

The PM tasks registered in the Computerized Maintenance Management System (CMMS) Plania regarding our system, are task numbers 2533 and 153 which can be seen in Figure 26 and Figure 27.

Periodic routine 2533 - Greasing main motor, 5 pumps per bearing	
Time interval	3 months
Calculation	40 g grease per 6000 hours = 30 g grease per 4500 hours (approx. 4500 h/year) = 7,5 g each 3 months = approx. 10 g = 5 pumps of 2 g
Description	Greased with special pump. Grease type "Alvania RL 3"

Figure 26 Periodic routine 2533 - Greasing main motor.

Periodic routine 153 - Extruder service		
Mechanical checklist	1	Control coupling between gear and shaft.
	2	Control bearings on shaft (Regularly).
	3	Control twisting of shaft (Regularly).
	4	Control/ tighten screw caps (Regularly).
	5	Wear measuring of sylinder and screw element (Regularly).
	6	Control screw elements.
	7	Control feeder.
	8	Control steam valve (Rust).
	9	Control coupling between motor and reducer.
	10	Control cooling fan on main engine.
	11	Control coupling between reducer and main gear.
	12	Control cooling circuit in cylinder.
Greasing	13	Control oil level on main gear; reducer; feeder and pumps.
	14	Oil test samples on main gear and reducer gear.
	15	Control greasing-oil pressure.
	16	Grease shaft bearings (Regularly).
Yearly	17	Oil change on main gear, reducer, pumps and feeder (Depending on sample).
	18	Change oil filter.

Figure 27 Plania: Periodic routine 153 - Extruder service.

Maintenance management aside from the scheduled tasks include those which arise when operators identify deviations in production. In these cases, the skilled workers on-site react quickly to perform inspections, correction, and feedback. Scenarios may include deviations in e.g.:

- Barrel temperature (Temperature monitoring)
- SME (Extruder engine effect)
- Feeding engines (Feeding rate monitoring devices)
- Water/ steam injection (Saturation monitoring)
- Pellet size (Output flow rate vs cutter speed)

Furthermore, a change in the SME parameter during the process monitoring may be a sign of degraded screw elements. The manual SPM vibration monitoring tool is used by the maintenance personnel when controlling the bearings. Other than this, there does not exist any machine health monitoring except for the audiovisual evaluation that the skilled maintenance and operating personnel performs when they are working with the extruder.

4.1.4.4 System view of monitoring scenarios

In Figure 28, Figure 29 and Figure 30, the process, quality, and health monitoring system views are given.

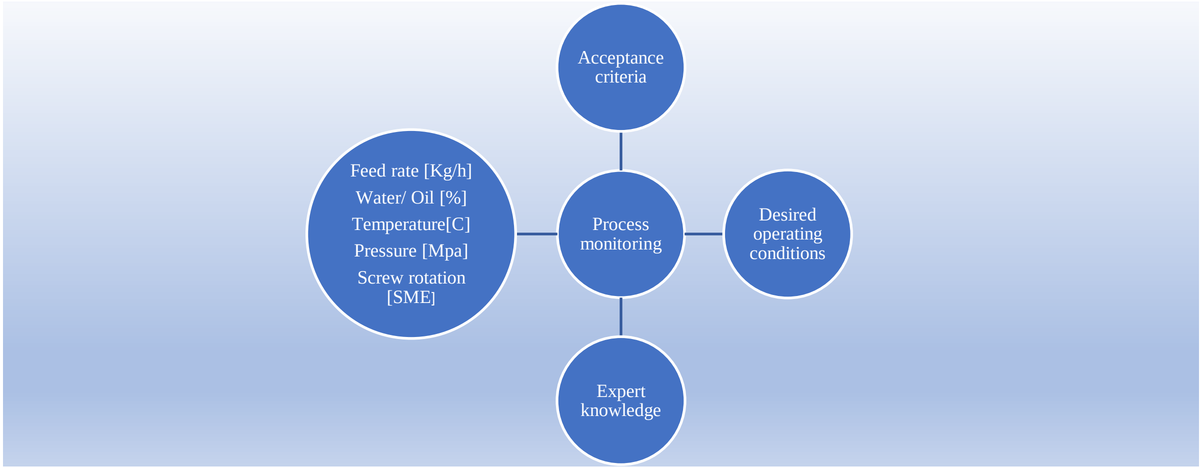


Figure 28 Process monitoring system view.

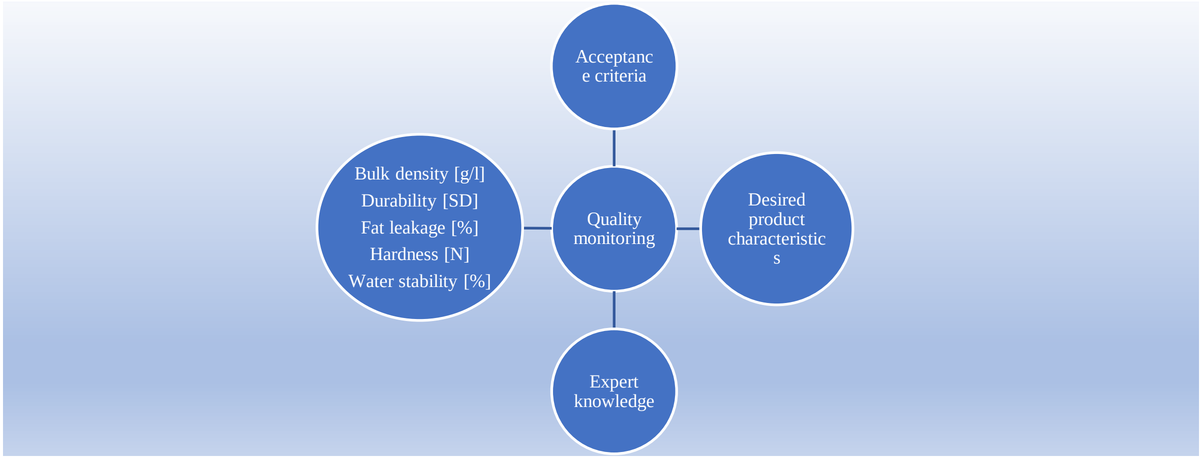


Figure 29 Quality monitoring system view.

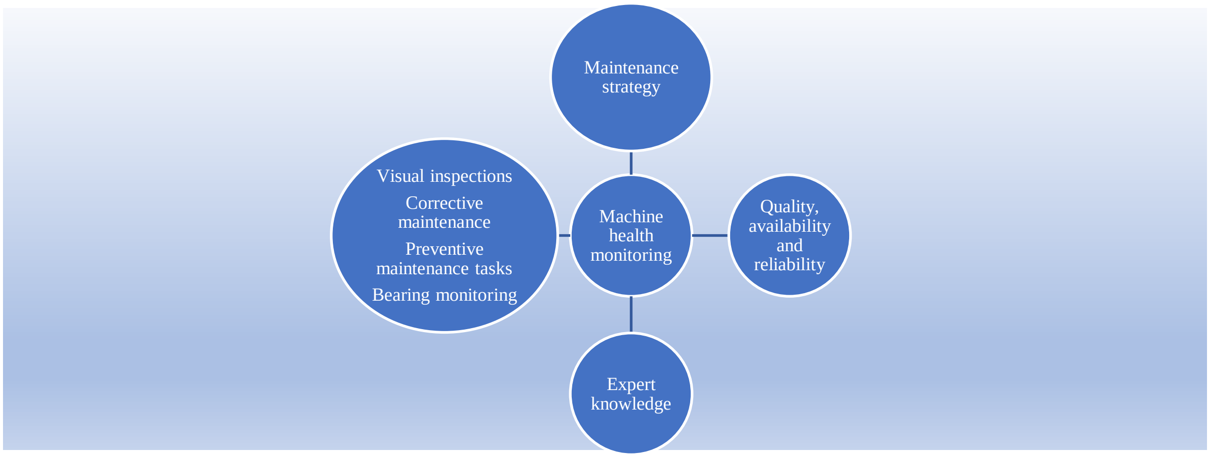


Figure 30 Machine health monitoring system view.

4.1.5 System stakeholders

Through interviews and observations, the stakeholders of the system are identified, and their needs are documented. The resulting criteria are given in the Stakeholder Requirement Specification [47] in Table 14.

Table 14 Stakeholder Requirement Specification.

Stakeholder	Needs	Requirements	Criteria
Management	A system that works when they need to produce a work order ordered by a customer.	**Maximum uptime to the minimum amount of effort**, Profitability, avoiding unplanned downtime, fulfilling regulations.	Availability, Reliability, Cost-effective.
Operators	A stable system that creates a product with high durability and water stability.	High SME, Stable input parameter (Non-fluctuating).	Performance, Stability.
Maintenance staff	A durable system that indicates when it is about to fail. Ability to perform corrective measures in a rapid manner when needed.	Avoid foreign object being able to enter the system under production. Ease of access, communication, and documentation of work orders.	Maintainability, Accessibility.
Quality control staff	A system giving legible output concerning product's accurate composition according to individual requirements.	Stable parameters.	Stability.

4.1.6 System context

We have identified the system boundary, the physical and functional architecture of the system, along with the needs of the stakeholders. By identifying and documenting these in a systematic manner, we have gained a clear system context. An illustration of this is given in Figure 31. In the next chapter, we focus on which failures modes can occur that can affect the criteria of the relevant stakeholders.

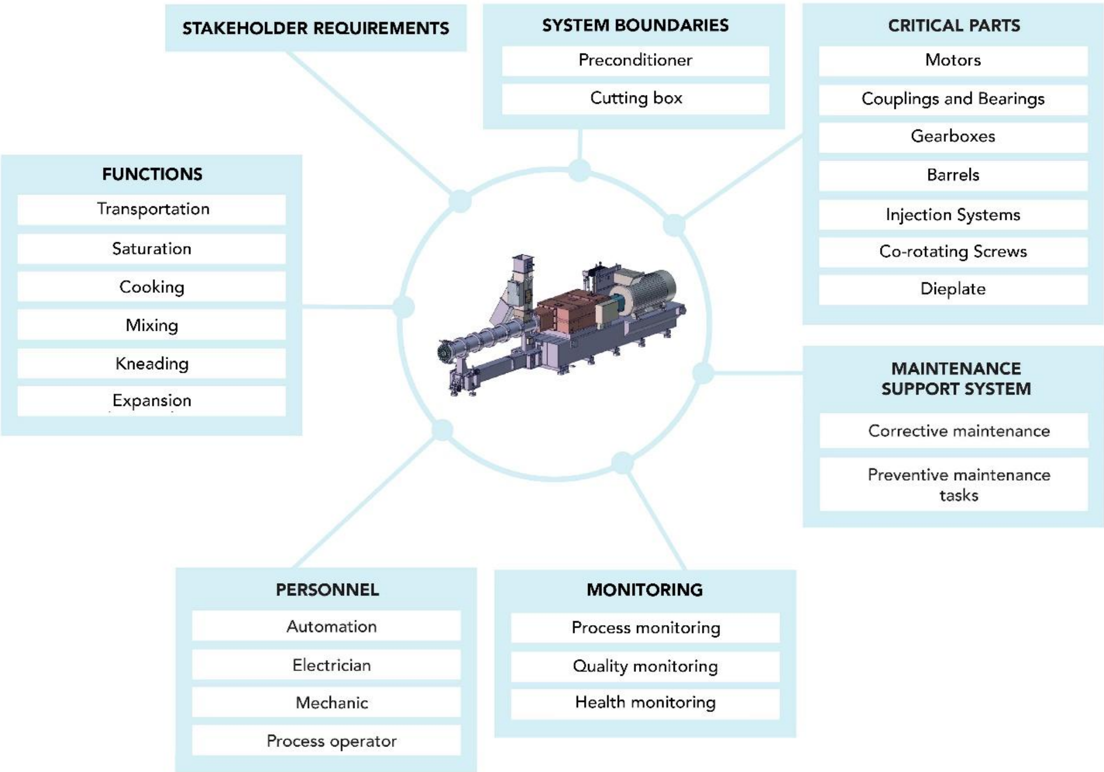


Figure 31 Extruder system context.

4.1.7 *Failure scenarios*

Through discussions with the management, maintenance personnel, and on-site operators, four scenarios have been identified where the extruder might fail to the extent of stopping the production process or result in losses:

1) The pre-conditioner is equipped with a series of small paddles connected to the two drive shafts which mixes the product before it enters the extruder. A paddle might come loose and enter the extrusion process, which might result in breaking the drive shaft. The other drive shaft still connected to the gear box could then make the gear box break down.

2) The oil, water and steam injection system can malfunction, causing the mass inside the extruder to solidify. This can cause the extruder to clog and stop.
3) The drive shafts can break due to a fatigue crack failure. This can in addition have the stated consequence of breaking the main gear box.
4) The screw elements connected to the two drive shafts that produce the mechanical energy needed in the product may need to be changed during production.

Breaking down the scenarios using the FTA tool, we obtain the fault tree illustrated Figure 32. Since the system boundary of this case study is the extruder, and the scope is rotating equipment, the two last scenarios will be considered. We see from this analysis that the application of interest is the twin co-rotating screws.

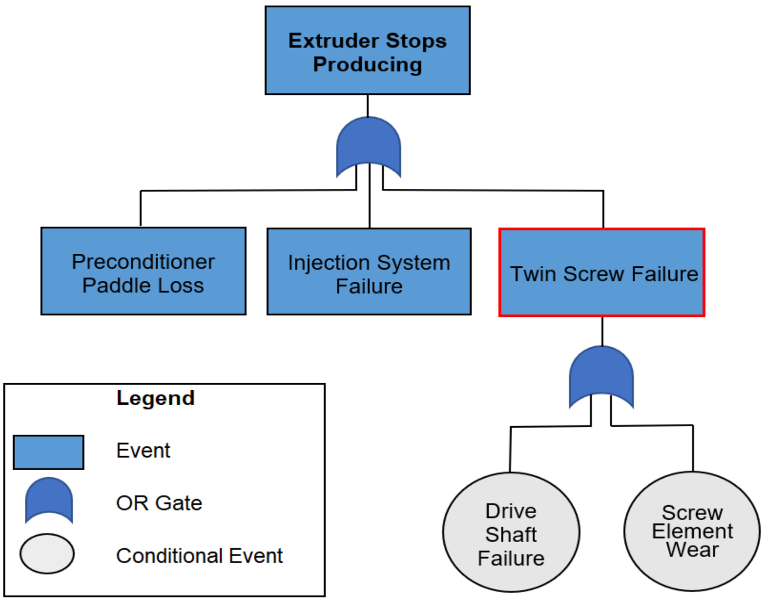


Figure 32 FTA of the Extruder application.

4.1.8 Application: Twin co-rotating screws

The driving force of the extrusion process are the twin co-rotating screw shafts. The function of the screw shafts is simple, they produce the rotational mechanical energy in the process. However, extrusion is a thermodynamic process in which heat, pressure, and mechanical energy affect the product to gain the desired properties. When we look at the driveshafts function in relation with the screw elements which are attached to them, the function becomes more complex. Various screw elements are put together in configuration to perform the functions of transportation, mixing of the product, and reverse flow. An illustration of the twin co-rotating screw shafts with various screw elements is given is Figure 33.

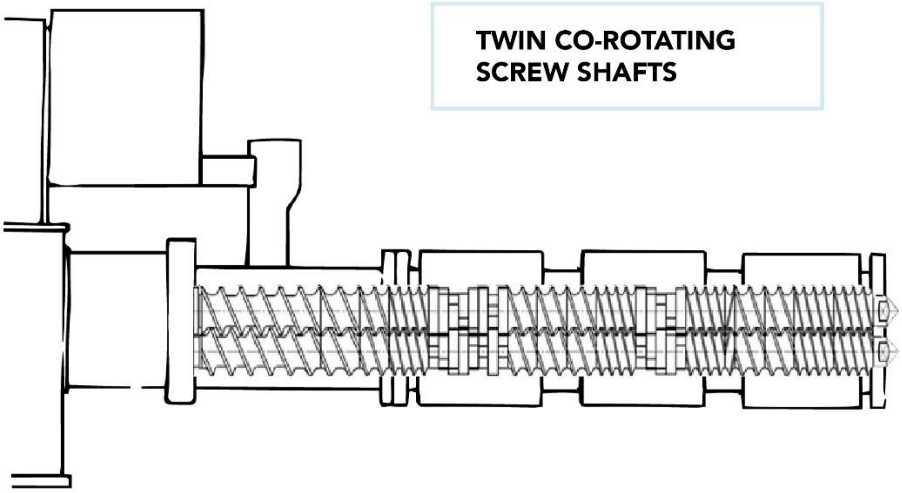
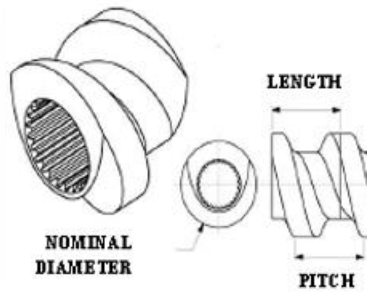
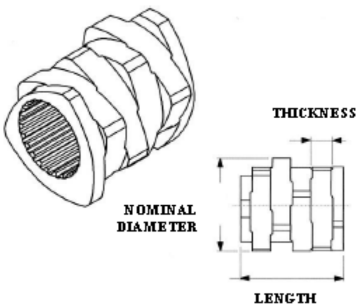
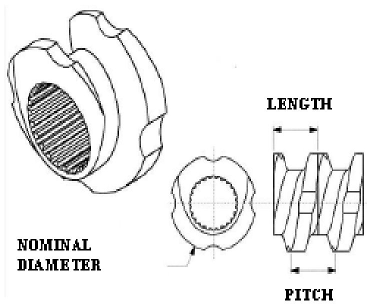


Figure 33 Application: Twin co-rotating screw shafts.

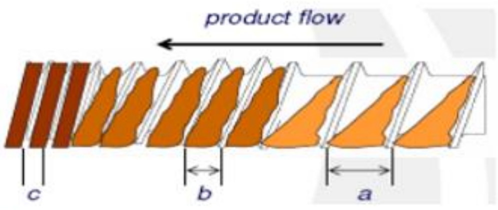
Some transport elements, mixing elements, and reverse elements are given in Table 15.

Table 15 Transport and mixing screw elements.

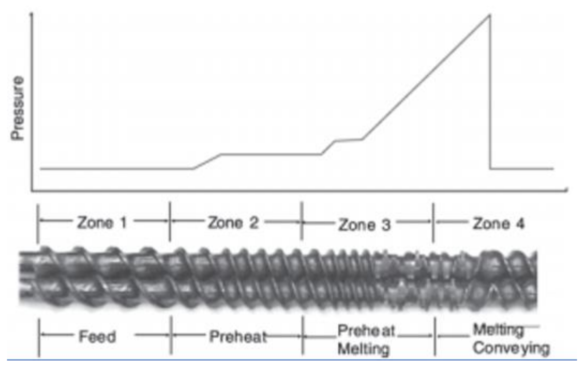
C1F: Conjugated section 1 thread – **Transport and compression of the material.**	**BL05:** Block of MAL2 (input) and MAL3 elements. **Mixing of the material.**	**CF1C:** Conjugated screw segment section 1 thread – **Reverse elements**
		

In Table 16 to the left is a figure illustrating how the screw parameters pitch and length affect the product flow. When the pitch is short, there is a high degree of fill and longer residence time. To the right, a figure from the extrusion handbook illustrates the pressure profile inside the extruder, which is dependent on the screw element configuration [48, p. 126]. We identify the extrusion phases; feeding/conveying, preheating/compression, melting/mixing, and pumping/conveying.

Table 16 Screw parameters and barrel pressure profile [48].



Part	c	b	a
Pitch	short	medium	long
Degree of fill	high	medium	low
Residence time	long	medium	short



The pressure profile and the residence time will vary depending on the zone that the product is in, and the pitch of the screw elements in that zone. In the BC160 extruder, the pressure profile will be the highest at the end of the barrel towards the dieplate. The desired operating parameters may vary depending on which product is being produced, but generally when producing high-energy feed, the conditions inside the extruder are close to what is illustrated in Figure 34.

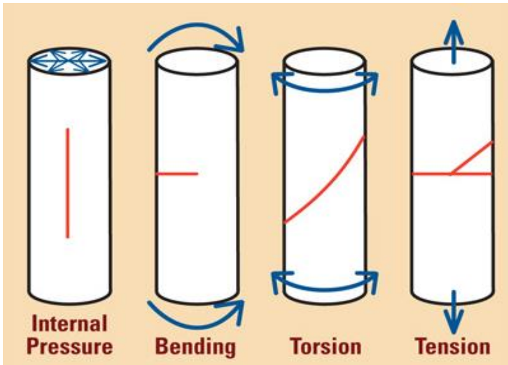
Illustrated operating conditions		
Parameter	**Value**	**Unit**
Screw motor speed	320	Rpm
Extrudate	1400	kg/h
SME	30	kWh/t
Pressure	30-40	Mpa
Temperature	<140	Celcius
Moisture	25	%

Figure 34 Extruder operating conditions.

4.1.8.1 Screw shaft fatigue crack fault

The relevant failure mechanism for the screw shaft to break is fatigue crack propagation in the fixed part of the drive shafts. See the left figure in Table 17. In the right figure there is an illustration of the four types of forces that can cause a fatigue crack propagation; internal pressure, bending, torsion, and tension [49]. Sachs claims that cracks always grow perpendicular to the plane of maximum stress, so a failure typically provides strong clues to the type and magnitude of forces on the shaft and the direction they acted in.

Table 17 Illustration of fixed end of screw shafts and types of fatigue cracks [49].

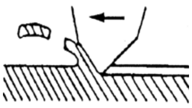
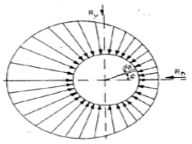
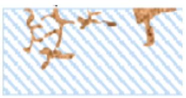
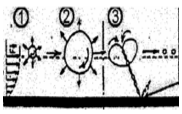
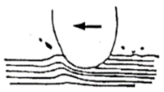
The drive shafts on the extruder may break as a standalone event, or the breaking of one shaft could cause the other co-rotating shaft to lodge and consequently break the main gear box. According to information given by the management at Skretting, there have been 4 serious breakdowns where the extruder main gearbox has been damaged, and 6 shaft breakdowns that could have led to an extruder gearbox breakdown. These events are from the five extruder lines equipped with the BC160 extruder in a time period of 10 years.

The average downtime in the event of the gearbox breaking down is 48 – 72 hours depending on when spare parts are available, and 6 – 12 hours if the gearbox is not damaged. Spare parts are shared, so range includes transport time from spare part location to breakdown location. What one could gain from monitoring this failure mode would be to schedule when the drive shaft can be changed before it breaks in a period where maintenance is planned to be performed and knowing that it is not changed too early. The value is related to saving the cost of the spare parts, transportation, and man-hours needed for CM, and more effective spare part utilization.

4.1.8.2 Screw element wear

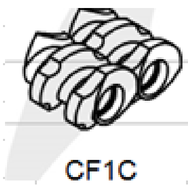
The failure mechanism for the screw elements is wear. There are several wear types that occur in different places in the extruder barrel for different reasons. In Table 18, an overview of the wear types and causes is given.

Table 18 Screw element wear types and causes.

Wear type	Illustration	Description
Abrasive		Contact between two surfaces with different hardness. Many of the ingredients used in the recipes can be very hard. This gives them a substantial abrasiveness property.
Adhesive		Peripheral pressure distribution causes the screw to move. This leads to direct contact between the screw and the cylinder wall. At the microscopic level, the steel in the extruder has a very rough finish and can lead to the formation of cold welding.
Corrosive		Some ingredients in some recipes may have a corrosive effect. For example, flavoring additives that are alkaline or special chemicals. Significant PH changes will affect the steel. Usually a localized damage after a chemical reaction between raw materials and metal surface.
Cavitation		As the melt melts move from one section to another in the extruder, a marked pressure drop will occur. If the change in pressure is high enough, the liquid can boil immediately. The bubbles that are formed will then implode and form shock waves. These waves cause the metal to vibrate ultrasonically, which in turn leads to metal damage.
Laminar		Repeating cycles of stress/ strain in the metal leads to deformation and metal fatigue

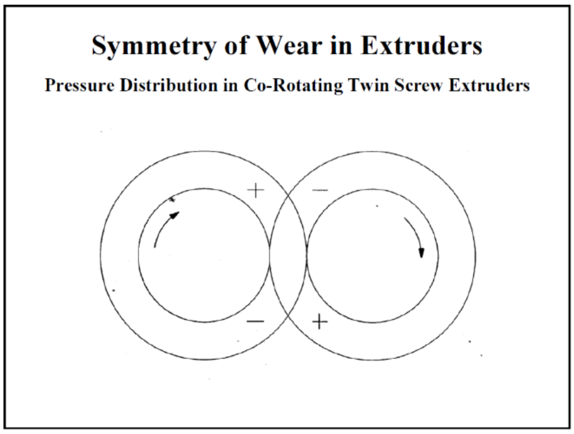
The various screw elements are subjected to different types of wear which is given in Table 19.

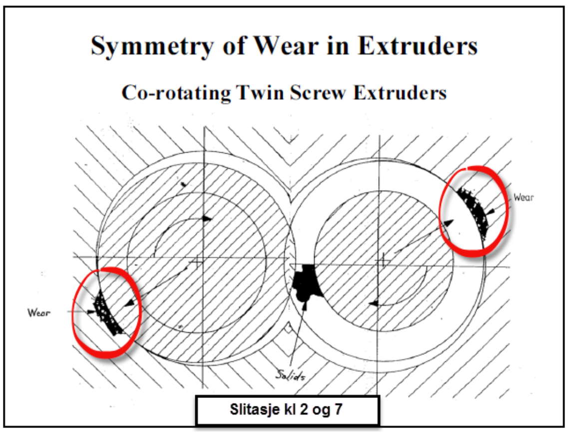
Table 19 Characteristic wear types subjected to various screw elements

Screw element	Illustration	Wear types
Transportation		Abrasive, adhesive, and corrosive wear.
Mixing and kneading		Adhesive, corrosive, cavitation, and laminar wear.
Reverse-element. (Mixing and kneading)		Cavitation and laminar wear.

Furthermore, there is a characteristic pressure distribution inside the barrel module which can be viewed as “2 and 7 o’clock”. In Table 20, an illustration of the symmetry of wear in the barrel is given.

Table 20 Symmetry of wear in extruders.





The consequence of the wear of the screw elements becoming too big, is that the pressure near the dieplate will become lower and the temperature will be lower. The result is inability to obtain sufficient energy into the extrusion process, which can lead to a quality loss for the pellet e.g. the bulk weight measures 460 g/l instead of 440 g/l, which means the pellet is not able to expand as much as desired and there will not be enough free volume inside the pellet where it can store fat.

The screw elements are inspected 2-5 times before they are changed, which generally happen 2 times a year. The inspections are manual measurements of the clearance in the screw element from the barrel output. Due to an exponential wear characteristic of the screw elements, they may deteriorate to the point where it is necessary to stop production to inspect and change them. The reverse elements are typically changed 4-5 times before a transport element is changed.

What one could gain from monitoring the health of the screw elements would be to avoid unnecessary inspections and schedule the changing of the screw elements to a period where maintenance is planned to be performed and avoid unplanned downtime and eliminate the risk of needing to reproduce the product.

4.1.8.3 Criticality analysis

In Table 21, a risk assessment has been performed on the failure modes identified in the FTA. The RPN's are based on the tables presented in chapter 2.3.1.2 and the author's degree of knowledge of the system.

Table 21 Risk analysis.

	Severity	Occurrence	Detection	RPN
Crack	9	2	9	162
Wear	6	7	3	126

We see that the RPN of the crack is based on a high severity, low occurrence, and difficulty of detection. The wear failure mode has a lower consequence but has a relatively high occurrence related to the inspections needed to detect it.

4.1.8.4 Failure symptom description

The symptoms that these failures modes are expected to show are:

1) A growing fatigue crack will affect the forces exerted by the shaft when it rotates which should affect the harmonic oscillations produced by the system.
2) When the screw elements lose mass due to wear it will affect the natural frequency of the system.

4.1.8.5 Pugh matrix

Using the system knowledge and stakeholder criteria, we evaluate the key conceptual condition monitoring techniques identified in chapter 2.1.3 in a Pugh matrix given in Table 22. The following assumptions are made based on the author’s knowledge:

- Oil-debris has been taken out of account since there is no oil in the selected application to be monitored.
- Thermography has been eliminated. It is assumed that the heat caused by crack propagation and the wear of the screw elements will not be possible to detect since it will be conducted to the product.

Table 22 Pugh matrix evaluation of condition monitoring techniques.

PUGH MATRIX			
Conceptual system design alternatives			
	Vibration monitoring	**Process parameter monitoring**	**Acoustic Emission monitoring**
Cost-effective	0	2	1
Stability	1	0	2
Reliability	1	-1	-1
Maintainability	2	2	0
Availability	2	2	1
Accuracy	2	0	-1
Total score ∑	8	5	2

Acoustic Emission Technology can be used to monitor rotating equipment based on the sound it emits. The problem with using this technique on the extruder application is the scale of the machine and the amount of moving parts which could influence the sensors.

Process monitoring is already implemented to control the production process and the quality of the product. It would be more cost-effective to develop the program with this technique due to the already existing instrumentation. The problem is that it does not currently give any accurate diagnosis of the state of the machine and is therefore not reliable enough. It could however be used in addition to the vibration monitoring technique.

Vibration monitoring is a technique well suited for analyzing faults in critical rotational equipment. It can analyze the operating conditions of critical rotational equipment in real time and compare to acceptance limits. Considering the application, the implementation of vibration monitoring is well justified [50]. In the field of machinery vibration monitoring and analysis, a variety of relevant standards are developed and published by ISO [13].

4.2 Development of Predictive maintenance programme

The 7-layer intelligent maintenance model proposed in chapter 2.2.5: Industry 4.0 and intelligent maintenance is here presented in Figure 35. The model illustrates the logic of the seven layers with the cost-effect analysis in the center. In this chapter we demonstrate how to develop a PHM system using the seven-layer structure of this model.

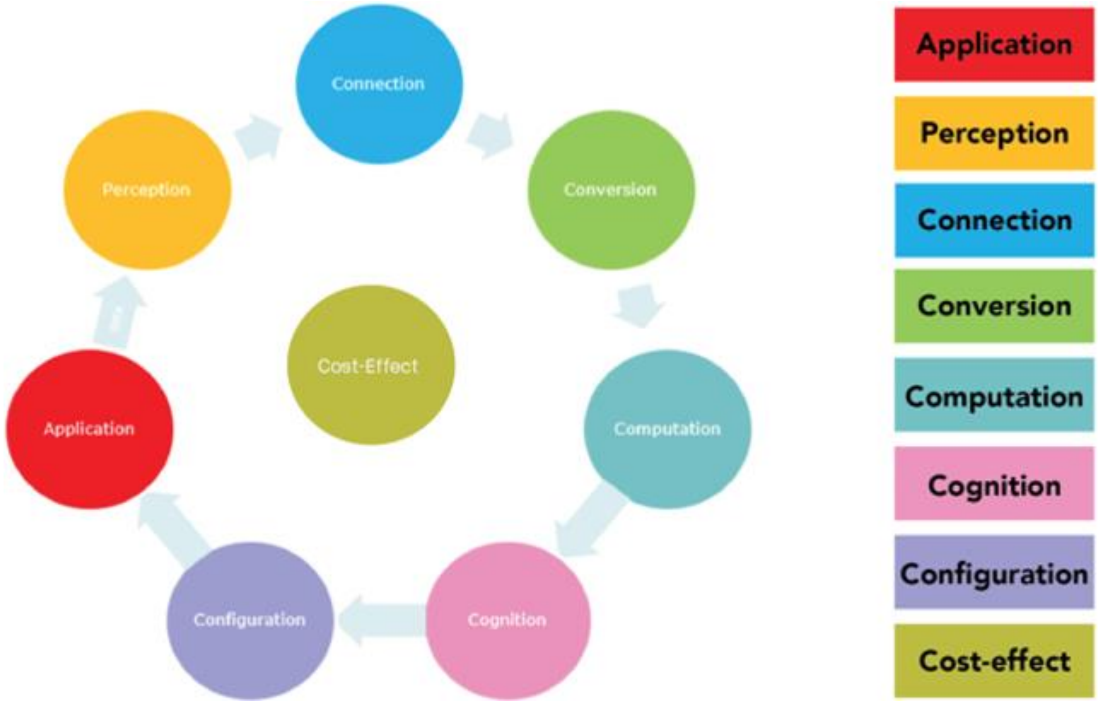


Figure 35 7-layer intelligent maintenance model.

4.2.1 Application

Through a system analysis we gained a system context of the extruders critical components, the functions they perform, and the operating conditions. Based on this knowledge, a failure analysis showed that the wear and fatigue crack faults are the most critical failure causes within the selected critical system, and the vibration monitoring technique has been evaluated as the most suitable to build the programme. The faults are related to the twin co-rotating screws application.

4.2.2 Perception

The application has been chosen and the symptoms that the identified faults exert has been analyzed. The aim is now to build a monitoring system that enables maintenance decision support related to detection of these. The foundation of the digitalisation process is the creation of data. In order to produce data, we need to find suitable sensors.

Three parameters representing motion are displacement, velocity, and acceleration. Selection of a sensor proportional to these parameters depend on the frequencies of interest and signal levels that are involved [51]. Displacement sensors are used to measure shaft motion and internal clearances in low frequency (1-100 Hz). Velocity sensors are used for low to medium frequencies (1-1000 Hz), while accelerometers measure low to very high frequencies (10-40 Khz) [52].

Endevco gives with this report [53] some insights in the complexity of choosing between sensors which are offered in various technologies, shapes, sizes, ranges etc. Important aspects to consider are:

- Technology selection
- Measurement type
- Number of axis to be measured
- Frequency response
- Sensitivity and resolution
- Environment and mounting

Piezoelectric accelerometers are the most widely used and are the first choice due to their wide frequency response, good sensitivity, and resolution and, ease of installment. There are two subdivision of piezoelectric accelerometers which include the basic charge-mode accelerometer, and the voltage mode internal electronic piezoelectric (IEPE) types. Of these, the charge mode accelerometer type is most suitable to the extruder application due to its high temperature capability (-55 ˚C to 288 ˚C) on standard sensors, with special purpose versions available for temperatures up to 760 ˚C [53].

There are a number of ways to mount accelerometers, where by far the best mounting method is the use of threaded studs or screws mounting the sensor [53]. The mounting of the sensors directly impacts on its performance. Some standards of vibration monitoring (British Standards Institution, 2009) suggest using three mutually perpendicular directions, while other studies (Elbhah and Sinha 2013) use a single sensor to monitor bearings [54]. A paper on fault diagnosis of rotating machines using an experimental rig suggests using accelerometers mounted horizontally and vertically to keep both data acquisition and processing simple, while preserving moderate computational load [55, p. 46].

A conceptual solution for the sensor setup of the extruder is given in Figure 36**,** with horizontally and vertically mounted accelerometers near the fixed end of the driveshafts as well as in the end of the barrel module where the most substantial wear occurs.

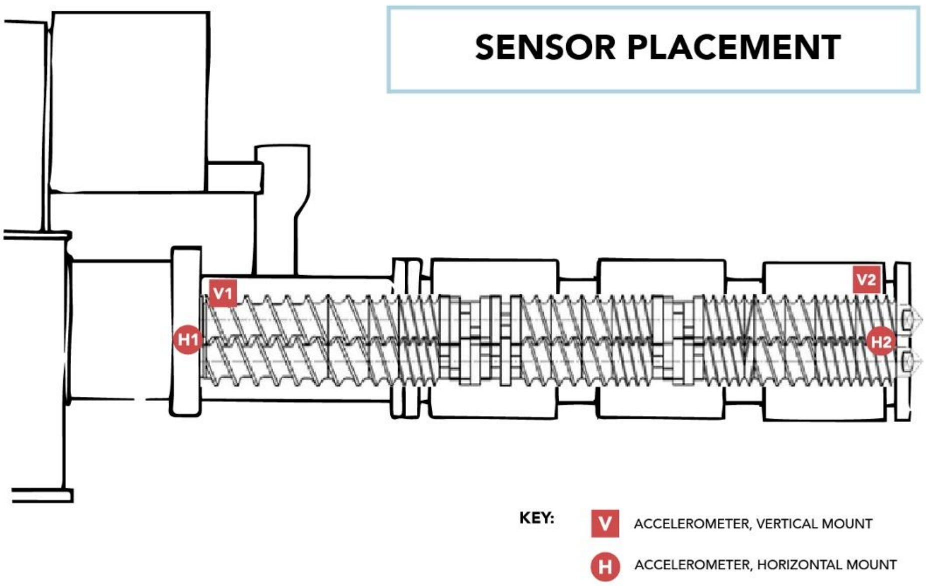


Figure 36 Accelerometer sensor placement.

4.2.3 Connection

There are different ways to connect sensors to various types of hardware for performing calculations depending on the type of system one aims to build. Due to the criticality of the machine, a continuous online monitoring system will be considered. In the referenced paper [55, p. 46], the vibration data were transmitted through two four-channel signal conditioners to a 16 Bit Analogue to Digital (A/D) Data Acquisition System, which was sent to a personal computer where a data logging software (MATLAB) was used to store the digitized vibration data. An illustration of how this setup would look on the extruder application is given in Figure 37.

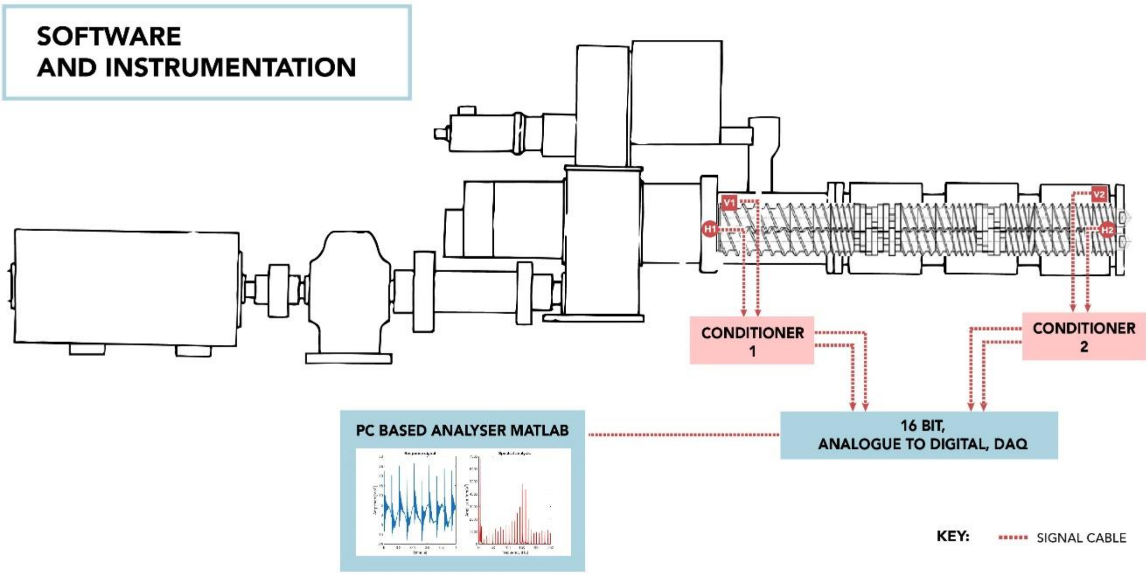


Figure 37 PHM software and instrumentation.

The proposed architecture is a proved. However, an important aspect to keep in mind is that the architecture of the proposed PHM system should be able to include more applications without any substantial changes. A wireless connection solution is therefore illustrated in the following.

A recent report (2016) on the feasibility of fully autonomous wireless health monitoring of wind turbine blades, showed that using piezo devices in a wireless sensor network with a microprocessor sending signals to a radio transmitter was a viable solution [56]. A report presenting the implementation of a wireless sensor network on a real application can be used as an inspiration. A wireless sensor network was used to monitor the environment of an instant coffee production process inside a factory [57] where they used the application structure illustrated in Figure 38.

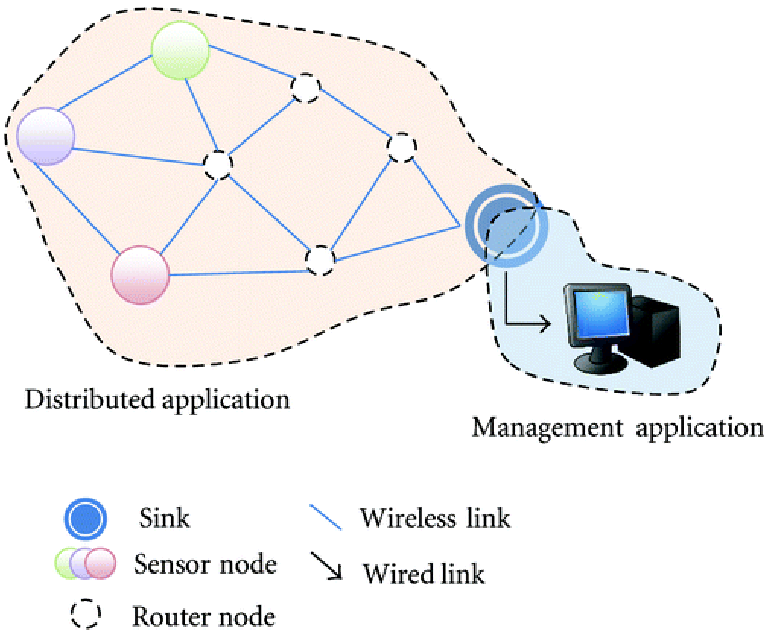


Figure 38 Wireless sensor network architecture [57].

The architecture is built out of two groups where each has its own software. The distribution application works like a router node where the signals from each sensor is sent to a sink node that works like a gateway between the network and the PC. The sink node can then translate the information to the management application running on the computer via wired link, or to a private, public, or hybrid cloud storage solution [58]. Further opportunities can then be realized with the use of CC. The scalability of this setup would depend on the chosen service provider and available software.

For the cost-effect analysis we will use a solution given in an offer by the service provider SKF. The four sensor locations illustrated in Figure 37 are used with two spare sensors and a single 8-channel conditioner unit connected to SKF’s cloud solution which the management application can collect data from.

4.2.4 Conversion

When data capture has been realized through the setup of sensors with corresponding connection to suitable data acquisition tools, we must process the signal. Real world vibration measurements often contain a lot of signal components originating from different machine elements. There are many techniques that can be used to filter out other components in the signal e.g. Time-Synchronous Averaging (TSA), Self-Adaptive Noise Cancellation (SANC), Discrete/Random Separation (DRS) and Cepstral Editing Procedure (CEP) [59].

Not only is it necessary filter out noise from other components, the signal itself also needs to be pre-processed to achieve the final relevant output. The signal is processed with the following steps [36]:

1) Analog signal input
2) Anti-alias filter
3) A/D converter
4) Overlap
5) Windowing
6) Averaging
7) Display/storage

4.2.5 Computation

In this chapter we produce frequency spectrums for simulated vibration signals of the identified machine faults. The data used in this computation is a set of 50000 data sampled in a time period of 48 seconds, which is created as two column vectors in Excel.

The time-domain response signal and the frequency-domain spectral analysis is plotted using MATLAB.

4.2.5.1 Wear fault

The analysis illustrates how the vibration data looks like in a normal operating state (reference case), and a state where the fault is present (secondary case). In Figure 39, the time response signals (for the reference case and secondary case) for the screw element wear fault is plotted for a period of two seconds.

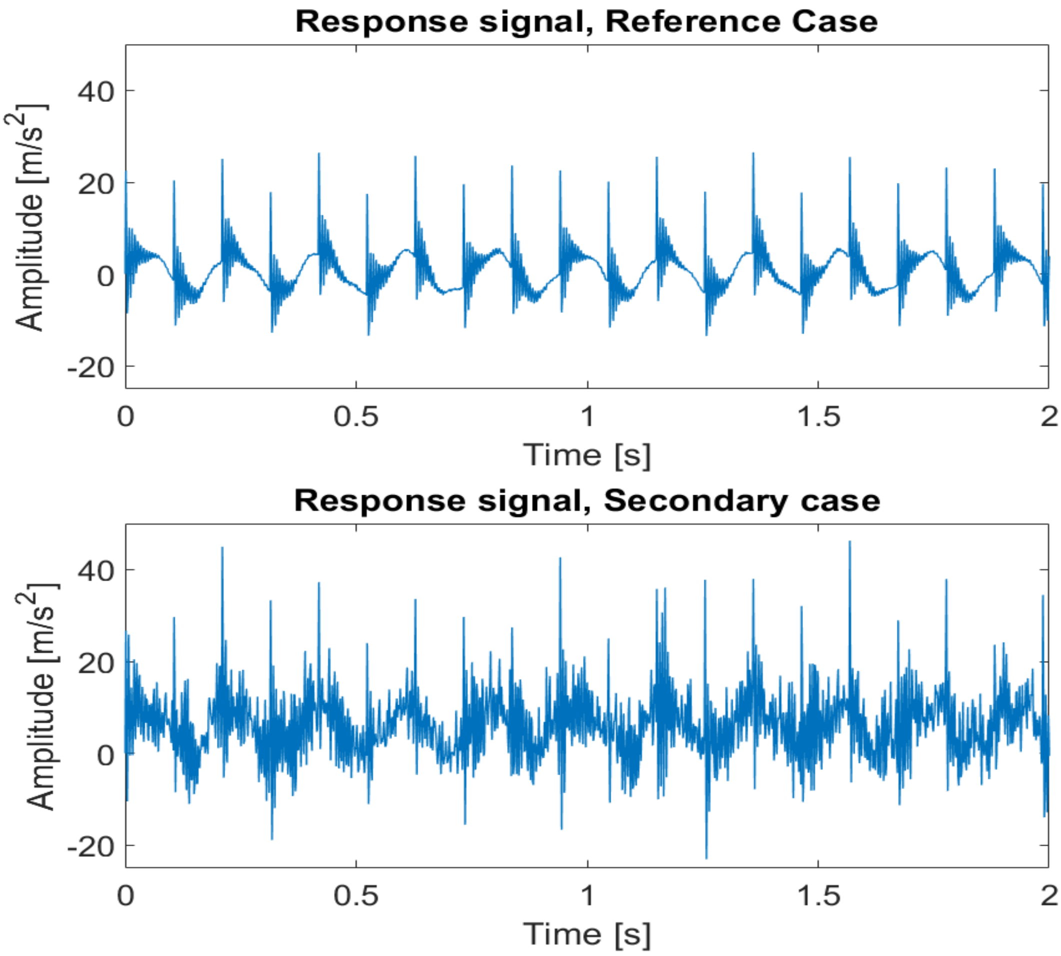


Figure 39 Wear fault time-response signal.

Sampling 4096 data points and using the FFT and IMABS (Imaginary Absolute Value) functions in Excel, gives us the relevant output we need to plot the frequency spectrums in MATLAB. We find the step frequency which is (3):

$$F_{step} = \frac{1}{T} = \frac{1}{6.11194} \tag{3}$$

Where T is the total time that the 4096 data occur. The spectral analysis plot for the wear fault is given in Figure 40.

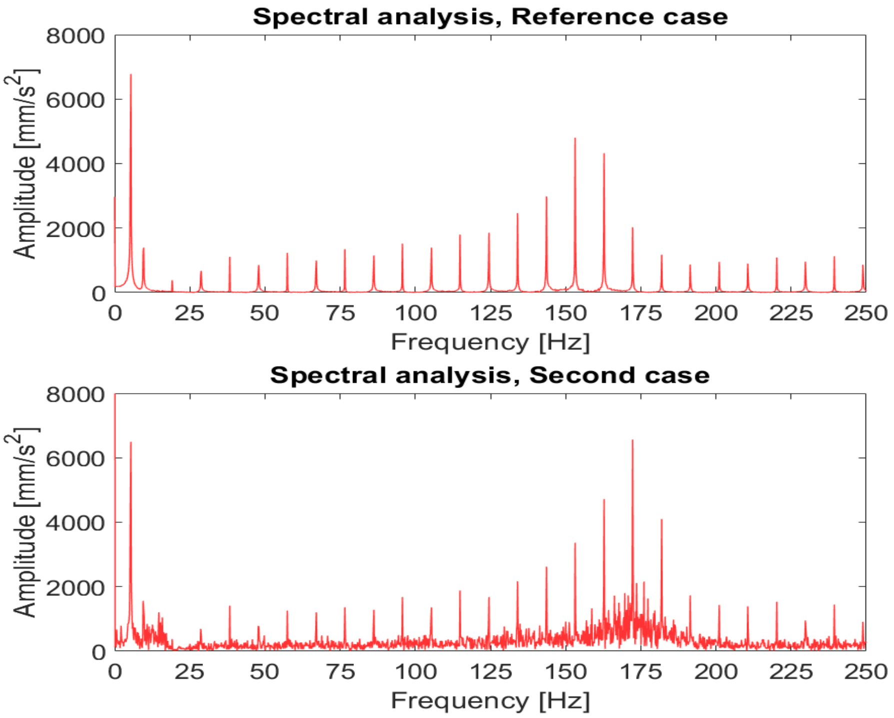


Figure 40 Wear fault frequency spectrum.

4.2.5.2 Crack fault included

The following data sets are simulated with both faults present and computed in the same way as in 4.2.5.1. See Figure 41.

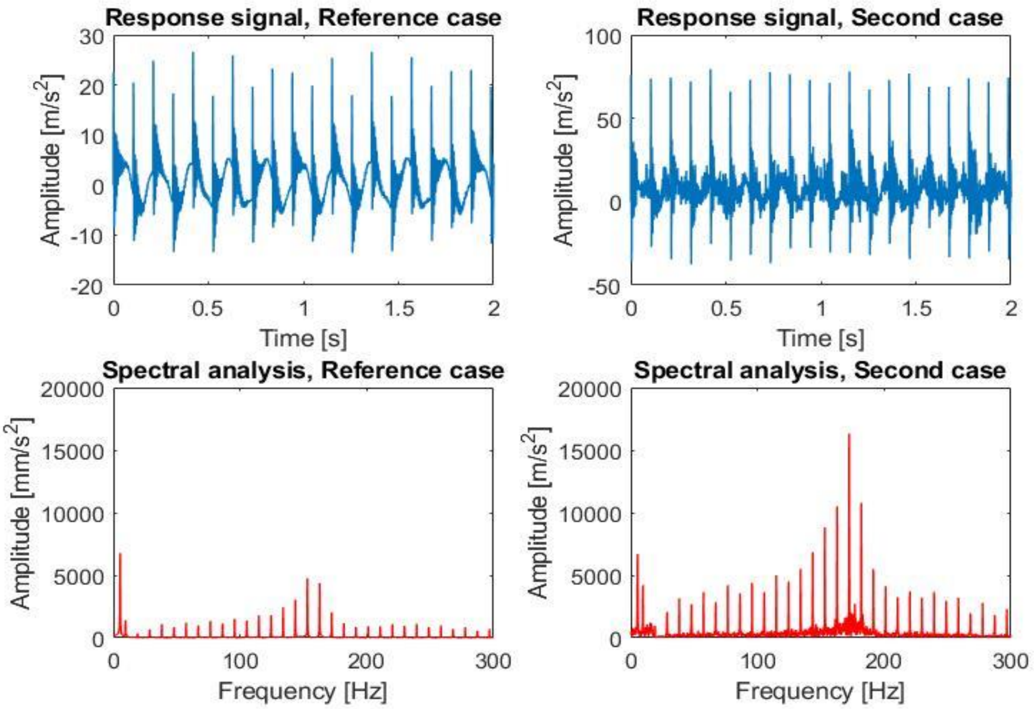


Figure 41 Response signal and spectral analysis for crack and wear faults simultaneously.

4.2.6 Cognition layer

When the time and frequency domain spectrums have been obtained, we can use them to diagnose the faults. Since we know the physics of the symptoms, we can use a model-based approach.

4.2.6.1 Diagnosis

Looking at the reference time-response signal for the normal operating state, we count 10.5 cycles in 2 seconds and find the operating speed (4) to correspond well with the extruder's operating conditions (320 Revolutions Per Minute (RPM)).

$$\frac{10.5}{2}\left[\frac{cycles}{second}\right] * 60 \left[\frac{seconds}{minute}\right] = 315\ RPM \left[\frac{cycles}{minute}\right] \tag{4}$$

4.2.6.1.1 Wear fault

We have assumed that when the screw elements lose mass due to wear, it will affect the natural frequency of the system. The equation (2) for natural frequency is:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2}$$

Where k is the stiffness related to the material, and m is the mass. We see that when the screw elements lose mass, the natural frequency of the screw elements will become higher. By monitoring the natural frequency peak of vibration amplitude in the area of 100 to 200 Hz such as illustrated in Figure 42, we can set an acceptance limit and diagnose accordingly.

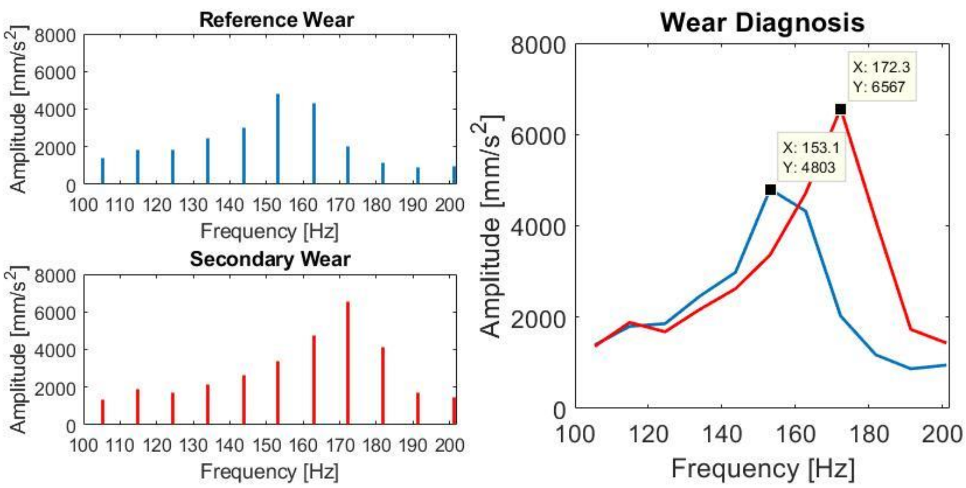


Figure 42 Wear diagnosis.

4.2.6.1.2 Crack fault

There are two characteristic symptoms of a crack shaft [60]:

1) The first is unexplained changes in the vibration amplitude relating to 1X RPM frequency due to the shaft bending as the crack propagates.
2) The other is an increased vibration amplitude in the 2X RPM frequency.

Figure 43 illustrates the change in the signal in the 2X RPM area. The crack fault can be diagnosed by setting an alert when the vibration amplitude exceeds a certain acceptance limit. The acceptance limit should be set in relation to how the wear characteristic of the shaft looks like, and the time it takes from symptoms arise to failure state.

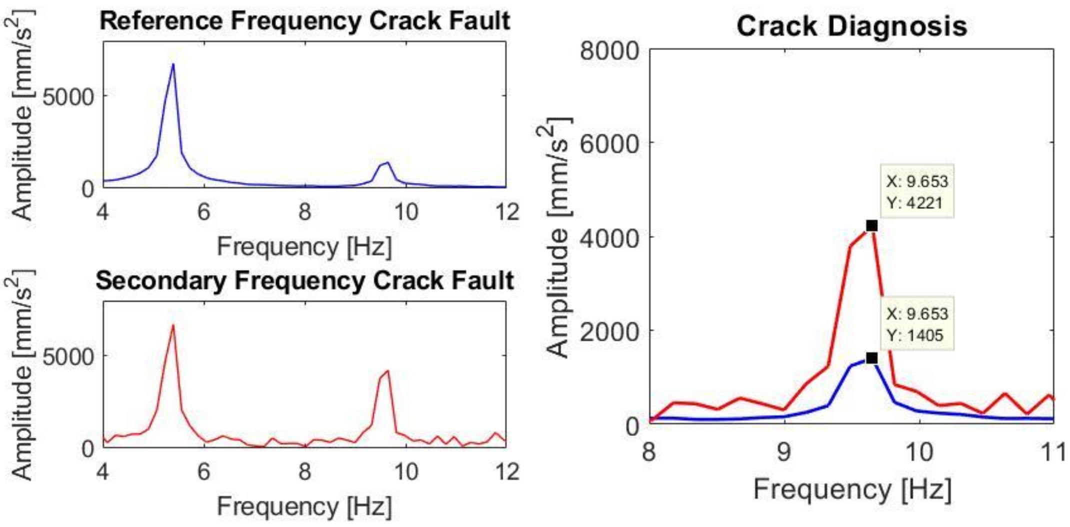


Figure 43 Crack fault diagnosis.

4.2.6.2 Prognosis

Diagnostics of machine fault identify the damage that has occurred, while prognostics is concerned with predicting the damage that is yet to occur. Prognostic modelling for RUL of assets is a research field that has received a lot of attention. There exist many prognostics options, which can be grouped in Knowledge-based (expert and fuzzy), Life expectancy (stochastic and statistical), Artificial Neural Networks, and Physical models [14]. In this chapter we illustrate how the knowledge derived trough discussions with maintenance personnel can be used to develop a simple prognosis model.

4.2.6.2.1 Wear fault

In the case of the wear of the screw elements, we know that there is a growing wear characteristic towards the screw elements end of life.

We assume that the time between our reference case and our secondary case is 6 months where the reference case is from when the screw element has just been changed (week 0) and the secondary case is from a state where the screw elements should be changed (week 24).

Based on these assumptions a data set is produced in Table 23 where the wear characteristic is trained with a 1% linear degradation the first two months.

Table 23 Dataset used for training wear fault degradation prognosis model.

Week	0	4	8	12	16	20	24
Frequency	153.1	154.631	156.17731				172.3

Based on the data provided in Table 23, a regression analysis is performed in MATLAB giving the quadratic polynomial prognosis line $f(t)$ (5):

$$f(t) = 0.025224 * \mathrm{t}^2 + 0.18965 * \mathrm{t} + 153.21 \quad (5)$$

Where f(t) is the frequency at natural frequency peak amplitude, and t is the time given in weeks from screw element change. The acceptance limit in the model is 172.3 Hz. An alarm is suggested at 165 Hz to provide management with sufficient time for maintenance scheduling. The prognosis model is given in Figure 44.

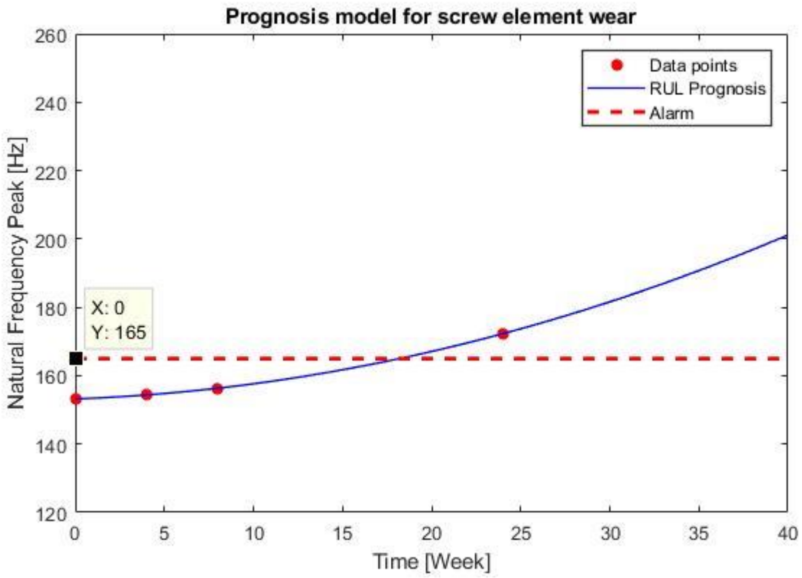


Figure 44 Prognosis model for screw element wear.

4.2.6.2.2 Crack fault

We assume that the crack propagation has a linear characteristic over a long period from start until the crack suddenly grows rapidly. We assume that the time between our reference case and our secondary case is 12 months, where the reference case is from when the crack starts growing (t = 0) and the secondary case is from a failure state where the drive shaft has failed (T = t + 12 months). Using a shape-preserving fitting with 5% monthly linear degradation, the prognosis model in Figure 45 is suggested.

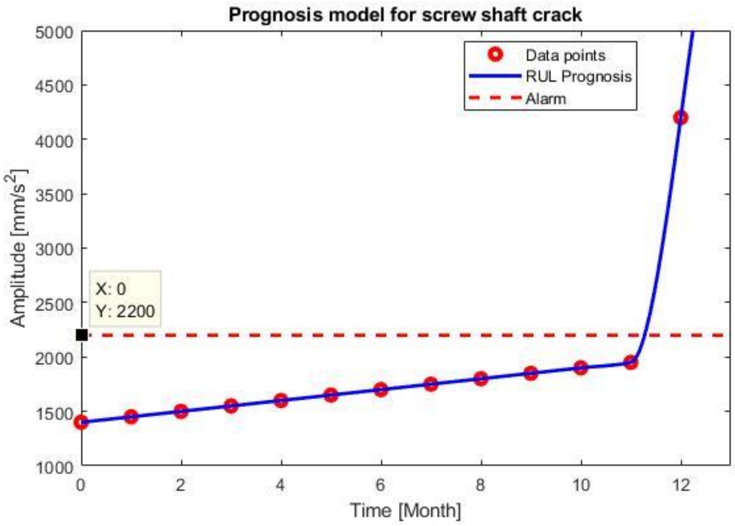


Figure 45 Prognosis model for screw shaft crack.

4.2.7 Configuration

The generated information shall lead to action. In the configuration layer the goal is to visualize the results from the analysis in a clear manner to provide maintenance decision support. The author suggests displaying current vibration amplitude and natural frequency in relation to the set limits at any given time to provide a health bar status with a number of the predicted time to failure state given in weeks for the two faults.

Augmented Reality (AR) technologies have been a research topic for many years, but some technical issues still prevent AR from being suitable for industrial applications [61]. For the sake of this case study, a tablet could be permanently installed on the extruder to show the data and enable maintenance support for operators. These simplified data can be displayed through an application or be integrated into the process monitoring software (Siemens).

4.3 Cost-benefit Analysis

4.3.1 Cost of PHM programme

Prices of sensors and instrumentation are unlisted and often sent in a customized version only to commercial customers. For the purpose of this cost-effect analysis, an offer provided by SKF for the PHM lab system currently being built at the University of Stavanger will be used as a reference. It is important to note that any software or hardware mentioned in this chapter is solely for the purpose of producing a cost estimate for the architecture of the system.

We use 10 years as the lifecycle cost of the system. The prices for the hardware is given in Table 24 and the cost for renting the cloud solution is given in Table 25. Remaining costs are assumed in Table 26.

Table 24 Installation cost - An offer including SKF IMX-8 device [62]

Product nr.	Description	No.	Unit price	Total price
CMON 4108	SKF IMX-8 Online system (Incl. CMON 4134)	1	19800	19800
SKF Enlight	Quick Collect sensor	1	9400	9400
Total		**29200 NOK**		

Table 25 10-year life cycle cost of cloud computation service.

Product nr.	Description	No.	Unit price	Total price
AMDS-CFCA	One-time activation and system setup	1	1050	1050
AMDS-HEAS-SC	Analyst single client – (Yearly rent)	10	1561	15610
AMDS HEAS-AC	Additional users (Yearly rent)	0	697	0
Total		**16660 NOK**		

Table 26 Cost of perception and configuration.

Item	Description	No.	Unit price	Total price
Sensors	4 accelerometers + 2 spares	6	3350 [63]	20100
Tablet	Illustration purposes	1	4490 [64]	4490
Total		**36760 NOK**		

4.3.2 Benefit from successful implementation

Figure 46 is a baseline optimal maintenance schedule provided by Skretting and modelled in MATLAB by the author. It is desired that all maintenance should occur within these planned intervals.

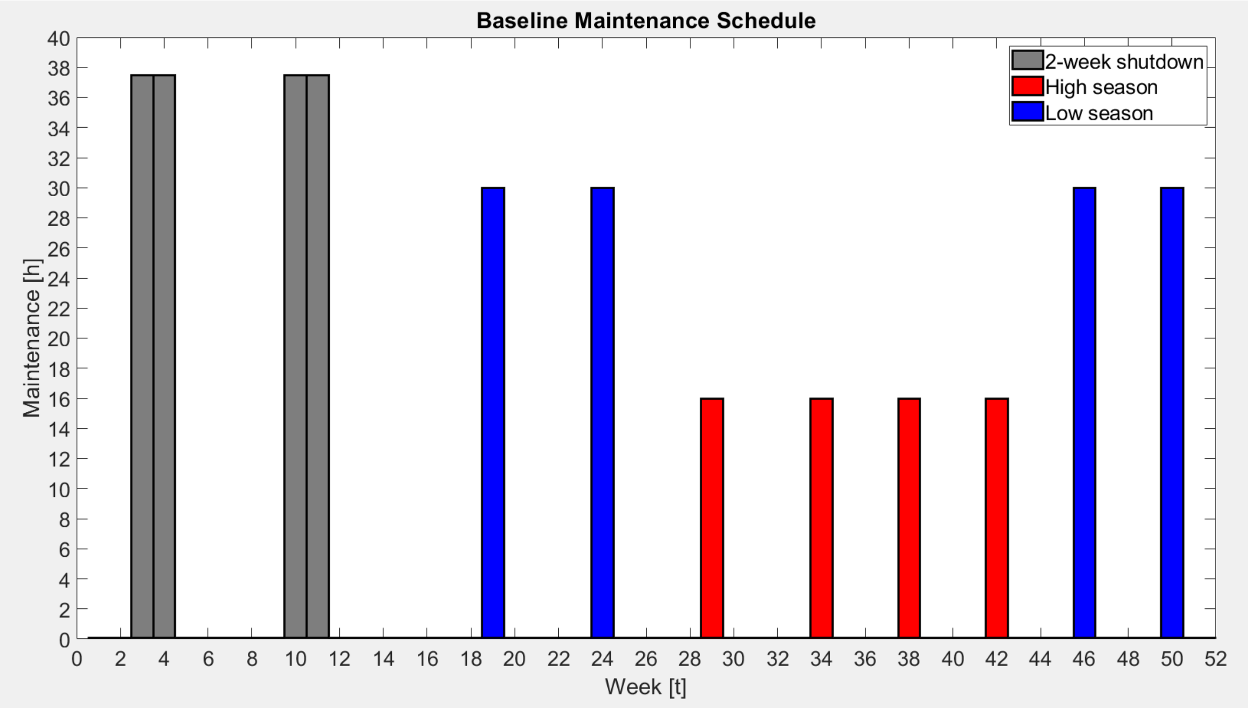


Figure 46 Baseline optimal maintenance schedule.

There are two 2-week periods of downtime for maintenance where it is possible to perform larger maintenance operations and upgrades. Other than that, there is one maintenance period each month. In the high season which is around week 26 to week 45 the planned maintenance is a period of 16 hours, while in the low-season the maintenance period can be up to 30 hours.

4.3.2.1 Screw shaft failure scenario

Based on information given by the industrial supervisor and from interviews of the maintenance personnel at Skretting in Stavanger, the following assumptions are made:

- Ten incidents in 10 years for 5 extruder lines gives a Mean Time To Failure (MTTF) [65] of 5 years for a single extruder.
- We can assume that in the event of a screw shaft failing it will have a 40% chance of destroying the gearbox.
- The cost of replacing shafts is provided in Table 27.

Table 27 Cost of drive shaft failure.

Component	Cost
2 shafts	420000 NOK
Alt. 1 New bearing block	195000 NOK
Alt. 2 New bearings and bushings	32500 NOK
Man-hours 2 men, 3 days	20000 NOK
Transport + other	10000 NOK

- The useful life of a drive shaft is 5 years; therefore the driveshaft cost is neglected.
- We will assume that alternatives 1 and 2 for the bearing are equally likely.
- The additional cost of a gearbox breakdown is 900000 NOK in spare parts and with transportation and other costs included the total cost is assumed to be 1.1 mill NOK
- No value is given to lost production time since the production is normally not lost, just postponed.
- Unplanned downtime will not be given a monetary value. It is however worth considering the value of avoiding the event illustrated in Figure 47.

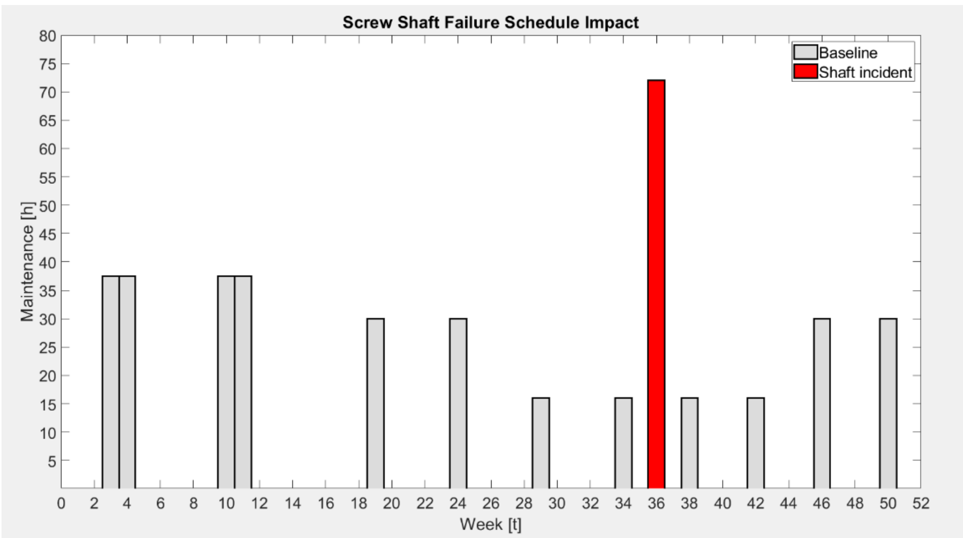


Figure 47 Screw shaft failure schedule impact.

4.3.2.2 Screw element wear scenario

The information we have related to this failure mode is a result of a 2-hour interview with a process operator who has worked with extruders for over 30 years.

- The screw elements are changed approximately 2 times a year.
- Changing of the screw elements takes 4 hours.
- Before they are changed, they are inspected 3-4 times.
- The inspection of the screw elements takes 2 hours.
- The wear characteristic of the screw-elements is exponential.

The inspection is usually performed when there is a maintenance stop or when the opportunity arises e.g. when the dieplate is changed due to product change. A worst-case scenario has been proposed where there is a sudden drop in SME which could lead to a need for an unplanned inspection and changing of the elements. This can also have the consequence of need to re-process some of the product.

- For this case-study we will assume no unplanned downtime related to the inspections.
- We give no monetary value to the risk of re-processing the product.

Figure 48 is given to illustrate the impact on the maintenance schedule. The model assumes that the screw elements are changed right before high season starts, and right after.

Figure 48 Screw element inspection and replacement schedule.

4.3.3 Calculation

Based on the information on the drive shaft event we have received we can calculate the Risk Cost (RC1) related to the bearing block, bearings and bushings:

- $RC1 = (0.5 * 195000 + 0.5 * 32500) \left[\frac{NOK}{Event}\right] * 2 \left[\frac{Event}{10\,Years}\right] = 227500\,NOK$

The Risk Cost (RC2) related to the additional consequence of the outcome of the gear box failure event:

- $RC2 = 0.4 * 1100000 \left[\frac{NOK}{Event}\right] * 2 \left[\frac{Event}{10\,Years}\right] = 880000\,NOK$

The Man-Hour cost (MH) related to performing the CM is included in the risk calculation.

We can define the benefit gained from predicting the wear of the screw elements as removing the need for preventive inspections. Based on the information we have received we can calculate the saved cost related to Man-Hours saved (MH1) considering a period of 10 years:

- $MH1 = 2 \left[\frac{\text{h}}{\text{Inspection}}\right] * 500 \left[\frac{\text{NOK}}{\text{h}}\right] * 6 \left[\frac{\text{Inspections}}{\text{Year}}\right] * 10[\text{Years}] = 60000\ \text{NOK}$

It can be noted that there is a very large uncertainty in taking average estimates due to the large variance of the best-case (RCB) and worst-case (RCW) outcomes of the shaft failure event:

- $RCB = 32500$
- $RCW = 195000 + 1100000 = 1295000\,NOK$
- $Var = 1262500\,NOK$

4.3.4 Cost-effect analysis

A simple cost-effect analysis assuming a period of 10 years is given in Table 28. The OPEX cash flows are not discounted, but rather assumed to be a one-time payment at the time of procurement. The following definitions for the expenditures and gains are used:

Expenditures:

- CAPEX – Capital expenditure needed to buy the equipment (hardware).
- OPEX – The operational costs to run the system for 10 years.

Gains

- RC1 – The spare part cost saved due to predicting the failure of the drive shaft.
- RC2 – The cost related to the additional consequence of the outcome of the gear box.
- MH1 – Man-hours saved from eliminating the need for inspections/ maintenance.

Table 28 Cost-effect analysis.

Cash flow	**Cash value**
CAPEX	(-) 65960
OPEX	(-) 16660
RC1	(+) 227500
RC2	(+) 880000
MH1	(+) 60000
Result	**(+) 1084880**

A low-estimate of the cost-effect is given in Table 29 based on the best-case scenario presented in chapter 4.3.3.

Table 29 Cost-effect analysis using best-case scenario.

Cash flow	**Cash value**
CAPEX	(-) 65960
OPEX	(-) 16660
RCB	(+) 32500
MH1	(+) 60000
Result	**(+) 10150**

We see that with the lowest assumed benefit, the proposed architecture is still cost-effective.

4.4 Implementing a predictive maintenance strategy

We have illustrated through a case-study how a PdM strategy can be implemented on machine level by utilizing a 7-layer intelligent maintenance model to develop a PHM programme for specific machine faults. In this chapter we want to look at the issue in a broader perspective and identify key aspects towards successful implementation of PdM on an organizational level.

The predictive analytics company Presidion says the key to implementing a successful PdM strategy is to fully understand the intricacies of PdM, have the wisdom to think big but start small, have clear success criteria, and build a comprehensive corporate wide roadmap [66]. This model is illustrated in Figure 49. In this chapter we adopt this model's structure and discuss some of the key aspects in these steps.

Figure 49 The key to implementing a successful predictive maintenance strategy [66].

4.4.1 Understand the big picture

Before setting up a strategy for implementing PdM, it is important to gain insight on the current role of PdM in the bigger picture of Industry 4.0.

Lower computing costs, cheaper storage, and less costly bandwidth has made it feasible for companies to invest in digital technologies. The core process of digitalisation can be seen as a flow occurring through an iterative series of three steps, collectively known as the physical-to-digital-to-physical loop illustrated in Figure 50.

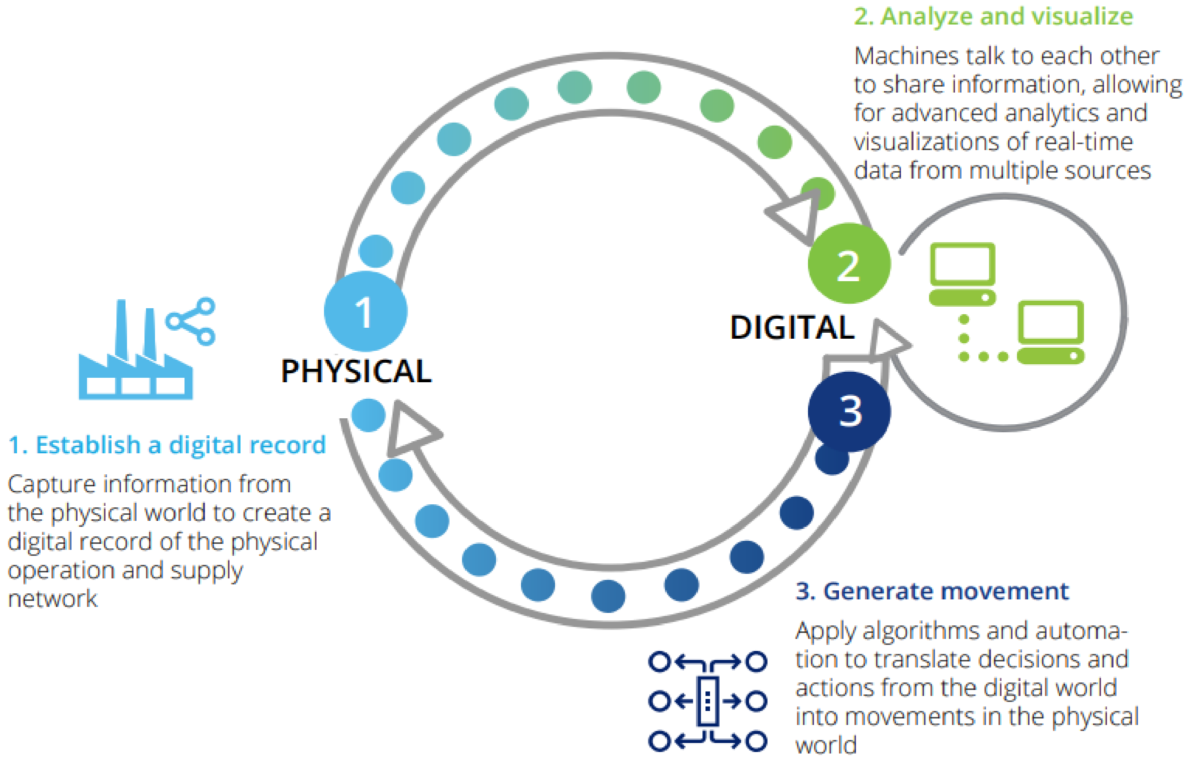


Figure 50 Physical-to-digital-to-physical loop [67].

4.4.1.1 Digital supply networks

By applying the physical-to-digital-to-physical loop to various parts of the value chain, digital information can be gathered from many different sources and locations. With the combination of information technology (IT) and operations technology (OT), the supply chains can be disrupted. An opportunity is identified where the traditional supply chain shifts from a linear nature; to an interconnected, open system called a Digital Supply Network (DSN) [67]. This change in supply chain structure is illustrated in Figure 51.

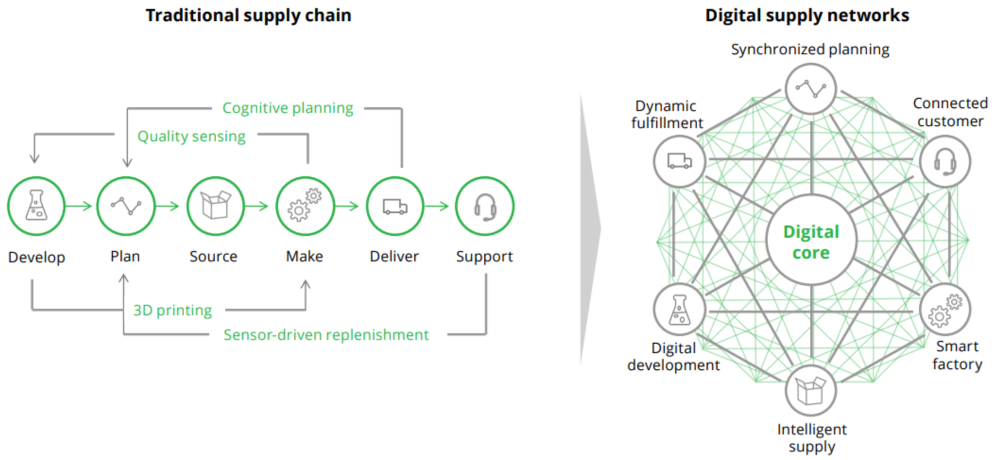


Figure 51 Shift from traditional supply chain to digital supply network [67].

4.4.1.2 Smart factories

The smart factory is the result of applying the physical-to-digital-to-physical loop to various processes within the factory. Every smart factory will be very different due to the large variety of possible industrial applications. Five major features of any smart factory are given in Table 30, which is based on a white paper by Deloitte where they define and describe the concept of the smart factory [68].

Table 30 5 features of a smart factory: Connected, optimized, transparent, proactive, and agile [68].

Connected	Optimized	Transparent	Proactive	Agile
• Old and new data (sensors) • Real time collaboration • Communication across departments	• Predictable production capacity • Increased asset uptime • Highly automated production • Minimized cost of quality and production	• Live metrics to support decisions • Real-time linkage to customer demand • Transparent customer order tracking	• Predictive anomaly identification • Early quality issue identification • Automated restocking • Real-time safety monitoring	• Flexible scheduling • Real-time impact of product change • Configurable factory layout and equipment

Even with large variations in line layouts, products, automation equipment, and other potential differences across the facilities of different factories; the components needed to enable a successful smart factory are largely universal. The main areas for consideration to anyone considering making the transition to the smart factory are: Data, technology, process, people, and security. Table 31 is given to summarize some key aspects in each of these areas:

Table 31 Smart factory transition: Areas for consideration [68].

Data and algorithms	Need to have the means to create and collect ongoing streams of data, manage and store the massive loads of information generated, and analyze and act upon them in varied, potentially sophisticated ways.
Technology	Assets need to be able to communicate with each other and with a central control system: Transaction and enterprise resource planning systems, IoT and analytics platforms, and requirements for edge processing and cloud storage, analytics, additive manufacturing, robotics, high-performance computing, AI and cognitive technologies, advanced materials, and augmented reality.
Process	One of the most valuable features of the smart factory—its ability to self-optimize, self-adapt, and autonomously run production processes. The connectivity of the smart factory may extend beyond its four walls to include increased integration with suppliers, customers, and other factories.
People	The smart factory can cause profound changes in the operations and IT/OT organizations, resulting in a realignment of roles to support new processes and capabilities. New, unfamiliar roles will likely emerge. Organizational change management play an important role in the adoption of any smart factory solution.
Cyber security	By its nature, the smart factory is connected. Thus, cybersecurity risk presents a greater concern. Cyberattacks can have a more widespread impact and may be more difficult to protect against, given the multitude of connection points.

4.4.1.3 Predictive maintenance

The first step towards a successful implementation of a PdM strategy is understanding how PdM is different from traditional maintenance methods. We covered a description and an evaluation of pros and cons of the three major maintenance philosophies; corrective, preventive, and predictive, in the background chapter 2.1.

When we apply the physical-to-digital-to-physical loop on asset level, we enable decision support based on asset specific usage, wear, and conditional data from both historic and real time sources to predict where, when, and why a fault will occur. In this report we do this by developing a model-based PHM system for specific faults in a crucial asset.

As more applications are included in the program, Industry 4.0 drivers enable more opportunities. When several models are included in the system, a network of sensors connected to the internet constitutes an IoT. This opens up for the use of data-driven methods, which again drives the opportunity of new maintenance models such as Deep Digital Maintenance (DDM) [69, p. 299]. This model suggests using an AI Module such as illustrated in Figure 52.

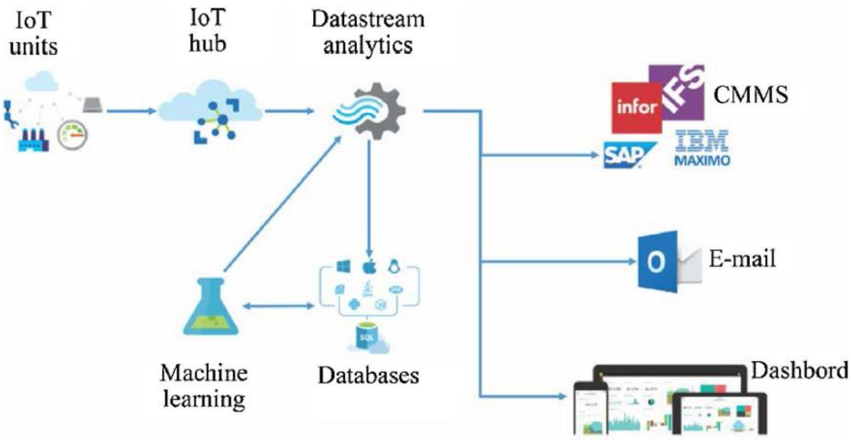


Figure 52 Structure of the AI module [69].

Here, real-time data are fed from the IoT units to a common IoT hub, where the data are processed using Big Data processing algorithms, and ML is used to train the prediction models by recognizing patterns and obtain real-time predictions of RUL. The hub can of course be a cloud storage solution, and the analysis can be performed using CC. The prediction results are then communicated via the CMMS, e-mail, or customized dashboards.

ML uses statistical techniques to learn and recognize patterns in big data. A typical ML process is illustrated in Figure 53:

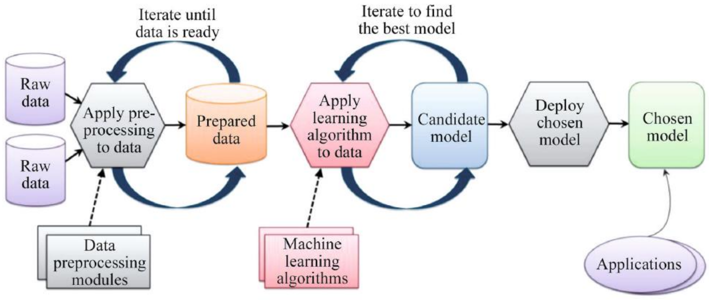


Figure 53 Typical ML process [69].

4.4.1.4 Industry 4.0 maturity

An important aspect to keep in mind, is that there is a large variety in the maturity of various concepts and technologies often mentioned within the concept of Industry 4.0. Gartner suggests a model where the expectations of emerging technologies are plotted versus time [70]. The characteristic is that all technologies reach a "peak of inflated expectations" before they drop. After a while when the technology matures, it follows a "slope of enlightenment" before it reaches a "plateau of productivity". In Figure 54, some emerging technologies are mapped on this "Hype Cycle" with a prognosis of how many years it will take for them to reach the plateau. The IoT platform, which is the basis of Industry 4.0, is here plotted on the top of the inflated expectations hype, with an estimate of reaching the plateau in two to five years.

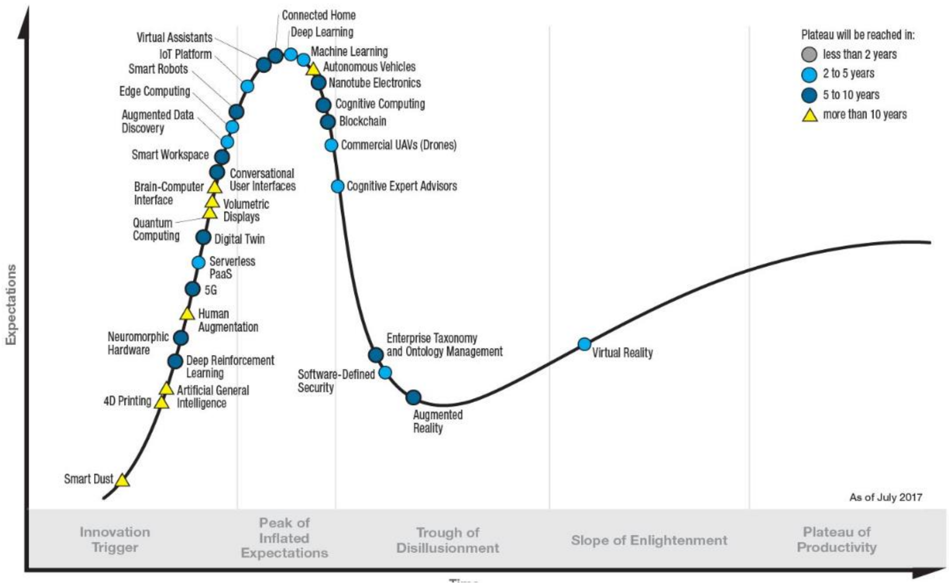


Figure 54 Gartner hype cycle for emerging technologies, 2017 [70].

McKinsey claims that the hype of the IoT may actually be an understatement, but that capturing the maximum benefits will require an understanding of where real value can be created and successfully addressing a set of systems issues [71]. An interesting finding in this report is that most of the IoT data collected are not used at all, and data that are used are not fully exploited. An example is given in Figure 55 from an offshore oil rig where less than 1 percent of the data being gathered was used to make decisions. Another interesting finding of this research is that a great deal of additional value remains to be captured, by using more data as well as deploying more sophisticated IoT applications such as using performance data for PdM.

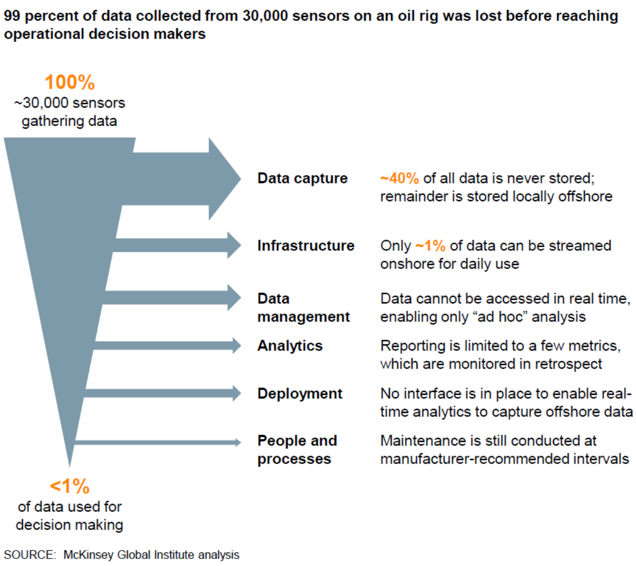


Figure 55 Most IoT data collected are not used or not fully exploited [71].

When it comes to smart factories, recent global research (2017) [72] shows that 76% of manufacturers have smart factory initiatives, but only 14% of companies are satisfied with their level of smart factory success. An executive summary of this report is given in Table 32.

Table 32 Key findings from global research on smart factory initiatives [72].

The prize	The challenge
• Smart factories could add $500 billion to $1.5 trillion in value added to the global economy in five years.	• 76% of manufacturers either have a smart factory initiative that is ongoing or are working on formulating it. And more than half of manufacturers (56%) have aligned $100 million or more towards smart factories.
• Manufacturers predict overall efficiency to grow annually over the next five years at 7 times the rate of growth since 1990.	• However, only 14% of companies are satisfied with their level of smart factory success. Only 6% of manufacturers are 'Digital Masters': at an advanced stage in digitizing production processes and with a strong foundation of vision, governance and employee skills.
• We estimate that smart factories can nearly double operating profit and margin for an average automotive OEM manufacturer.	• Digital Masters outpace all other categories in realizing the benefits of smart factories.

As we can see, there is a huge potential, but there are also many challenges that must be addressed when looking at the bigger picture. In this era of digitalisation it is necessary to engineer and manage assets in a smarter, safer, cost-effective, and efficient way.

4.4.2 *Start small, think big*

After gaining some insight on the current role of PdM in the bigger picture of Industry 4.0, it is time to build a strategy for implementation. A good place to start is to identify business goals, priority assets, and relevant data.

In order to do this, Presidion suggests producing a matrix of how the business goals align to operational readiness, data availability, and business alignment, to prioritize the most appropriate assets to begin with [63]. By starting small with an initial pilot project, it is possible to confidently asses the accuracy and effectiveness of the PdM strategy.

Deloitte also suggests that it can be more effective to start with a single asset. They say "*think big, start small, and scale fast*". By focusing on a single asset until a "win" is achieved, the solution can scale to additional assets, production lines, and factories, thus creating a potentially exponential value creation opportunity such as illustrated in Figure 56 [68, p. 15].

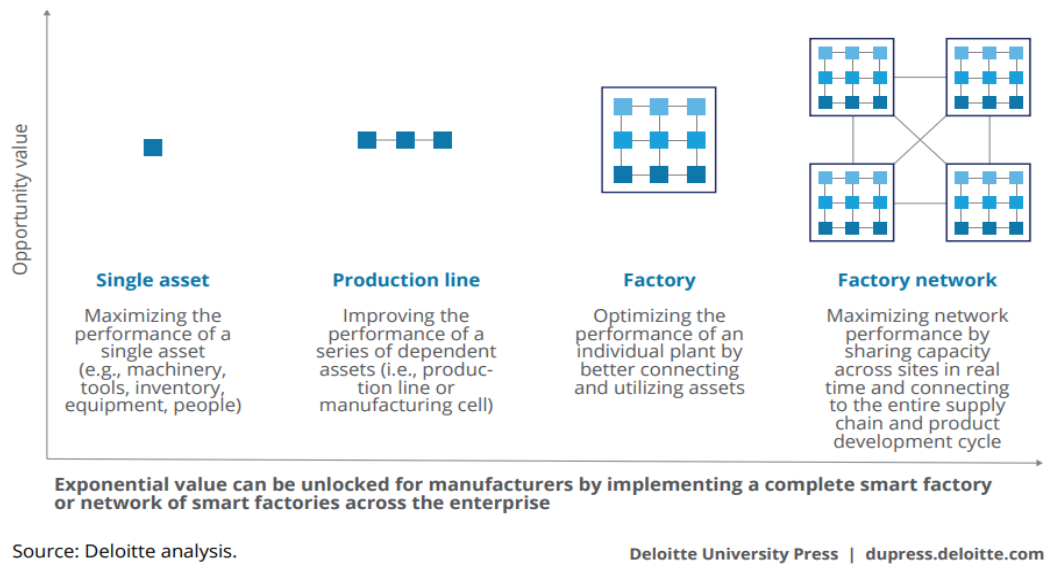


Figure 56 Starting small and scaling to unlock value [65].

4.4.3 *Evaluate for continued success*

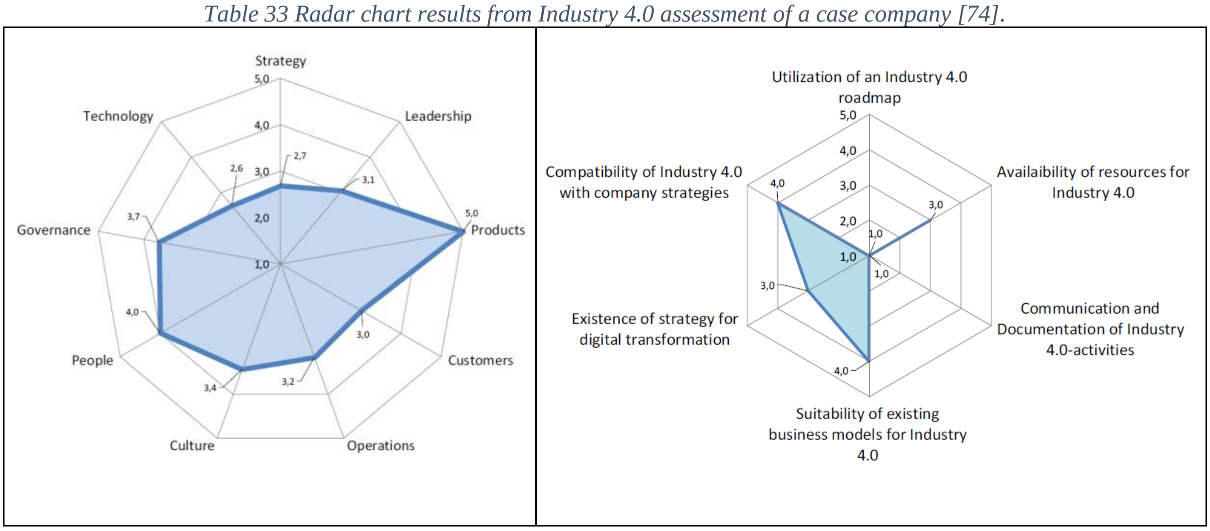
When implementing a PdM strategy, there is always an investment cost related to it. In order to know if the pilot project is a success, there needs to be some criteria to be achieved in a certain time frame. Setting evaluation criteria gives clear objectives to measure the success of the project. Typical Key Performance Indicators (KPI's) to measure Return on Investments

(ROI) can be; reduction in downtime, reduction in maintenance costs, increase in production output.

Furthermore, the company's organizational and technological capabilities need to be evaluated to assess Industry 4.0 maturity as a first step towards developing a strategy. A scientifically well-grounded assessment is the "IMPULS – Industrie 4.0 Readiness" tool, which is available as an online self-check for businesses [73]. Another model has been developed with the goal of extending the dominating technology focus of IMPULS and other existing models by including organizational aspects [74]. In this model, there are 9 defined dimensions with 62 items for evaluation. The dimensions; products, customers, operations, and technology have been created to assess the basic enablers. The dimensions; strategy, leadership, governance, culture, and people allow for including organizational aspects into the assessment.

Table 33 is given to increase understanding about the models systemic, illustrating a radar chart of the Industry 4.0 maturity of a case company to the left, and the detailed results for the strategy dimension to the right [74, p. 165]:

Table 33 Radar chart results from Industry 4.0 assessment of a case company [74].



4.4.4 Create a roadmap to know where you want to go

To ensure long term development it is necessary to build a roadmap based on the key corporate and operational goals you want to achieve. A roadmap is *"a high-level plan, defining an overarching strategic objective and capturing the major steps planned for* *achieving that objective"* [75]. The main challenge of developing a roadmap lies in defining the long-term goals of the company. The company needs to assess their current status to know which processes they need to achieve their goals within existing constraints.

After that has been done, one can start from the formulated end goal and work backwards to know where to start. In the following, some recommendations are given for Skretting to consider when developing their roadmap on a short-term and a long-term basis.

4.4.4.1 Short-term roadmap

In a short-term perspective, Skretting should focus on grasping the opportunity identified in this paper and make efforts towards verifying and developing the proposed program. The extruder can work as a pilot project to start on the road towards implementing a PdM strategy. If the solution is verified, the knowledge gained can be used to monitor all the extruders in the company, as well as enabling the architecture to include vibration monitoring on other components of the extruder such as bearings, drive shafts and gears.

If desired, the extruder can work as a pilot project towards building a smart machine, where the illustrated methodology is utilized to monitor other critical faults, possibly needing different measurement techniques.

4.4.4.2 Long-term roadmap

When creating a long-term roadmap, it is necessary to look at digitalisation as a means to develop new business opportunities, not only as a tool for developing efficiency measures, such as is the current trend in the Norwegian business community according to a survey from 2017 by Siemens [76].

After every industrial revolution; markets, products, and processes are different. This means that the digital transformation does not just affect a single department. It is a cross-functional effort that needs to be addressed by the whole company. In McKinsey's white paper on how to navigate digitization of the manufacturing sector; five digital pillars are identified for a company to establish the foundations for a digital transformation [77]. A summary is given in Table 34:

Table 34 Five digital pillars for managing the digital transformation of Industry 4.0 [77].

Pillar	Description
Digital capabilities	Build relevant digital capabilities along two dimensions: 1) Attract digital talent 2) Set up cross-functional governance and steering.
Collaboration	Facilitate collaboration in the industry ecosystem by: 1) Seeking alliances and strategic partnerships 2) Get involved in the definition of standards.
Data	Data will be precious raw material. Companies must: 1) Develop data as an asset 2) Manage data strategically
IT development	Enable rapid and agile IT development by: 1) Introducing a parallel fast-speed IT and data infrastructure 2) Establish data interfaces
Cybersecurity	Four practices should be employed to effectively manage cyberrisk: 1) Prioritize protection around key assets 2) Integrate cybersecurity into core processes 3) Engage management and employees 4) Safeguard the technology

Norsk Industri has worked out a roadmap on digitalisation for the Norwegian industry [78]. The goal of the paper is visualizing the practical application of new and feasible technology through corporate examples from the members. They identify important prerequisites for further progress for the industries, give recommendations about what to do, and which means can be used.

For the production of Norwegian goods to win global market shares, the industry needs to increase its use of digitalisation. Businesses who do not, will not be able to remain competitive in the long run. Four recommendations are given about what should be done:

1) A strong recommendation is given towards businesses putting digitalisation and new technologies on the agenda
2) Identify possibilities brought by changes in technologies and production processes and be flexible so that it is possible to adapt.

3) Pay attention to what is happening locally, nationally and globally by attending physical and virtual meeting places for digitalisation.
- Forums for digitalisation should be actively used.
- Find initiatives such as “Norsk Katapult” (Norwegian catapult), which is an initiative that the government is funding to give companies opportunity to test, simulate and visualize the use of new technologies. Other include BIA, SFI, and Cluster programs.

4) Companies are recommended to include the possibilities with digitalisation in their lean-programs.

Inspiration can be taken from looking at what other companies are doing. For example, PwC published a report entitled “Industry 4.0: Building the digital enterprise” [79] where they provide a perspective on Industry 4.0 with their “Blueprint for digital success” illustrated in Figure 57.

Figure 57 PwC's "Blueprint for digital success" [79].

4.4.5 Get the right people involved

It is very important that all the key stakeholders are engaged with the process, from management to machine operators. All participants need to be involved with the strategy and know how it will affect their role within the organization.

4.4.5.1 Vibration analysis competencies

The need for competencies or new roles depends strongly on the long-term strategy of the company. That is, the level of competence needed depends on how much of the analysis service will be integrated into the organization, and how much will be outsourced to the service provider. In the following, some insights will be given based on a training day provided by SKF personnel the 25th May 2018 after installing the vibration monitoring lab for educational purposes at the University of Stavanger.

If the aim of the implementation of condition monitoring into the maintenance strategy is to streamline the maintenance process, then it might be a desirable solution to outsource as much of the analysis as possible. Assuming the machine is set up with a continuous monitoring architecture, e.g. the SKF IMX-8 Online system suggested in chapter 4.3.1, the analysis can be performed by a vibration analysist outside the company at the desired sample period e.g. trimonthly, once a month, or once week. On the other hand, if the goal is to integrate vibration monitoring as a part of a digitalisation process, where such data and knowledge will be viewed as a valuable asset, then it will be desirable to build such a competence within the organization and make new roles. Operators can then take readings onsite, e.g. with the use of the "Quick Collect sensor", and the analysis team within the organization can look further into any anomalies using the real-time data available in the cloud.

The need for training related to vibration analysis is defined in ISO 18436. Table 35 is provided on the next page, giving information on the levels of training needed for various functions [80].

Table 35 Overview of the four categories of Vibration Analyst training from ISO 18436 [80].

Certificate	Requirements	Gained knowledge	New function
Category 1 (Basic)	• Demonstrated six months experience in vibration analysis	In-depth understanding of spectrum and waveform relationships.	Collect vibration data, new vibration analysts.
Category 2 (Intermediate)	• Category I certification • Eighteen months experience	Know how to test machines correctly, how to diagnose faults accurately, perform additional diagnostic tests for verification, how to set vibration alarm limits, and how to correct certain types of faults	Test, diagnose, set limits, verify equipment settings
Category 3 (Advanced)	• Category II certification • At least 24 months of experience	Fully understand all data collector options, special test capabilities, all analysis tools and must understand the widest range of fault conditions	Leader of the vibration team or takes a leading role in diagnosing faults and making the final recommendation.
Category 4 – Part 1 (Master)	• Category III certification • At least 60 months of active experience	Advanced signal processing, cross channel measurements, dynamics (mass/stiffness/damping, natural frequencies, modes), resonance testing (run-up/coast down tests, impact tests, ODS, modal analysis), and corrective action (flow control, resonance correction, isolation and damping).	If advanced analysis, design modification or modeling is required, a specialist in those areas will be called-in.
Category 4 – Part 2 (Master)	• Category III certification • At least 60 months of active experience	Proximity probe and casing measurements, orbit and centerline plot analysis, rotor dynamics (natural frequencies, modeling), journal bearings (design, fluid film instabilities), and flexible rotor balancing, torsional vibration.	

4.4.5.2 Digitalisation competencies

We have seen the need for businesses to put digitalisation on the agenda. As with any major business initiative, data analytics should have its own strategic direction [81]. In order for the initiative to be successful, it is necessary to have a clear vision for the analytics programs and the initial use-cases as well as having clearly defined analytics roles [82]. McKinsey Analytics define a set of skills that organizations need in the years ahead; business skills, technology skills and analytics skills. Figure 58 is given below illustrating a set of well-defined roles fulfilling the various skill sets.

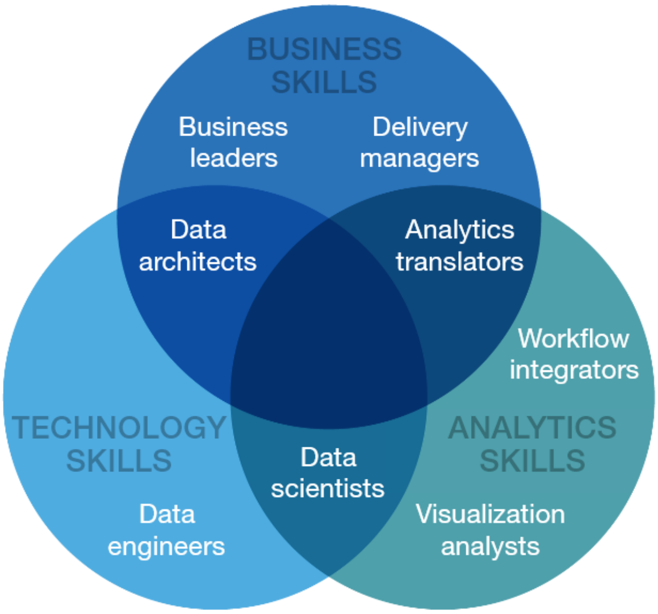


Figure 58 Skills and roles needed for successful digitalisation initiatives [82].

The roles each organization needs will vary depending on the business strategy or project. However, one of the most important roles identified which organizations should seek to begin with is the “Analytics translator” [83]. A person in this role can help leaders identify use-cases and translate the business needs to data scientists and engineers to build feasible solutions. A person with technological skills in addition to business and analytics skills is the perfect candidate for any organization looking to gain the value promised by Industry 4.0. The first step should be to identify the roles needed, and those currently existing within the organization, before filling the remaining roles by hiring externally.

5 Results and discussion

A PdM strategy should be developed and implemented through four phases; systems analysis of the physical assets, programme development based on Industry 4.0 architecture, cost-benefit analysis, and roadmap development for programme implementation at organizational level. The 4-phase model is presented in Figure 59.

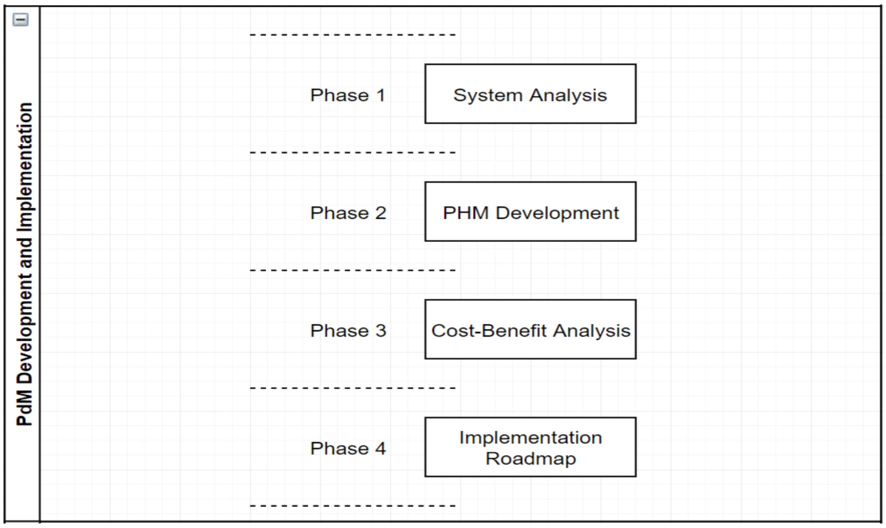


Figure 59 4-phase model for developing and implementing predictive maintenance.

5.1 System analysis

Through the case study, we developed the system analysis flowchart presented in Figure 60. The extrusion process was defined as the heart of the production process. By using the flowchart, an understanding of the system and the most critical failure modes was gained. The twin-co-rotating screws were identified as the most crucial application, and vibration monitoring was identified as the most suitable condition monitoring technique to monitor the symptoms of the wear and crack faults.

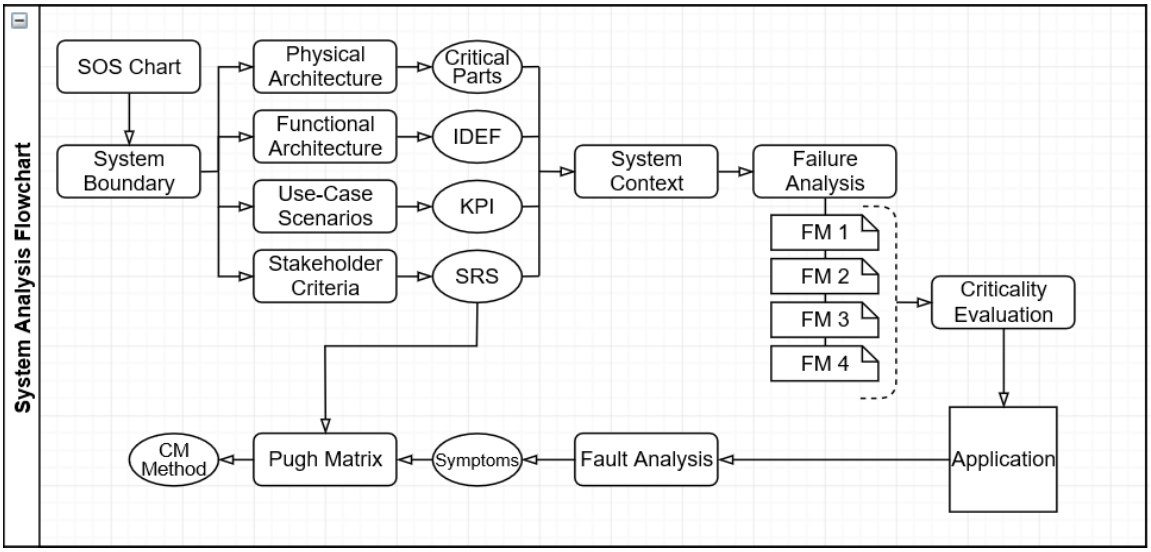


Figure 60 System Analysis Flowchart.

5.2 Predictive health monitoring programme

Based on the knowledge gained of the system, the developed 7-layer intelligent maintenance model was utilized to demonstrate how to develop a PHM programme in compliance with Industry 4.0. A summary of the results from each of the layers is provided in Figure 61.

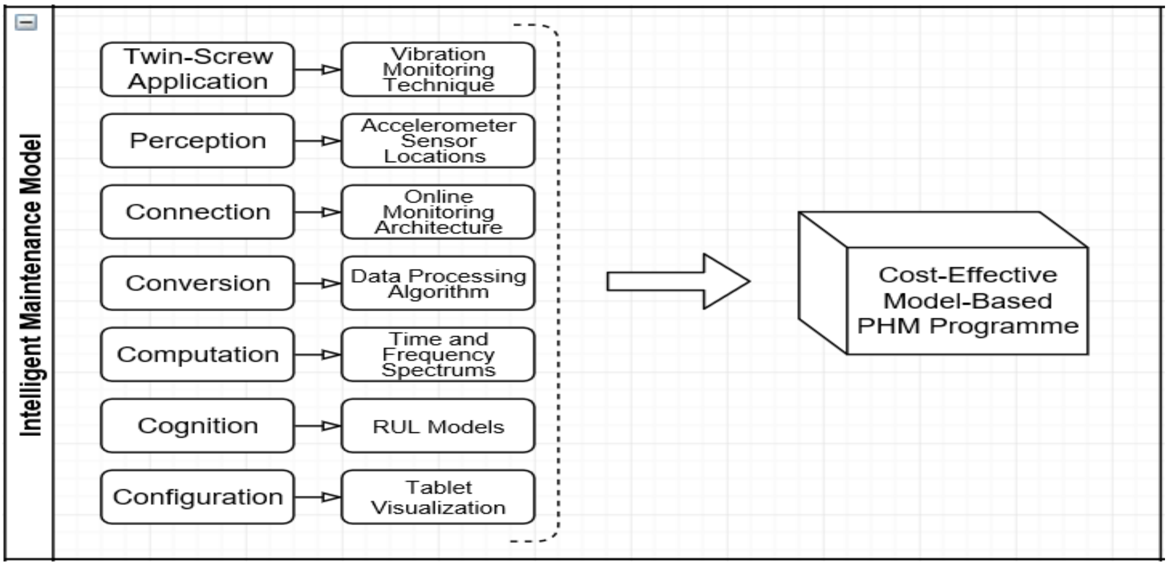


Figure 61 PHM programme results.

5.3 Cost-benefit analysis

The capital expenditure needed to acquire the PHM architecture and the operational expenditures needed to operate it for ten years was evaluated against the benefit gained from mitigating the failure events from the optimal baseline maintenance schedule. A simple cost-effect analysis showed a result of over 1 million NOK in possible savings from a single extruder. Considering there are five BC160 extruders in the three Norwegian factories, we can conclude that a successful implementation will result in substantial value for Skretting.

5.4 Implementation

Implementation of PdM should, on an organizational level, be considered in relation to how the organization intends to face digitalization. Based on available recommendations within the literature, the 5-step model given in Figure 62 is given to show the steps needed for successful implementation of the PdM strategy: A self-assessment should be performed, and goals should be defined to set up a strategy; a roadmap should be developed to visualize how the resulting gap between the current and desired status will be closed; people with the right skills (business, technology and analytic) should be identified; and a pilot project should be used to initiate the process.

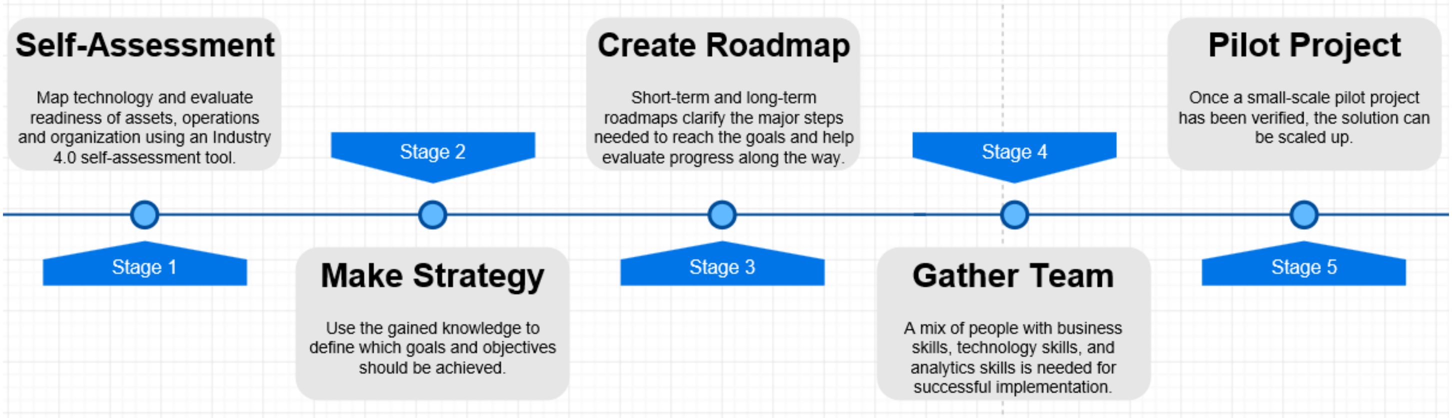


Figure 62 5-Step model to implement PdM in the era of Industry 4.0.

5.5 Discussion

In the view of RCM, no maintenance philosophy is considered better than the other, as the goal is to achieve high availability with low life cycle costs [9]. Others argue that the quality of the maintenance program increases as you move from a reactive to a strategic maintenance approach [84]. Industry 4.0 further supports this view with the value that can be gained from generating data on whole processes to create smart machines and enable a prescriptive maintenance strategy [15]. On the other hand, the current level of smart machine technologies is not yet smart enough to fulfill the promise [31]. Organizations are struggling [72] to navigate through the hype [70] to make digitalisation initiatives successful [81].

In this report, we have looked at the role of PdM in a bigger picture of Industry 4.0 and how value can be created on machine level. The 7-layer intelligent maintenance model used in the case study was based on the 5C CPS architecture of Jay Lee. There exists a discrepancy between the purpose of this model and the function it serves in this report. The model's purpose is to develop CPS for managing Big Data generated from a network of machines to reach intelligent, resilient, and self-adaptable machines [29]. Since this report mainly concerns a single source of data, the real value of this model is not presented in the case study. The model has been adopted due to the clarity it provides on machine level for horizontal development of a PHM system architecture. However, once such an infrastructure is in place, more applications can be added into the network, enabling the possibility to reap the benefits of having a network of machines exchanging information through cyber-interfaces. Software, hardware, and algorithms focused on PdM are still in early stages compared with other approaches of maintenance. It might therefore be advisable to take a pilot approach to Industry 4.0 technologies in the PdM strategy, testing and learning before scaling up [85]. Collecting the *right* data and choosing the most appropriate *algorithms* relevant for each application is crucial for success.

Choosing the application for implementing PdM requires a system analysis to identify where the highest risk is. The most common risk analysis methods regarding machine faults are FMEA and FTA. The main difference between these approaches is that the FMEA is a bottom-up approach while the FTA is a top-down approach. In this report we utilized the FTA. The advantage of FTA over an FMEA is the graphical results that is produces and the time it takes to perform the analysis [86]. The FMEA on the other hand, is a more detailed analysis that covers all components of the system, as well as analyzing the consequences of the failure modes. In this report we utilized the RPN consequence classification to remedy this. Performing an FMEA of the system does require a team of interdisciplinary stakeholders to do the analysis, but once performed the result could provide more value than the FTA utilized in this report due to more information being produced.

The proposed RUL models needs to be improved and then validated using real data. Once a system has been implemented, the investment cost of scaling the solution to the other five extruder lines will be lower than the initial project. With the architecture already in place, the more-cost is related to the sensors and the possible additional data storage and analysis service. Other rotating equipment such as engine, bearings, driveshafts, etc., can also be included in the architecture, possibly leading to an exponential value creation.

5.6 Further recommendations

Skretting should consider following the 5-step model for successful implementation of PdM. The knowledge gained from the case-study provided in this report can be used to initiate a pilot project as a part of the short-term roadmap. More research needs to be performed related to the validation of the RUL prognosis models, as the ones in this report are for illustration purposes. An assessment of the competencies within the organization in relation to the needed competencies for the pilot project should be performed to get the right people involved.

Once the pilot project is verified, the system analysis model can be used to identify more critical applications. A predictive health monitoring program can then be developed using the 7-layer intelligent maintenance model.

As more models are developed, more data will be produced. This will enable an opportunity to utilize more Industry 4.0 drivers such as IoT hubs, Big Data processing, and the use of ML in AI modules such as illustrated in chapter 4.4.1.3. An illustration where several knowledge-based models enable a Data-Driven PHM programme is given in Figure 63.

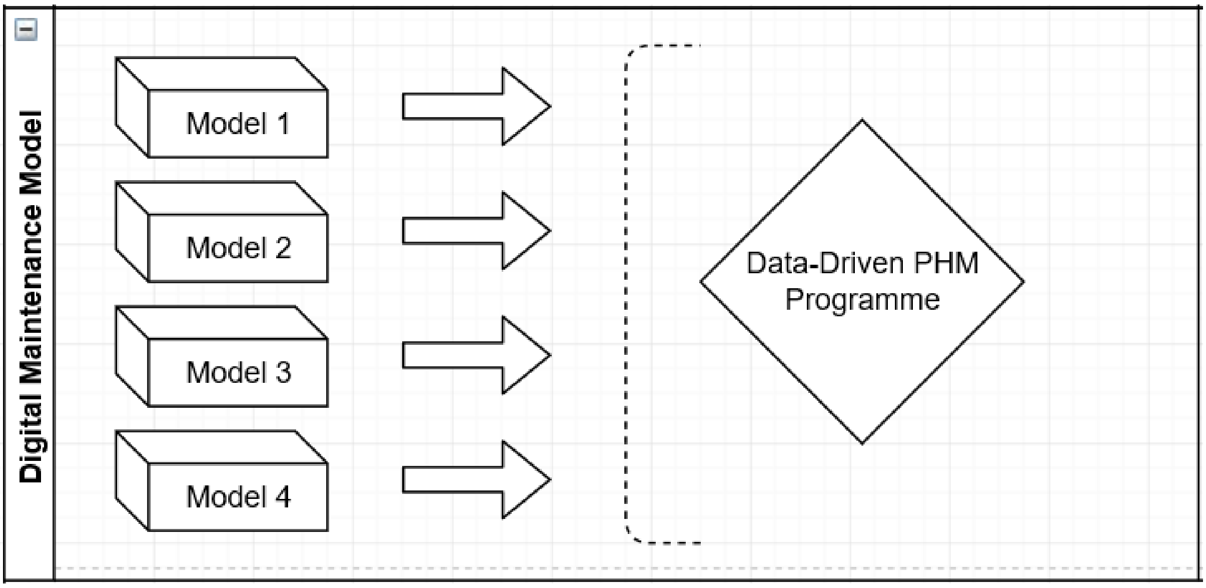


Figure 63 Knowledge-based models connecting to a Data-Driven PHM program.

6 Conclusion

A *predictive maintenance* programme can be *developed and implemented* in fish feed *processing industry* in a *cost-effective* manner that *complies with the Industry 4.0 vision* by using the 4-phase model presented in the results. The model proposes to develop and implement predictive maintenance programmes through four phases: Systems analysis of the physical assets, programme development based on Industry 4.0 architecture, cost-benefit analysis, and roadmap development for programme implementation at organizational level. In the first phase, the Systems Analysis Flowchart is used to find the most critical application. In the second phase, the 7-layer intelligent maintenance model is used to develop a PHM programme for that application, which is then evaluated in a cost-benefit analysis in the third phase. In the fourth phase, the 5-Step model to implement PdM in the era of Industry 4.0 is utilized to develop a roadmap. The proposed PHM programme can be included in the short-term roadmap as a pilot project.

The System Analysis Flowchart and the 7-layer intelligent maintenance model have been developed and demonstrated throughout an industrial case study where the twin co-rotating screws of the extruder system was the case system. Based on the performed systems analysis, it can be concluded that the wear and fatigue crack faults are the most critical failure causes within the selected critical system i.e. extruder. The wear fault can be monitored by detecting the natural frequency shift as main fault symptom. The fatigue fault located at the end (toward the cutting plate) of the twin screw shaft occurs frequently but has low cost of consequence. Moreover it requires inspection and replacement stoppage beside a potential re-production of product due to poor quality. The second fault is related to the fatigue fault, which can be monitored by detecting the amplitude values at the crack frequency as main fault symptom. The fatigue fault has a long MTBF, but a very high cost of consequence e.g. downtime and spare part cost.

This case study highlights the systems analysis as essential step to develop a predictive maintenance programme for a specific purpose. Moreover, it highlights how the same faults can be monitored or detected as abnormalities in the process parameters. However, such data-driven diagnostics approach requires further research and training.

The developed predictive maintenance programme based on the proposed seven layers (from data into decision) is effective and traceable to allocate the technical requirements to enhance the production revenue or cut variable and fixed maintenance costs. Even though, the operator might get outsourced solution provided by service providers (as many operators has no competence in digitalisation and analytics development), it recommended to use those sever layers to explore the qualities that are required during the procurement process of such outsourced services to gain the potential benefits.

The cost of the architecture of the proposed PHM system has been evaluated against the benefits gained by the potential mitigation of the several failure events related to the two faults. The simple cost-effect analysis shows that the proposed system could save over 1 million NOK in a ten year period for a single extruder.

Based on available recommendations within the literature and our understanding of current status extracted throughout the case study, we derived a 5-step model which serves as a key to successfully implement a PdM strategy in the era of Industry 4.0. It involves understanding the role of PdM as a part of the digitalisation process and shows that it is necessary for organizations to evaluate the current status of the company and set up a roadmap for how to gain the value promised by digitalisation. A good place to start after defining the status and setting up a strategy is to start with a pilot project and look at the roles needed to fill the competencies within the areas of business, technology, and analytics.

7 References

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All references accessed and working 14.06.2018.

8 Appendix

8.1 Problem formulation

Template for problem formulation

<table>
<tr><th>Step</th><th>What</th><th>How</th></tr>
<tr><td>1</td><td>Go from a broad topic to a more focused topic.</td><td>Provide:
A brief description of the studied field/application/industrial sector.
A short description of a set of opportunities or challenges that exist in the field.</td></tr>
<tr><td>2</td><td>Go from a focused topic into a clear challenge or industrial need.</td><td>Answer the following questions:
What is the motivation behind this project? Is it related to a critical problem or related to new technology to be explored?
Which indicators have indicated a problem or the need for new solutions? Downtimes, failures, bottlenecks, low performance, cut the cost, losses?
How was the issue noticed? Are there statistics, or is the situation already analyzed?</td></tr>
<tr><td>3</td><td>Create a research question such that its answer might solve the formulated problem.</td><td>1) Specify if the focus is general (on an overall system) or specific (focus on a subsystem or machine).

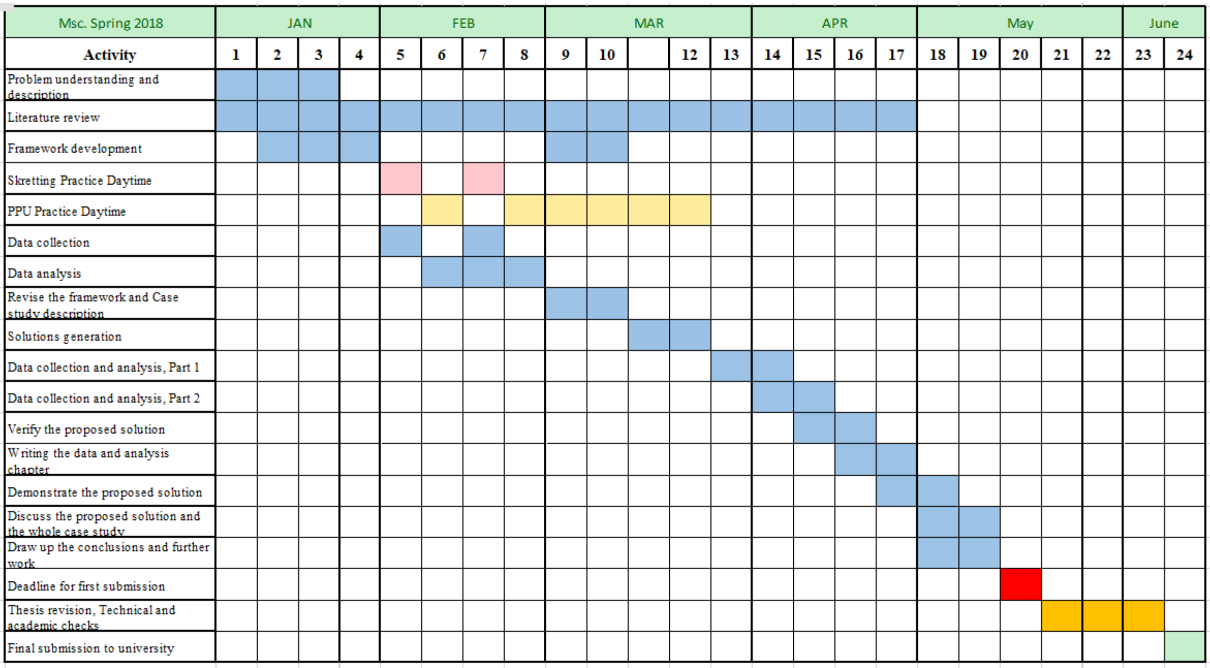
2) Formulate the problem in a concise manner and use it to find a research question on the form of:
How can "focused phenomenon/ problem" of "selected system" in/for "scope/application" be "actual task or analysis type" in "acceptance criteria"?
Example:
- How can "wear evolution" of "rolling bearings" in "wind turbines" be "analysed and monitored" in/to "a cost effective" manner?</td></tr>
<tr><td>4</td><td>Povide a description of how to answer the question</td><td>Describe:
Which research methodology might be the most effective to answer the research question.
(Deductive, inductive, abductive)
Which research method is needed
(e.g. experiment, case study, survey, …)
Which system is selected to be studied
Which data type is needed and which data sets are required
Which analysis and/or development method will be used
(e.g. statistical, dynamic modelling, FEM)</td></tr>
<tr><td>5</td><td>Describe the significance of the research</td><td>1) Provide the expected results of the formulated question.
2) Answer the following question:
Assume you could provide an answer for your research question, what is the significance of that answer?</td></tr>
</table>

8.2 Project planning

8.2.1 Project charter

1) Why are we doing the project? (Purpose)
2) Is there a common understanding of expectations? (Commitment)
3) What do we have to work with (Resources)
4) What are we trying to accomplish? (Goal)
5) What needs to be achieved and why? (Deliverables)
6) How will it be done? (Activities)
7) Have we defined the most significant milestones? (Time)
8) Have we uncovered all relevant opportunities? (Scope)
9) Have we uncovered all relevant limitations? (Constraints)
10) Have we defined: Who is involved, what is their role, responsibilities, and means of communication? (Organization)

8.2.2 Gantt chart



8.3 Extruder Schematic