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Development and implementation of a condition based maintenance system in ABB Electrical machines factory

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AUTHOR’S DECLARATION

I have written the Master’s thesis independently.

All works and major viewpoints of the other authors, data from other sources of literature and elsewhere used for writing this paper have been referenced.

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TUT Faculty of Mechanical Engineering
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Master's thesis task

2014/2015 academic year spring semester

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Field of study: Industrial Engineering and Management

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MASTER'S THESIS TOPIC:

Development and implementation of a condition based maintenance system in ABB Electrical Machines Factory

Seisukorrapõhise hooldussüsteemi väljatöötamine ja juurutamine ABB elektrimasinate tehases

Tasks and timeframe for their completion:

Nr	**Task description**	**Completion date**
1	Case study and analysis of the current preventive maintenance system, failure modes and repairs.	16.03.2015
2.	Map-out of the critical machine parts and related maintenance actions.	31.03.2015
3.	Assigning an individual set of monitoring devices for each machine. Set-up and installation.	15.04.2015
4.	Setting up a data management and an action flow-chart for CBM.	01.05.2015
5.	Creating complete CMB profiles for most critical equipment.	17.05.2015
6.	Results and economic efficiency.	20.05.2015

Engineering and economic problems to be solved:

The target is to lower labor hours spent on maintenance and increase the reliability of the machines by providing tailored maintenance plans for Electrical machines factory's equipment.

Defense application submitted to deanery not later than…..… Deadline ……...........

Student ……………………. /signature/ ………..……………. date …..........………

Supervisor…………………...../signature/ …………….….…… date …..........………

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Enterprise based confidentiality and other terms to formulate on the reverse side

MASTER'S THESIS OBJECTIVE

To develop and implement of a more advanced condition based maintenance (CBM) system that takes into account the real condition of the machine parts, based on periodical or continuous measurements and analysis.

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LIST OF ABBREVIATIONS

ABB – ASEA Brown Boveri

CBM – Condition Based Maintenance

CMMS – Computerized Maintenance Management System

DO – Design Out

EMF – Electrical Machines Factory

FDP – Failure Development Period

FTR – Fixed Time Replacement

OTF – Operate To Failure

OEM – Original Equipment Manufacturer

PM – Preventive Maintenance

RCA - Root Cause Analysis

RCM - Reliability Centered Maintenance

VPI – Vacuum Pressure Impregnation

WO – Work Order

COMPANY’S REVIEW

In this master thesis, there is given a brief overview about current situation of maintenance strategy in Quant Estonia OÜ ABB Electrical Machines Factory site. Different types of condition based monitoring solutions are described theoretically.

In this master thesis, author will work out 5 different monitoring solutions for ABB Electrical machine factory machinery – vibration analyses, oil analyses, thermography, pressure monitoring and work-hour counting. All these have been implemented, but not in systematic way. Until now, the outcome from condition monitoring has not been so effective as it should be in real life, if system is completely implemented.

During this short period there are good results from pressure monitoring, where one case study already exist, thanks to the author of this master thesis. Quant Estonia will state, that with no remarkable investments it is possible to create foundation for good condition based maintenance system. For example, there are already installed simple hour counters, which are giving effect for maintenance cost, when production load is not stable and there are remarkable variations.

Author of this thesis has been working in this service site more than 1 year in reliability specialist position and he has demonstrated different ideas to improve service personnel’s productivity. In current thesis, author has created concrete plans and instructions how to proceed with different monitoring methods.

Proposed updates for vacuum pumps and insulation machines will be taken into use in the future to improve maintenance efficiency and increase reliability of the machinery.

This work has given good knowledge and real skills for author in condition based maintenance methods. In addition, Quant Estonia OÜ will get some advantages from this development in the future. This method must be brought into effect with most machinery of this factory. This is real value for end customer, because it will help to reduce maintenance costs and saves production time.

Kaupo Mäesalu M.Sc.
Quant Estonia OÜ Site Manager
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The topic of the hereby thesis is inspired by the need for improvement in the maintenance system in ABB's Electrical machines factory. I would like to thank PhD Robert Hudjakov and Ass. Prof. Kristo Karjust for their guidance and help. In addition, I would like to thank Full Service site manager Kaupo Mäesalu for his continuous support. Finally, special thanks to Quant Estonia OÜ for giving me the chance to work and study in a leading industrial company.

1 INTRODUCTION

ABB Electrical Machines factory (EMF) in Jüri is the largest windmill generators producing factory in ABB Group. The factory spans over 20 000 m^2 and holds about 300 workers and more than 200 machines. Currently those machines are maintained over a fixed period. This means that no variable other than astronomical time is considered when servicing those machines. The current state of maintenance operations is described in detail in chapters 3,4 and 5.

The purpose of this master's thesis is to implement a more advanced and flexible condition based maintenance (CBM) system, that takes into account the real condition of the machine parts based on periodical or continuous measurements (chapters 6 and 7). The target is to lower the labor hours spent on servicing and increase the reliability of the machines by providing tailored maintenance plans. Both engineering and financial variables are considered when developing this new maintenance system.

The scope of the thesis includes the selection and installation of unique measurement devices, data flow set-up, monitoring process and an example of a condition based maintenance plan. CBM will be implemented only on machines where it is considered beneficial in terms of reliability. Less critical equipment will continue with the current maintenance system. Author has a three-year experience in industrial maintenance business and has worked for a year in that exact factory.

An alternative purpose of this thesis is to supplement the existing documentation of the machinery in ABB EMF. At the moment, the information about production equipment is incomplete and scattered. Some machinery is lacking detailed drawings and spare parts info. This makes the development process of new maintenance plans more difficult and time consuming.

The proposed maintenance plans, monitoring actions and other data will be reviewed by the site manager and will then be implemented immediately.

2 BACKGROUND

Full Service is a maintenance contract, according to which the service providing company is responsible for the condition of all the equipment in a manufacturing facility. Where the other party (usually manufacturing or industrial company) pays a monthly or yearly fixed price for the maintenance service. In addition to repairs and maintenance, the contract usually includes reliability, energy efficiency, design-out, data management and additional works. The service provider places a stationary crew in the client's facility and covers all the production shifts.

In ABB Electrical machines factory in Jüri, the aforementioned agreement has been in place since 2006. A crew of 15 (10 blue collars, 5 white collars) has been taking care of the production equipment for almost a decade now and has acquired remarkable knowledge about the clients equipment and technology This union is now seen as an efficient symbiosis, that is profitable for both parties. Quant Estonia OÜ (service provider – formerly known as ABB Full Service, hereinafter Quant) has put significant effort into making the manufacturing equipment more reliable.

ABB's electrical motor and generator production spans over five facilities (see Figure 2.1). The equipment includes but is not limited to 7 stamping machines, 15 insulating machines, 28 cranes, 2 forming machines, 2 balancing machines, 2 milling machines, 2 welding robots, several presses, 7 ovens, 2 impregnation vessels, many conveyors, testing areas and a lot of mobile equipment. Maintaining such significant amount on machinery requires knowledge of mechanics, lubrication, electronics, programming and materials. Throughout the years, the crew has put a lot of effort into trainings and self-improvement.

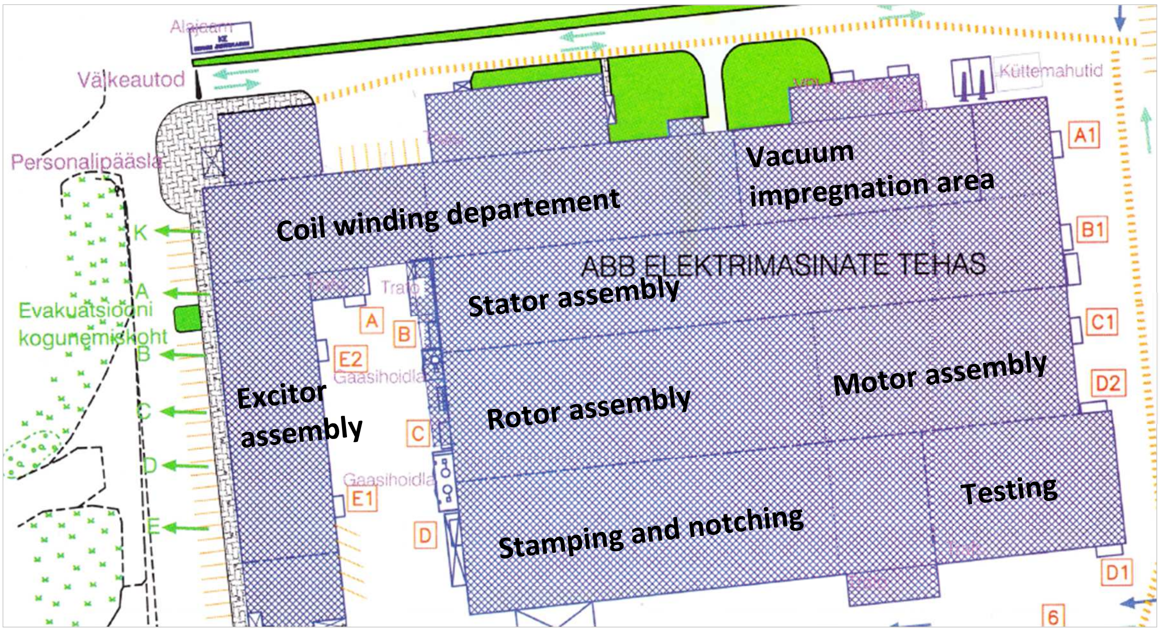


Figure 2.1 Factory layout

Quant Estonia OÜ follows ISO standards: ISO 9001 (quality management), ISO 14001 (environmental management) and ISO 180001 (occupational health and safety). In addition to the aforementioned standards EMF follows ISO 3834 (welding quality).

What Quant values most is safety. With more than 3000 days without a lost-time accident, Quant is definitely a front-runner in terms of creating safe working conditions. Safety is always kept in mind when making changes to original equipment or factory layouts. The vacuum impregnation area in ABB EMF requires special precautions because the chemicals used for the processes are hazardous to workers health. All in all, the purpose of the Full Service is ensure uninterrupted production workflow at maximum level of performance.

3 PROCESS OVERVIEW

3.1 Maintenance Works In ABB EMF

In maintenance business, it is customary to make difference between maintenance and repairs. Maintenance is a set of predefined actions that can be fulfilled on a working or shutdown machine with or without moderate disassembly. The purpose of maintenance is to ensure that the machine is functioning correctly and extend the useful lifetime of the equipment.

For example, a basic maintenance work order (a document that initializes the maintenance work and includes all the required tasks on paper) includes cleaning of the surfaces, checking for abnormalities (cracks, excessive noise and vibration, leakages), checking for loose fixtures, greasing bearings and sliding parts, and changing expandable materials like rubber seals etc. (Appendix 1 – Work Order Example). Cleaning the machine surfaces is important because otherwise it is almost impossible to notice potential issues.

Repairs on the other hand are often unplanned, and the set of actions is usually created after the disassembly of the system. Repairs often require the replacement of the dysfunctional part; rarely the damaged part can be retrofitted and reinstalled. Repairs can span from a couple of minutes to several days and come with production downtime. No matter how well the maintenance system is set up, breakdowns still happen. When the replacement parts and lubes can be ordered right before maintenance works, then breakdowns on the other hand require a decent stock of spare parts. The purchase of those parts is based on analysis and estimates but still it happens that sometimes the required part is not in stock. Spare parts inventory is a remarkable cost for the client.

Maintenance work requires skilled workers and unique know how. Some of the machinery in EMF is custom built or modified so that there are no other similar examples to relate to. In such cases the service engineers are on their own because there is no source for advice or instructions. Mostly the maintenance plan is based on OEM’s service manuals and is later supplemented on personal experiences.

3.2 Maintenance Types, Overview and Analyses

There are five maintenance types according to ABB's Maintenance Strategy Manual [1]. Divided into tree sub-categories: reactive, preventive and predictive (see Figure 3.1). Each representing a level of achievement. Every subsequent level requires improved expertise and becomes more difficult to manage.

1. Operate to failure (OTF) – Reactive repairs
2. Fixed term replacement (FTR) - Preventive (time-based replacement)
3. Preventive maintenance (PM) – Preventive (fixed term maintenance)
4. Condition based maintenance (CBM) – Predictive (based on observation)
5. Design out (DO) – Predictive (eliminates the root cause)

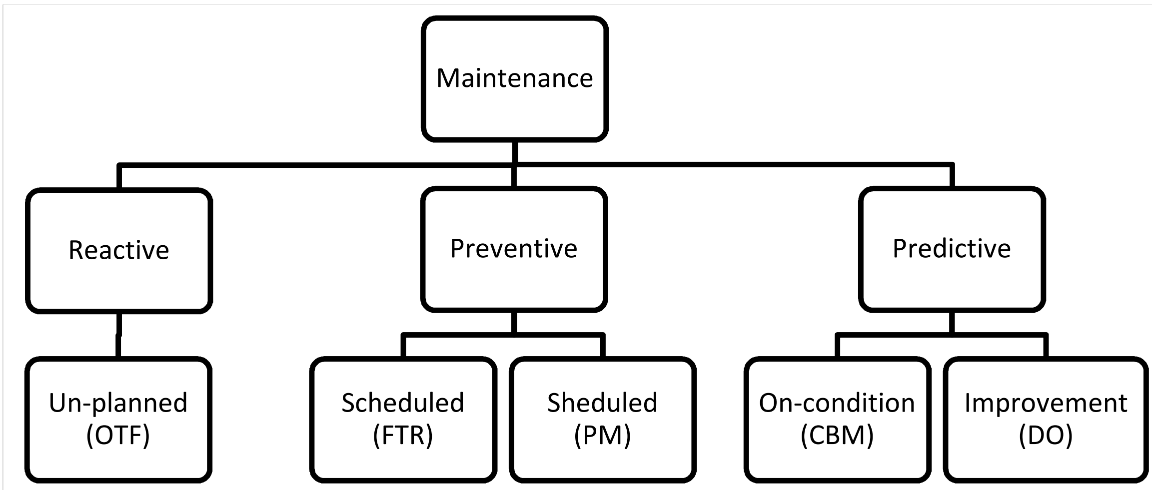


Figure 3.1 Maintenance types

Currently Quant at ABB EMF operates on the third level (PM), which means the maintenance work orders are scheduled without any reference to the actual condition of the machine. Usually the following fixed terms are used: monthly, 3 monthly, 6 monthly, yearly, 2 yearly. Myhre, Petersen and Ugarelli proposed in their work - "in planned maintenance, the frequency of maintenance operations is based on recommendations from the equipment manufacturer in combination with internal practices" [2]. According to the maintenance calendar, the service takes place regardless the fact that the machine has even worked since last maintenance. Furthermore, they stated, "the disadvantage of this scheme is that there are large deviation in the deterioration of seemingly identical equipment" [2]. This brings us to the two most obvious downsides of fixed term systems.

Firstly, it is always based on best practice, meaning that it could take years to set up the proper periods for each action and even then, one can miss the worn out part. This issue is best represented by the p-f curve:

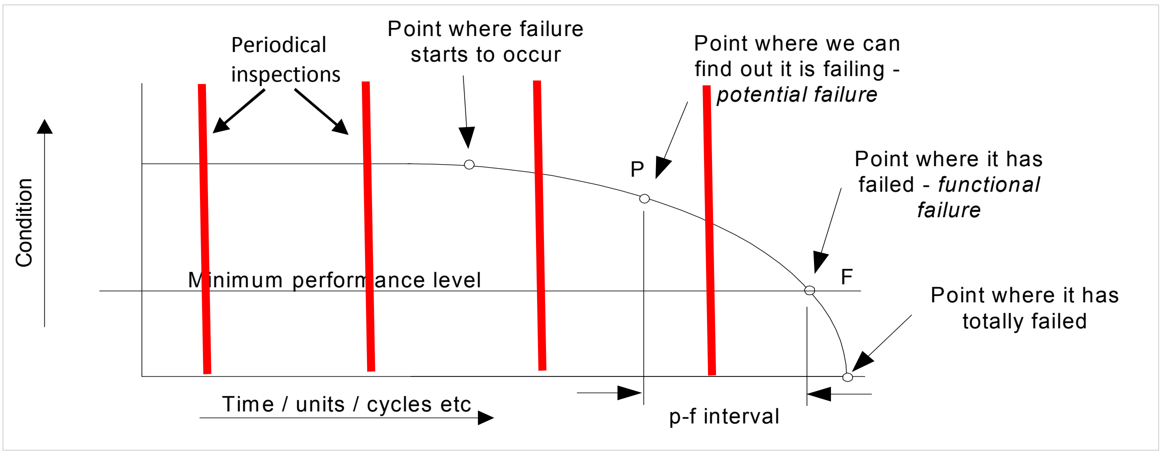


Figure 3.2 p-f curve [3]

The graph (see Figure 3.2) illustrates, that there is a short time frame where the failure is noticeable, but the machine is still functional. For the PM system to be reliable, the maintenance has to fit into that time frame. This is the reason why it is hard to detect electrical failures with PM. Because of electrical failures occur instantaneously (it either works or it does not) – the interval between the *p* and *f* is invalid. Red vertical lines (inspections) illustrate an ideal PM schedule where the last inspection is right between *p* and *f* points. In such case, the maintenance technician should notice the potential failure during inspection and still have enough time to replace or repair the faulty part.

The second shortcoming is the fact that both FTR and PM do not take into account the actual condition of the machine. It could be used in parallel with some kind of condition monitoring device to get better information about the workload the equipment is currently under. Otherwise, one could over or under maintain its machines, which in both cases could prove to be costly. For example, by including a work hour counter or a tachometer, we have much more information about the current state of the assembly and we can rule out the chance of maintaining a machine that has not done any work. The best-case scenario would be if the metering device were directly connected to the CMMS (computerized maintenance management system), which considers the reading when generating work orders. By integrating metering devices to the preventive maintenance system, we are incrementally moving towards condition-based maintenance.

The following table (Table 3.1) compares the different types of maintenances:

Table 3.1 Comparison of different maintenance types

Level of maintenance	Spare parts cost	Ease of implementation	Cost of implementation	Day-to-day expenses	Interruption type
Operate to failure	High	Easy	Low	Low	Unplanned
Fixed-term replacement	Medium	Moderate	Medium	High	Planned
Preventive maintenance	Medium	Moderate	Medium	High	Planned
Condition based maintenance	Low	Difficult	High	Medium	Planned
Design out	None	Difficult	High	Low	Single

In a way, all the aforementioned maintenance types are applicable in EMF. They just have to be assigned to independent assemblies, so that the interruption type is acceptable. In most cases, the production loss is the most costly factor. The following figure (see Figure 3.3) illustrates the balance point between failure costs and maintenance costs.

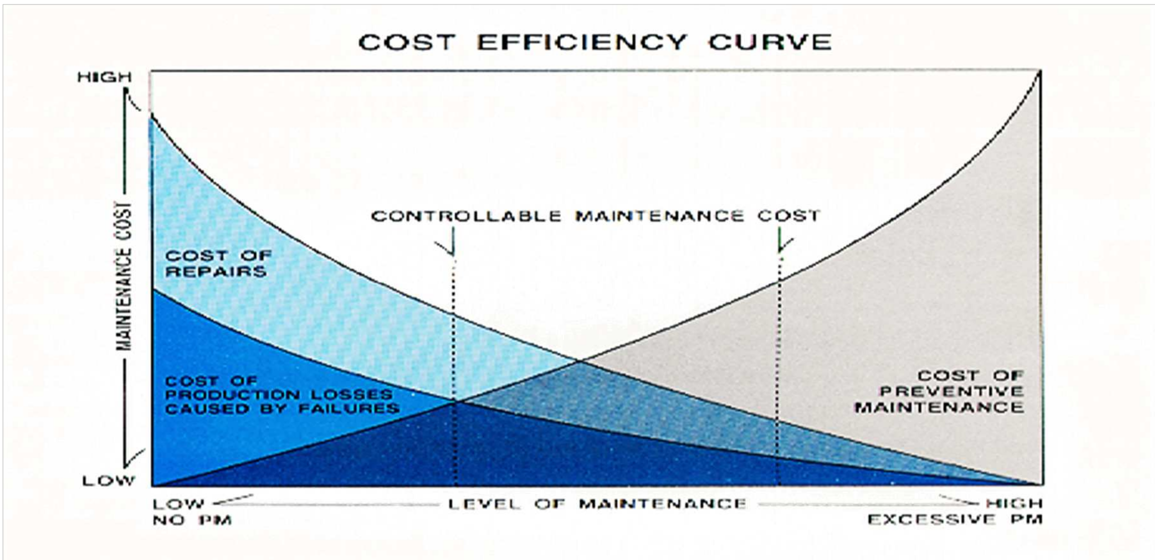


Figure 3.3 Cost efficiency curve [4]

4 ANALYTICAL TOOLS OVERVIEW

"The application of CBM requires the use of certain analytical tools, such as failure mode, effect, and criticality analysis (FMECA) and RCM to determine the likelihood of failure and how failure would occur; as well as a reliable information tool (i.e., CMMS) to capture and track repairs and associated costs of the assets under consideration" [5].

4.1 Computerized Maintenance Management System

The computerize maintenance management system assembles all the data about machines, spare parts, labor hours, invoices, shift planning etc. "Additionally, CMMS software aids businesses in maintaining the balance in cost for everything from properties and machines, to human resources and stock" [6]. "Several other duties that the CMMS software can accomplish for any manager includes archiving tasks and expenses, storing and distributing materials, and keeping close inventory for any abnormal events during the management process" [6]. The article [6] further proposes that CMMS software also helps to avoid any preventable losses and supports the upkeep of the facility.

When used correctly it is an indispensable assistant in planning works and resources. Currently Quant Estonia OÜ is using a system called Maximo 7.5 developed by IBM. However, as with any other IT system the data it delivers is always as reliable as the data inserted. Meaning that the authenticity of the information is in the hands of the administrator and users – the maintenance engineers.

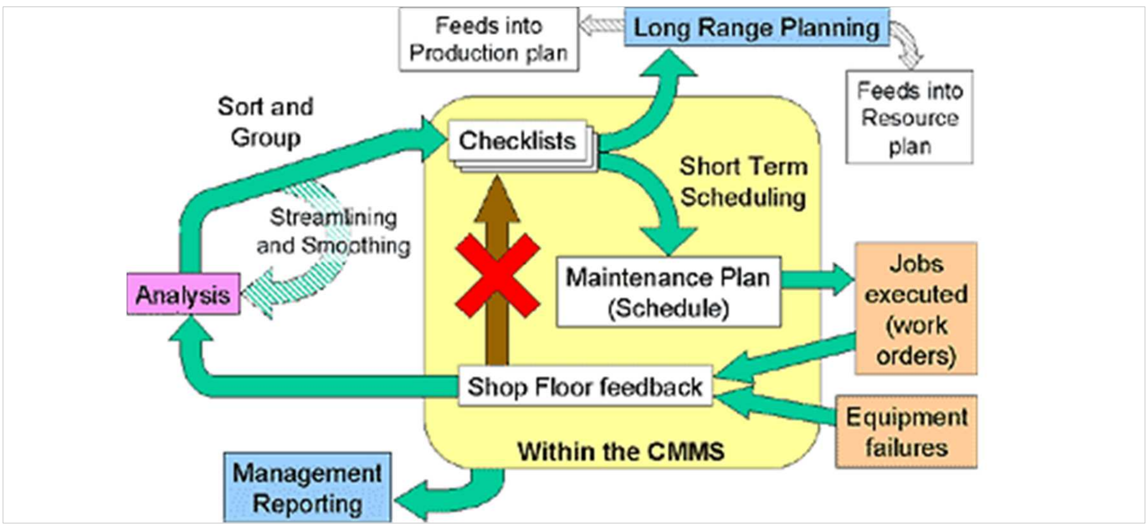


Figure 4.1 Data flow in CMMS [7]

This is the point where Quant is currently struggling to succeed, because the information going into the system is nowhere near the expected quality and this makes the later analysis difficult and unreliable. Therefore, it is essential to straighten the information in the CMMS, which is the foundation of analysis. This can be achieved by creating a set of specific rules (see Figure 4.1 above), which will assist the engineers when filling in the information. The development of the CMMS is not a topic of this thesis, but is rather a recommendation for future work.

4.2 Criticality Analysis

"Criticality analysis is a technique for identifying and ranking potential undesired events by importance" [8]. In order to differentiate machines, based on the consequences their breakdown will incorporate, Quant has composed a criticality table, which follows the RPN (Risk Priority Number) methodology. The final levels of criticality are A, B and C where A is the most critical. When assigning a level to each machine, 6 types of risks are analyzed by the following criteria (Figure 4.2).

Equipment Classification

EVALUATION FACTOR	LEVEL 1	LEVEL 2	LEVEL 3
Safety *Risks for people*	Equipment failure affects seriously people	Equipment failure causes risks to people	No consequence
Env *Risks for the environment*	Equipment failure affects seriously the environment	Equipment failure causes risks to the environment	No consequence
Quality *Effect of failure on product quality*	Failure affects quality, generating out-of-specification products or affecting seriously the revenue	Equipment failure makes product quality variable and affects revenue	No effect on the product or revenue
Working Shift *Working shift of the equipment*	Equipment is required 24 hours per day	Equipment is used more than half of a day	Occasional use
Production *Effect of equipment failure on production*	Equipment failure causes total interruption of production	Failure causes interruptio of an important system or unit, or reduces productio	There is spare equipment or it is cheaper to repair the equipment after failure
Frequency *Number of failures in determined period*	Many shutdowns due to failures (more the once per 6 months)	Occasional shutdowns (once per 6 months)	Not frequent (less than once a year)
Cost *Amount of money involved in the failure*	Repairing time and costs are very high	Repairing time and costs are high	Repairing time and costs are not significant

Figure 4.2 Guide for criticality classification [1]

Each year the criticality list is reviewed and updated. A flow analysis program is used to determine the appropriate level (Appendix 2 – Criticality Assignment Tool).

A good example of an A-critical machine is the scrap conveyor in stamping production line. In essence, the conveyor is nothing extraordinary but when it fails, it halts all the machines in stamping department, because all the five presses need the conveyor to carry out the scrap metal – a byproduct in stamping.

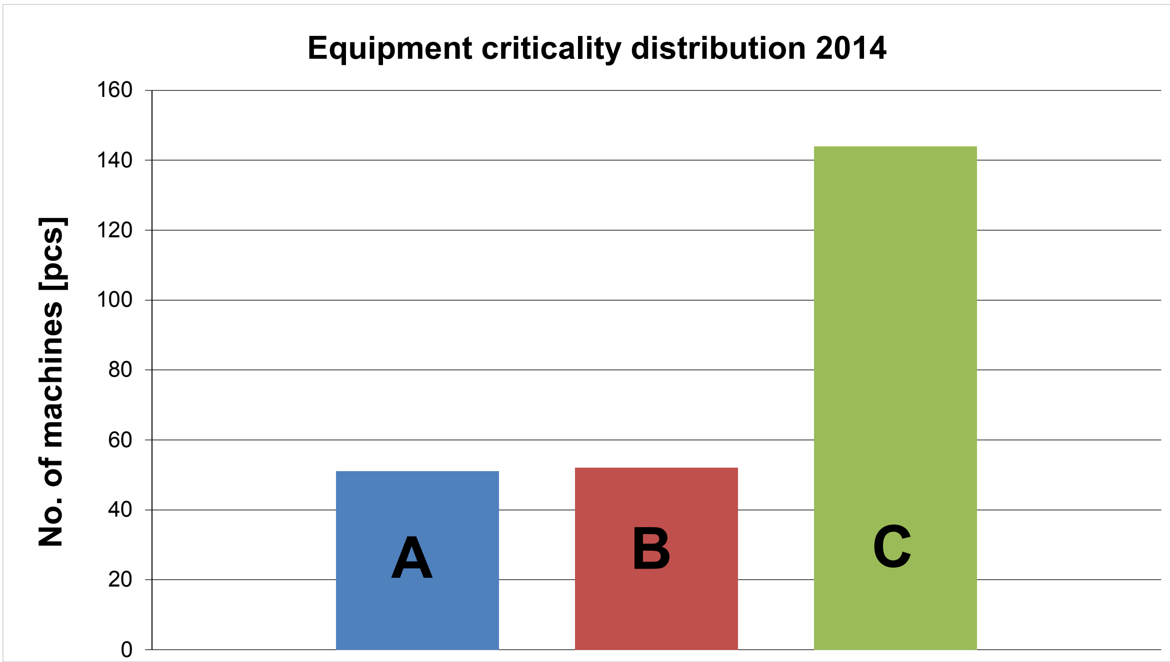


Figure 4.3 Equipment criticality distribution according to year 2014

The chart (Figure 4.3 above) indicates that the A-critical machines account for about 1/5 of all the machinery. All together 247 machines where evaluated in 2014, out of which 51 where A-critical and 144 where C-critical.

4.3 Analysis Methods Overview

In order to prevent breakdowns from reoccurring because of similar causes and to predict future failures, solid analysis needs to be conducted (Appendix 3 - RCA Flowchart). The most valuable information is gathered right after the breakdown, when all the defect parts are still in their failure formation. Most of the failed parts are photographed and stored for inspection. Later, when the set is cleaned and restored, there is no information to analyze. Therefore, it is necessary that the technician records the failure state.

For analyzing breakdown causes two methods are used in ABB EMF. 5-why method is a quick analysis form (see Figure 4.4) that guides a technician to find out the most likely reason for which the breakdown occurred. It is designed to take up to 10 minutes. The engineer is expected to find answers to five questions where each next one will specify the previous. The general idea is that every single root cause is identifiable by answering those five sequential questions.

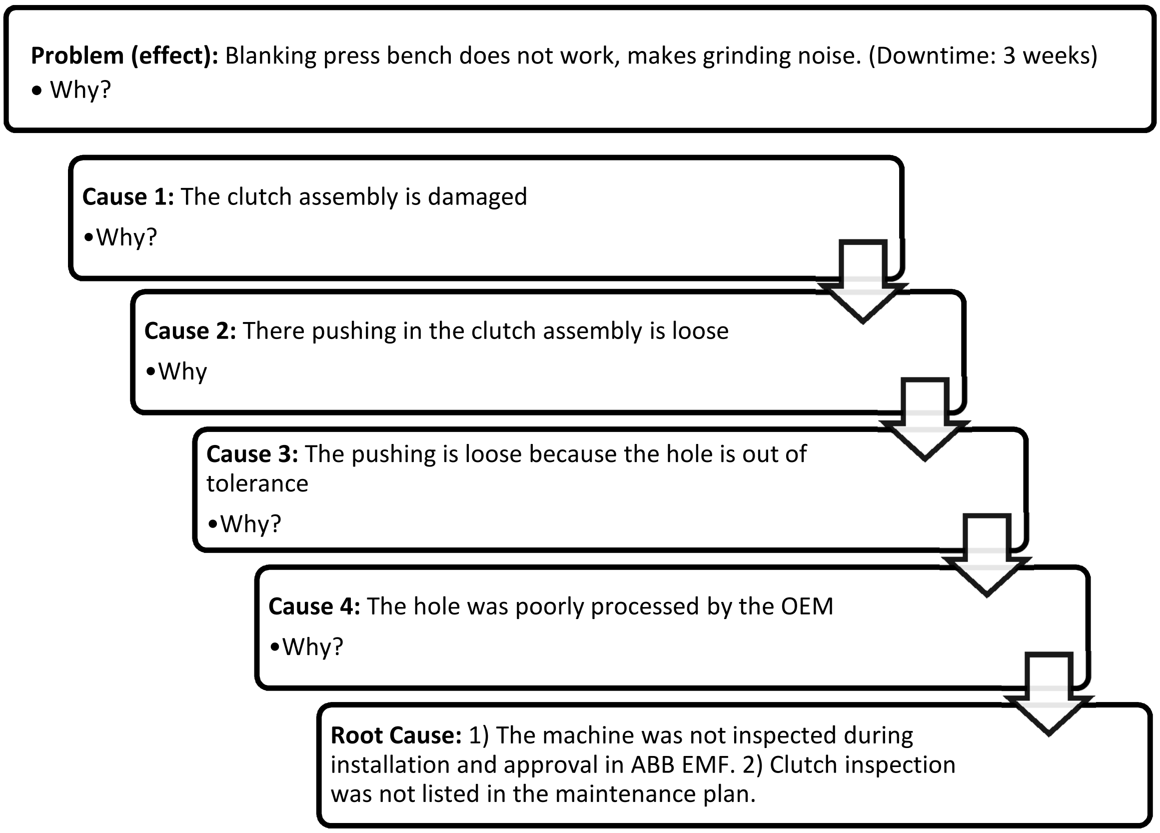


Figure 4.4 5-Why analysis sample

According to Rooney and Heuvel, “if the analysts stop here, they have not probed deeply enough to understand the reasons for the mistake” [9]. “Therefore, they do not know what to do to prevent it from occurring again” [9].

The second level of analysis– a root cause analysis (RCA) – is a tool for the reliability engineers and is quite similar to the 5-why method but more thorough. “Root cause analysis is a process designed for use in investigating and categorizing the root causes of events with safety, health, environmental, quality, reliability and production impacts” [9].

Reliability engineers will use the pre-filled 5-why form as a preliminary input and source of information. The RCA form will also include photos, the history of all the machine related actions before the breakdown, a list of actions that were executed right after the breakdown, etc.

The RCA is more effective when conducted in a group. For best results, engineers from different fields should be included. Brainstorming method is used to find out all the possible reasons for that breakdown, regardless of how unrealistic they might seem at that moment. Later with the help of group discussion, a most likely cause is selected and a set of actions is composed in order to remedy the situation and prevent the same breakdown from reoccurring in the future.

4.4 Failure Patterns

According to study, “until the mid-1970’s, the accepted theory of maintenance was that all equipment had a safe or economic life and that this life could be defined” [10].

Engineers Stanley Nowlan and Howard Heap studied the failures in United Airlines aircraft industry over four years. The data they collected disproved the theory that all equipment had a safe or economic life [10]. Later it became obvious that failures throughout the equipment life cycle follow six different patterns (Figure 4.5).

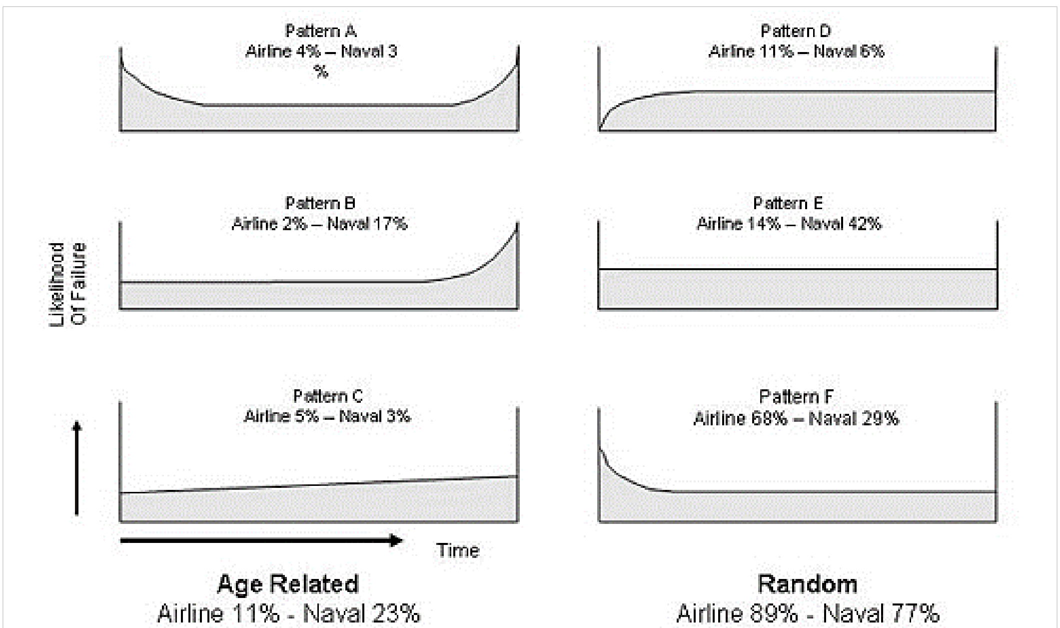


Figure 4.5 Nowlan and Heap failure Patterns [11]

From personal experience and the comments of Quant’s technicians, most equipment in EMF follows the bathtub curve (Pattern A). Usually the first slope (the infant mortality curve) is caused by incorrect installation, inaccurate adjustment or OEM’s poor engineering work. Followed by a useful life period, where the failure rate is constant. The last inclining curve (wear-out) is caused by the overall degradation of the equipment.

5 PREVENTIVE MAINTENANCE

5.1 Current State in ABB Electrical machines factory

Like previously described, the current fixed time maintenance system is proactive in essence but not as efficient as a CBM would be. Yet another issue is the ability to evaluate or measure the efficiency of current maintenance system. Every month the CMMS automatically generates around 100 predefined work orders for regular maintenance. About 80% are monthly services, which mainly compose of general inspection, cleaning and calibrations or adjustments.

Due to limited resources (mainly labor), not all of those planned service jobs are completed. Work orders for less critical (C-level) equipment are often rescheduled or cancelled. About 68% on all planned maintenance jobs were not completed in the first quarter of 2015 (see Figure 5.1).

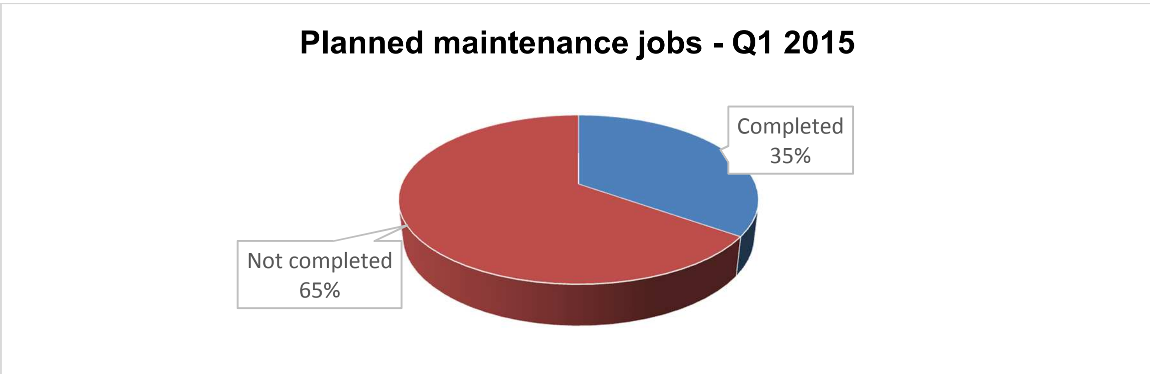


Figure 5.1 Completed and not completed maintenance jobs in Q1 2015

This is a clear indicator that the amount of planned jobs is not in accordance with available resources and needs to be adjusted. Service supervisor is responsible for PM planning. The following flow-chart describes the planning process and the people involved (Figure 5.2).

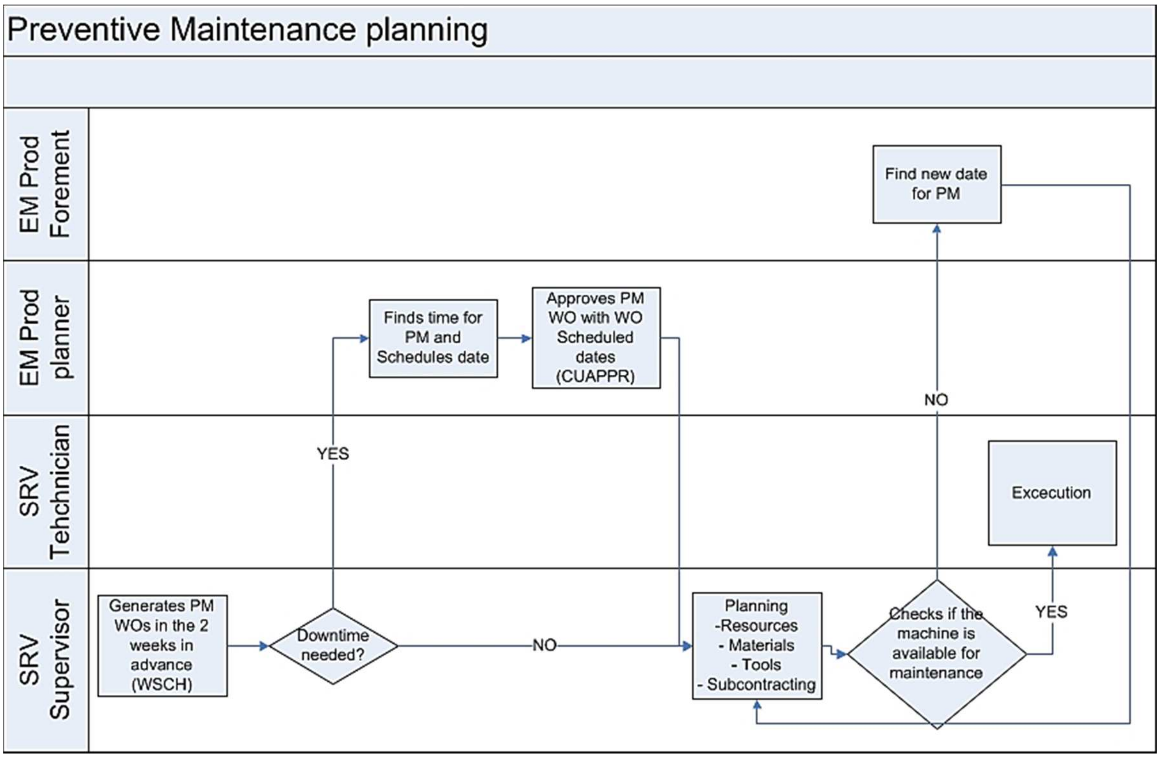


Figure 5.2 Preventive maintenance planning flowchart [1]

5.2 Maintenance Plans

According to the ABB Maintenance Strategy Manual, “optimum maintenance plans incorporate a combination of time-based, condition-based maintenance and operate-to-failure maintenance strategies” [1]. Quant Estonia OÜ has a “double objective - provide short-term effectiveness whilst ensuring long-term efficiency” [1]. Short-term effectiveness focuses on inspection, lubrication and maintenance plans that are targeted on ensuring the continuity of production [1]. Long-term efficiency on the other hand, focuses on setting up a continuous improvement process to enhance these maintenance plans by comparing maintenance history with the actual maintenance activity [1].

The following flowchart (Figure 5.3) guides the reliability specialist to assign an appropriate maintenance strategy to each equipment.

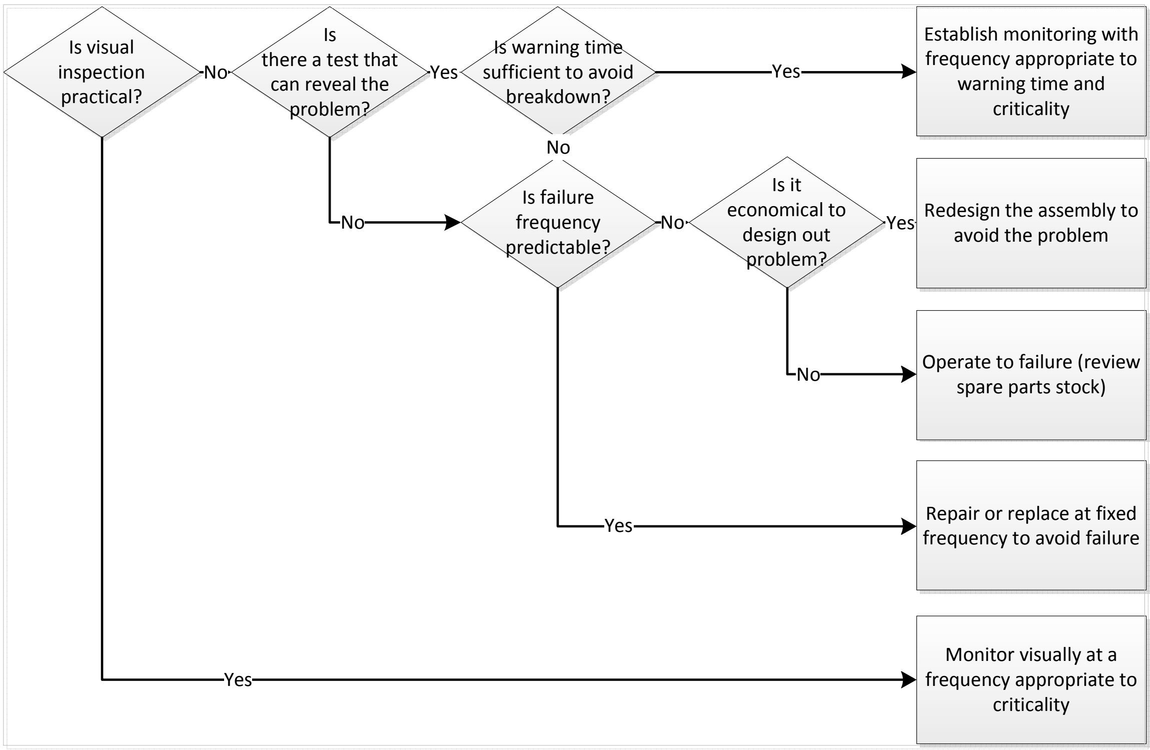


Figure 5.3 Maintenance strategy flowchart [1]

In theory, the reliability specialist should periodically review the maintenance plans and adjust them according to RCM (Reliability Centered Maintenance) concepts. “Reliability-Centered Maintenance is a process used to determine the maintenance requirements of any physical asset in its operating context” [12]. This includes changing the fixed periods according to the equipment life cycle phase, adding or removing job tasks, reviewing the spare parts requirements, etc.

5.3 Problems to Overcome

In the process of developing novel maintenance plans, the following issues have to be considered:

1. The condition of the equipment is not systematically considered when planning maintenances.
2. The amount of planned maintenance jobs is not in accordance with available resources and needs to be adjusted.
3. The current maintenance plans are superficial and do not contribute to outdated equipment.
4. The current state of CMMS does not support the analysis of failures, costs, resources etc.

6 CONDITION BASED MAINTENANCE

6.1 Introduction to CBM

"The concept of CBM was first introduced by the Rio Grande Railway company in late 1940s and initially it was called predictive maintenance" [13]. "The objective of CBM is to minimize the total cost of inspection and repairs by collecting and interpreting intermittent or a continuous data related to the operating condition of critical components of an asset" [14]. Knapp et al. argued that, "monitoring, where cost-effective, could provide adequate notice on pending failures, which would allow for planned repairs based on asset degradation, as opposed to costly time-based (fixed intervals) repairs or emergency breakdowns" [15].

"The CBM gives us prior warning of impending failure and increased precision in failure prediction" [16]. "Thus, it can effectively reduce the product failure compared to other approaches" [16]. "From the viewpoint of product safety management, the CBM is useful for the product types where safety is considered important since it can increase safety by detecting problems in advance before serious problems occur, which leads to the improvement of customer satisfactions due to the high quality assurance" [16].

According to Moubray, "unless there is a dominant age-related failure mode, time-based overhauls do not improve the reliability of complex items" [17]. Furthermore, "it is highly possible that time-based overhauls would introduce infant mortality failures in otherwise stable systems" [17].

"With condition-based monitoring, managers can focus on just-in-time (JIT) replacement" [5]. "In addition, the CBM can optimize the production process and improve its productivity" [5]. "However, CBM is not applicable to all maintenance assets and should only be applied to instances where condition-monitoring techniques are available and cost-effective" [19]. Condition based maintenance consists of three key steps [19]:

- *Data acquisition, to obtain data relevant to the system health*
- *Signal processing, to handle the data or signals collected in step 1 for better understanding and interpretation of the data*
- *Maintenance decision making, to recommend efficient maintenance policies based on diagnosis and prognosis extracted from the data.*

6.2 Monitoring Solutions

The choice and variety of monitoring devices is beyond measure. A limited selection of monitoring solutions that are suitable for ABB EMF are highlighted in this paper. This thesis focuses on five types of measurements.

1. Vibration analysis
2. Hour counting
3. Oil analysis
4. Temperature reading (thermography)
5. Pressure monitoring

There are many other measures and KPIs to monitor in production facilities, but Quant is primarily interested in data that supports maintenance activities. For example, the factory itself measures: machine speeds, product quality, quantity produced and labor hours. Based on such data one can promptly make adjustments to processes or reorganize resources.

Some of this data can be used for maintenance. For example the count of products produced can be used similarly to machine work hours. This is a method widely used in continuous flow production where line maintenance is planned after every 10 000 units for example. ABB EMF uses a cell layout where separate operations are made in each department. Therefore, the aforementioned maintenance system is not the best solution for this factory. The more suitable measurement devices are described as follows.

6.3 Vibration Analysis

"Vibration analysis allows the maximum interval between repairs to be realized through monitoring the actual mechanical condition of rotating machinery" [21]. "Equipment downtime is not required for monitoring activities to occur" [21]. "The monitoring, in turn, directly minimizes the number and cost of unscheduled machine outages created by component failures" [21]. "Hence, optimum equipment availability may be obtained" [21]. "Vibration analysis is predicated on two basic facts" [21]:

1. *All common failure modes have distinct vibration frequency components that can be isolated and identified.*
2. *The amplitude of each distinct vibration component will remain constant unless there is a change in the operating dynamics of the machinery.*

As every condition monitoring solution, vibration monitoring can also be continuous or recurrent. In case of a recurrent measurement system, the frequency of the measurements has to be higher than the period between the point of failure occurrence and point of breakdown (See Figure 3.2 above). Otherwise, the technician is unable to intervene the failure and the vibration analysis has no effect.

Unfortunately, the measurement device does not refer to the source of the vibration, which means that the cause could be anything from the worn out bearings to misbalanced pulley to loose motor fittings. “Therefore, technicians need to be trained in basics of vibration analysis techniques to improve the measurements and to detect failures” [1].

6.4 Vibration Case Study

In October 2014, one of the largest presses in EMF, the “Schuler SP250” stopped working. The main drive (Figure 6.1) (Siemens 1PH7137-7QD02-0ba0) broke down because of a worn out bearing. Most likely, the symptoms (vibration, noise and heat) were noticeable months if not even years before the breakdown occurred. Because the motor is located deep inside the press and it is not recommended to run the press with personnel inside the cabin, the symptoms were not detected until the motor crashed and the machine shut down. The main drive was damaged beyond repair. The subsequent root cause analyze indicated that no proper monitoring actions were implemented in the maintenance plan and the inside of the machine was only inspected during shutdowns.

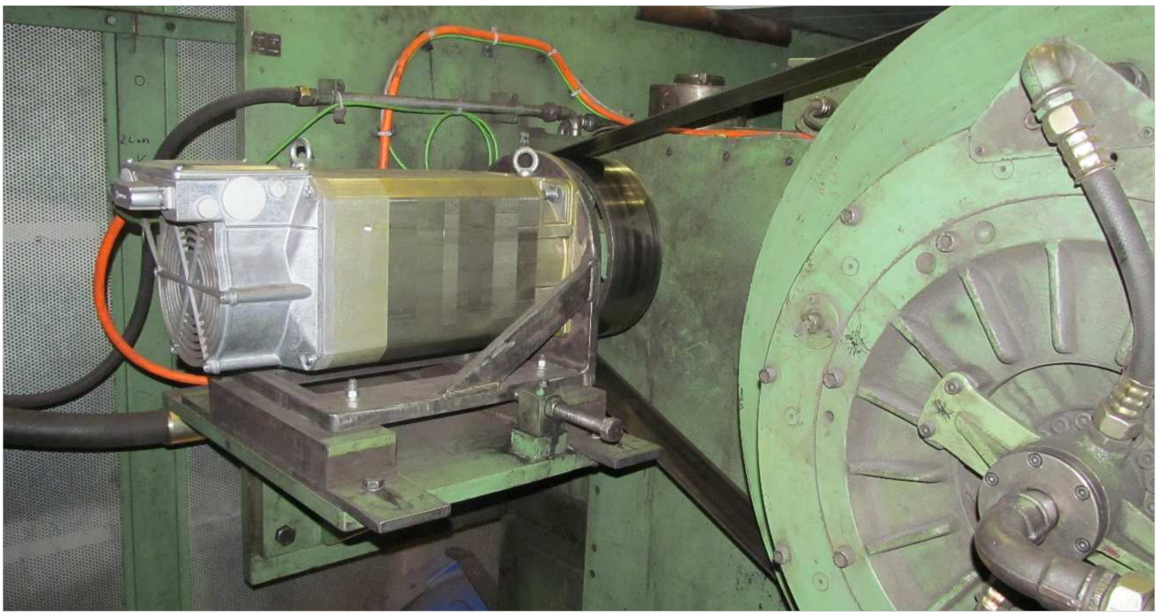


Figure 6.1 Failed motor

After the breakdown, Quant received a quotation for a fixed vibration monitoring system. The quotation composed a 4260 € investment which included a vibration sensor and a multi-cable transit system. For continuous monitoring, it still needs some additional equipment – a programmable logic controller (PLC) or a distributed control system (DCS). The cost of a new motor on the other hand was 3495 €. The motor replacement takes around 50 minutes. The total cost of motor replacement with production downtime included is still less than the continuous monitoring solution and therefore, is not financially reasonable. An alternative would be to assign a OTF (operate to failure) method and buy a new motor into stock as an spare part.

There are also several portable devices for vibration measurement. For example, the Microlog GX is a high-end device that uses the same sensor (CMSS 2200) as in the previously mentioned quotation but displays the data on a handheld device. The specialist walks around the site and measures all the required assemblies. Then the device saves the data and later composes a report. Therefore, the data recording is intermittent, but on the other hand, you can measure all the assemblies with one investment. For example, the cost of such service is 10 EUR/measurement point. Each motor has at least two measurement points (drive-end bearing and opposite drive-end bearing). A survey conducted in SKF indicated, that a reasonable frequency to cycle the vibration measurement would be 4 times a year.

The third option is that, the technicians themselves measure the vibration. There is less professional equipment on the market like the SKF CMAS 100-SL Machine Condition Advisor. According to the SKF sales brochure, the "Machine Condition Advisor measures the absolute values of the machine vibration to indicate machine health or bearing damage" [22].

The technicians still need a short training to properly operate with the CMAS 100-SL, although it is the easiest to use. The following table (Table 6.1) compares different vibration monitoring solutions.

Table 6.1 Comparison of vibration measurement methods

Method	Price/cost	Sampling frequency	Data quality	Figure
Fixed sensor	4260€ per 1-2 measurement points	Continuous	Good and consitent	 [23]
Monitoring service	10€ per measurement point	Starting from 4 samples/year	Good but intermittent	 [24]
Self service	1600€ (device)	Starting from 4 samples/year	Intermittent, manual recording	 [25]

There are not so critical installations in EMF where the fixed sensor would prove itself economically reasonable. Therefore, the better solution would be to outsource the service. In addition, it would be wise to consider purchasing the cheaper monitoring device to gain that vibration monitoring experience and do additional monitoring to the equipment that is highlighted in the service provider’s quarterly reports.

6.5 Oil Analysis

According to a study, “many plants get involved in routine oil sampling and analysis to help reduce the costs associated with maintaining lubrication systems” [28]. “The most significant costs involve periodic oil changes based on a time schedule as recommended by the equipment specific manufacturer” [26].

“Oil analysis is a predictive maintenance technique used to monitor operating conditions of oil and to identify component wear through periodic analysis of specific parameters such as viscosity, water content, color, suspended solids etc.” [1]. The analysis results reveal the changes in the characteristics of lubricant and wear of components in the initial phase, allowing the reliability specialist to plan the corrective and preventive actions (monitor, centrifuge, filter, replace, etc.) [1].

“One of the biggest concerns in implementing an oil analysis program is to determine which equipment should be sampled” [26]. “For larger systems (greater than 40-50 liters), it is usually more cost effective to establish a condition based oil change program, rather than a time-based one” [26].

For proper and trustworthy results, some additional data is also required. Knowing the actual machine working hours since the last oil change (or oil sampling), gives a lot of background info about the reliability of the test. It also makes it easier to plan future actions and gives a good overview about the durability of the lubricant. When changing all kinds of fluids (including oil and cooling water) it is recommended to write the date and chemical identification info on the tank. The hours can be counted with an add-on device (Chapter 6.8) or reviewed from the machine controller or PC – if it has one.

Quant Estonia OÜ’s partner in oil analysis is Konetex OÜ – a local importer and wholesaler of oil and lubricants. A reliability engineer (author) assembles and labels the sample containers and hands them over to a technician with corresponding work order. The technician takes samples from the oil tank with a syringe (preferably after the pump has worked for some time). The importer sends the samples to an independent laboratory. The laboratory returns the analysis reports after a couple of weeks. There is a separate report sheet for each machine, where the condition of the lubricant is clearly stated, together with recommended actions (Appendix 4 – Oil Analysis Report). All the sampling points are labeled and recorded in the following table (Table 6.2). Konetex OÜ’s specialist advised

Quant to take oil samples 2 times a year and take intermediary samples when the results are in red or yellow.

Table 6.2 –Oil sampling points information and scheduling

Serial No.	Make	Model	System	Brand	Grade	Tank size (L)	Last change
EMF 1.1	Weingarten	HD400	Hydraulic	Enduratex EP 150	100	600L	28.04.15
EMF 2.1	Schuler	SP250	Lubrication	Mobil 600 XP	100	160L	12.03.12
EMF 2.2	Schuler	SP250	Haspel	PC Hydrex AW	46	120L	16.05.14
EMF 2.3	Schuler	SP250	Hydraulic	Mobil DTE 25	46	200L	unknown
EMF 3.1	Steineman	62PR300	Hydraulic	PC Hydrex AW	46	90L	11.07.13
EMF 4.1	Netstal	62PR200	Hydraulic	Mobil DTE 25	46	120L	unknown
EMF 5.1	Hydrogard	P500-1	Hydraulic	PC Hydrex AW	46	150L	09.07.13
EMF 5.2	Hydrogard	P500-2	Hydraulic	PC Hydrex AW	46	150L	09.07.13
EMF 6.1	Danobat	VTC175/210	Lubrication	PC Hydrex AW	46	400L	08.08.13
EMF 6.2	Danobat	VTC175/210	Hydraulic	PC Hydrex AW	46	250L	20.06.13
EMF 7.1	Ziersch	ZT1524	Hydraulic	PC Hyderx AW	46	900L	17.06.14

6.6 Temperature Monitoring (Thermography)

“A thermographic inspection (thermography) is a non-destructive technique that uses infrared ray to measure temperature or observe different patterns of temperature distribution, with the objective of providing information concerning the operational condition of a component, equipment or process” [1]. This method reveals anomalies otherwise invisible to the naked eye.

“Thermography allows to perform measurements without physical contact with the installation (safety), check equipment in full operation (no interference with the production) and inspect large areas very quickly (high efficiency)” [1]. Thermographic inspection in suitable for detecting anomalies in both mechanical (bearings, bushings, hinges, rollers, conveyors, pumps, etc.) and electrical (cabinets, circuit breakers, connections, fuses, switches, power lines, etc.) equipment (see Figure 6.2).

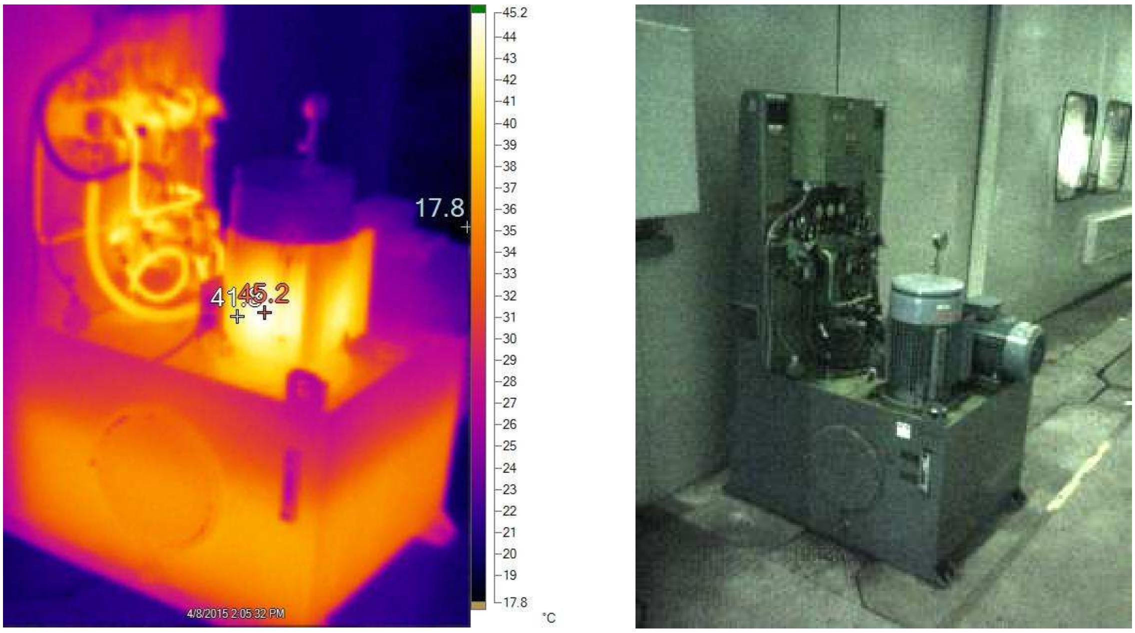


Figure 6.2 Hydraulic station's thermography and visual light image

A thermal imaging camera gives the technician a thorough overview of the heat distribution in the assembly. The bright spots on the camera's display indicate surfaces that have higher temperature compared to the nearby areas. From there on, it is up to the technician to decide if the temperature level is normal or needs further examination. Various sources give us the following temperature limits:

- Bearings (on the housing) 82°C [27]
- Hydraulic oil 82°C [28]

6.6.1 On Board Sensors

Most machines have several safety related temperature sensors already installed by the OEM. These usually include motors, oil systems, electrical cabinets and other enclosed spaces. The purpose of such sensors is to prevent overheating in various assemblies and components. For example, large electric motors have a sensor that prevents the motor from overheating by shutting it down. Sometimes, those readings can be monitored via the machine's display but in most cases those sensors do not have a numeric output and are therefore of no help when it comes to maintenance.

6.7 Pressure Monitoring

There is a lot of vacuum related machines and processes in electrical motor and generator production. In essence, vacuum monitoring is nothing more than pressure measurement, except for the fact that the pressures are extremely low. Specially calibrated measuring devices are used to measure the low pressure in the vacuum grid. A pressure sensor and an analogue-digital converter is used to get the reading. The pumps' working pressure in vacuum impregnation area reach as low as 0,3 mbar.

There could be many reasons why the pressure is out of limits (See Table 8.1 below), but either way, such reading calls for further inspection, during of which the engineer can find out the actual reason. Therefore, the vacuum monitoring device does not point out the exact failure mode, but it rather gives an alarm that there might be something wrong in the grid.

6.7.1 Pressure Sensors

The senor used for low pressure metering is Leybold's Thermovac TTR 91 (Figure 6.3). It gives an analog output 0...+10 VDC. The measureable pressure range is 5 x 10-4 mbar – 1000 mbar. A separate unit "Display One" is used to display the reading. There are 4 vacuum pumps in ABB EMF that could use periodic monitoring.

Figure 6.3 Thermovac TTR 91 [29]

6.8 Work-Hour Counting

The real machine working hours present the potential degradation of the equipment and therefore the need for maintenance or replacement. Intervals based on machine hours are more corresponding to the rate of wear than intervals based on astronomical hours. This is the reason why CBM is a more advanced level of maintenance compared to PM or FTR. Most of the machines do not have hours counters and therefore, the service team is unable to determine the equipment workload. A solution would be to install additional counters, and set up a monitoring routine. There are several add-on hour counters on the market, which are easy to install and use.

Electric motor hour counter

The electric motor hour counter is an add-on unit that is composed of a magnetic sensor and a display. The sensor is fixed on the motor body and is triggered by the magnetic field generated by the rotor. The display is powered by a separate battery. The five digit display (Figure 6.4) can count hours up to 99 999 h (equivalent to more than 11 years of continuous reading). On the downside, there is no data forwarding possibility, meaning that somebody has to visit the metering point and record the reading.

Figure 6.4 Hour counter for electric motor

DIN rail mounted block

When the previous add on device is suitable for electrical motors, the following (see Figure 6.5) DIN rail mounted device can be used to measure any electrical equipment. The point of connection in the electrical diagram defines the measureable grid. These are available with both digital and analog display. Similarly to the previous device this one also need somebody to record the reading manually.

Figure 6.5 DIN rail mounted hour meter [36]

6.9 The 4 Senses Inspection

"This inspection is a technique that uses four human senses (smell, touch, hearing and vision) and the equipment in running mode to identify abnormalities in early stage" [1]. Although it might seem unprofessional to subjectively evaluate the condition of something that is otherwise measureable, one must understand that the opinion of an experienced engineer is as valuable as any other data in maintenance business. Furthermore, this technique is low in costs and is applicable for all machines [1].

6.10 Data Recording and Management

According to a study, "determining when a failure mode has been initiated and predicting the time remaining for complete failure requires reliable data and effective algorithms" [5]. Although, the permanent monitoring devices integrated with continuous data transfer are more effective, their price and difficulty of installation is excessively high. Nevertheless, this does not make such solution unsuitable for EMF. But before moving towards permanent solutions the reliability of the data needs to be tested for months if not even years with manual measurement devices. Therefore, the next optimal step would be to set up a manual measurement and data collection routines.

7 CBM MAP OUT AND ACTION PLAN

As depicted on the following diagram (Figure 7.1) the plan is to build the CBM plans upon four pillars (temperature metering, vibration analysis, oil sampling and thermal imaging) all supported by hour counting – the foundation. The reason why hour counting is so important is the fact that other data has no relevant meaning without the time factor.

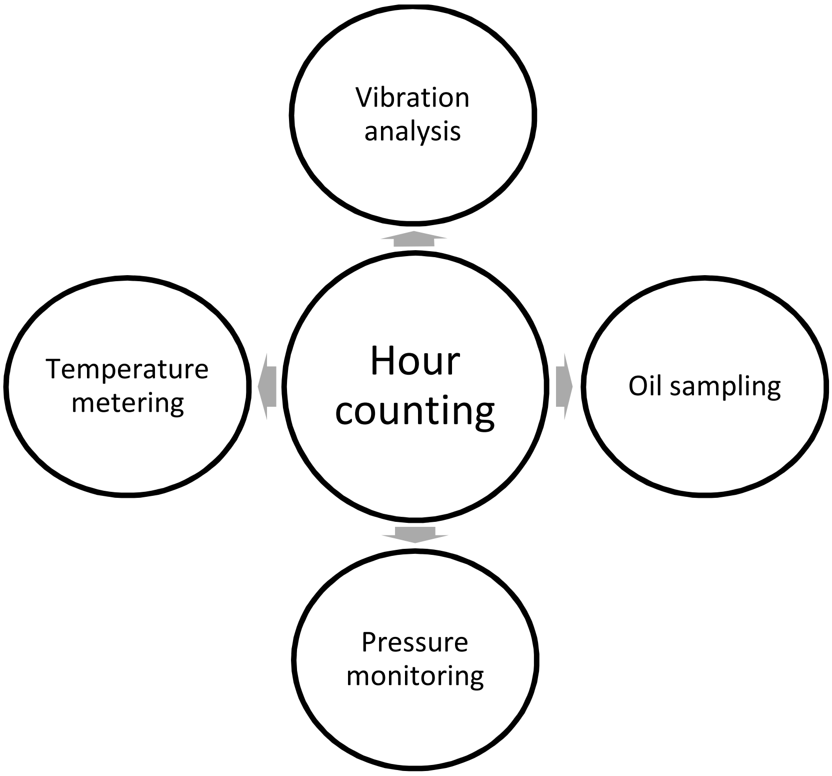


Figure 7.1 A basic representation of a CBM system

Hour counting is not just a trigger for maintenance actions but is also a tool for forecasting future failures. A service engineer must see potential issues before they occur. With the help of previous failures and the guidelines of OEM one can quite efficiently predict breakdowns and replacements.

Because industrial machinery is used for a long time, (5-30 years in ABB EMF) most issues keep reoccurring cyclically. By mapping down those cycles and adjusting the maintenance plans, the whole system becomes more efficient. Financially it is important not to over-maintain, because the cost of labor is twice as relevant as the cost of spare parts. For example in 2014, labor accounts for 47% of total costs in Quant Estonia OÜ, whereas spare parts account for only 23%. Baglee and Jantunen claimed that, "the economic benefit of

CBM is achieved, if the tools and techniques associated with CBM are applied to the right equipment" [30].

7.1 Methods of Calculations

Failure rate

$$\lambda = r / T \qquad (7.1)$$

Where: λ - failure rate

T - total running time, which could also be cycles or products

r - total number of failures in the investigation period.

This quantitative measurement presents the number of failures in a unit of time. Suitable for comparing the condition of identical equipment and estimating the number of failures in a given time in future.

Mean time between failures (MTBF)

$$\theta = T/r \qquad (7.2)$$

Where: θ - mean time between failures

T - total running time, which could also be cycles or products.

r - total number of failures occurring in investigation period.

This is a reciprocal value of failure rate. MTBF represents the time interval (or cycles, or products) between sequential failures. The longer the period the more reliable the equipment is. Useful when estimating occurrence of the next failure in the future.

7.2 Maintenance Frequencies

When it comes to calculating maintenance frequencies, there are no solid formulas. In maintenance related literature, [31] there is a rule of thumb that a suitable frequency is FDP/2, where FDP is the failure developing period or the period between the p and f in the p-f curve as mentioned above (see Paragraph 3.2). The only problem is that we don't know how long the FDP is. "There is no standard, no documentation and most plants do not have any history on FDP" [31]. Therefore, the first maintenance plan is scheduled on best guess. Then it is up the reliability specialist to monitor the failures and adjust the frequencies accordingly. “Criticality does not affect the FDP, but it might be a factor when we assign inspection frequency" [31]. After some time the schedule becomes true and starts to prevent breakdowns as it is supposed to do. Nevertheless, the frequencies are true only on the site they were developed in, because they are dependent on the equipment set-up and environment. This is the reason why there are no common maintenance plans (or frequencies) described in the literature.

8 CONDITION BASED MAINTENANCE PLANS

In the following chapters, the author proposes new maintenance plans for a selection of equipment. The first, is a rotary vane pump, used for vacuum processes in ABB vacuum pressure impregnation (VPI) department. There are four identical pumps, marked as A-critical. The second machine is a stator coil-insulating machine. There are two identical machines, that are C-critical in essence, but because of the increased failure rate and constant breakdowns, the machines are starting to influence production. All the previously analyzed CBM methods and measurement devices will be used in the newly proposed maintenance plans.

8.1 CBM PROFILE FOR ROTAR VANE PUMP

The entire vacuum impregnation department is considered an A-critical system. Firstly because the resin used for motor insulation is extremely hard natured. In case of any unplanned stoppage, the resin can set in the pipes or vessels and will be almost impossible to fix. In addition, the resin and its fumes are hazardous to human and environment. This is the reason why special attention has to be put on those machines.

The rotary vane pumps (see Figure 8.1 below) suck out all the air and moisture from the vacuum pressure chambers. This is a necessary step for a vacuum pressure impregnation process. Without the air, the resin penetrates all the numerous grooves and slots in the stator or rotor. This gives the apparatus better heat dissipation and insulation properties than with regular dipping process.

Figure 8.1 Rotary vane pumps

8.1.1 Known Issues (Troubleshooting)

The following effect and cause table (Table 8.1) is based on guidelines provided by the OEM and professional service provider. The current time based maintenance built upon checking the condition of the enlisted parts and assemblies. Currently only oil and filters are changed according to machine hours. The rest of the parts (see Figure 8.2 below) are inspected after every 3 months.

Table 8.1 Rotary vane pump effect and cause list

Effect	Cause
Pump does not start	Exhaust filter / exhaust line is clogged.
Pump does not reach ultimate pressure	Float valve does not close.
Pump does not reach ultimate pressure	Anti-suckback valve is malfunctioning
Pump does not reach ultimate pressure	Exhaust valve is malfunctioning
Pump does not reach ultimate pressure	Clogged oil filter or oil lines
Pump does not reach ultimate pressure	Unsuitable or contaminated oil
Pumping speed is too low	Dirt trap in the intake port is clogged
Pumping speed is too low	Exhaust filter / exhaust line is clogged.
Pumping speed is too low	Anti-suckback valve is hard to open
Pump gets too hot	Cooling air supply is obstructed
Pump gets too hot	Cooler is dirty
Pump gets too hot	Process gas is too hot
Pump gets too hot	Oil level is too low
Pump gets too hot	Oil cycle is obstructed
Pump gets too hot	Exhaust filter / exhaust line is obstructed
Pump gets too hot	Exhaust valve is malfunctioning.
Pump's oil consumption too high	Exhaust filters are clogged or damaged
Pump's oil consumption too high	Nozzle of float valve is clogged
Pump's oil consumption too high	Oil level is too high
Pump makes excessive noise	Oil level is very low
Pump makes excessive noise	Oil filter is clogged.
Pump makes excessive noise	Coupling elements worn
Pump makes excessive noise	Large vacuum leak in system

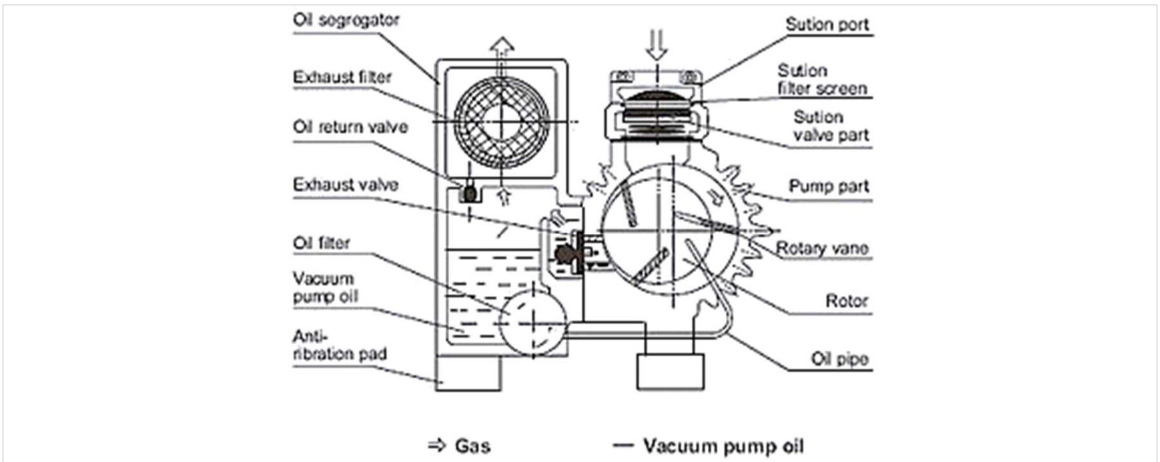


Figure 8.2 Rotary vane pump scheme [32]

8.1.2 Rotary Vane Pumps Case Study

Author established a pressure monitoring routine on the rotary wane pumps in April 2014. The goal was to measure the pressure in the system every time when the technicians maintained the pumps and reveal the correlation between them. The results of a one-year monitoring routine are presented in Appendix 5. Soon after first results the correlation between successful maintenance and a drop in the pressure (increase in suction) gained prominence.

When later consulting with an engineer who is highly experienced in vacuum pump maintenance, we agreed that our trigger point will be 1,0 mbar. The overhauled pumps reach a pressure as low as 0,33 mbar (best result so far) and the pumps in worst condition are struggling to hold 1,5 mbar. Quant's service technicians started to put special attention on pumps, where the reading was close to 1,0 mbar. In case where Quant's team cannot improve the condition by standard maintenance or repair, the pump is dismounted and shipped to a professional service station. The following chart (Figure 8.3) illustrates the correlation between pump's (71PM400) working pressure and maintenance activities.

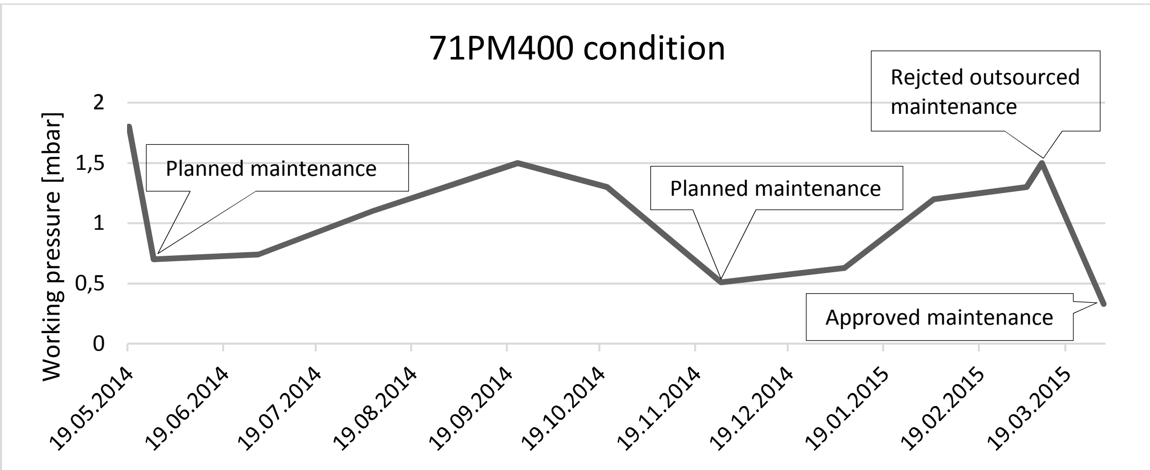


Figure 8.3 71PM400 condition

In March 2015 the same pump (pump 71PM400) was sent for overhaul. When returned the pressure was measured and the reading was at 1,3 mbar. Clearly the pump was rejected and returned to the service provider. This was a great example where an established monitoring routine and proper baseline gave Quant Estonia OÜ the foundation to reject or approve outsourced services.

During this thesis author installed hour counters to each vacuum pump. The first results indicate that the pumps' workload is as follows (Figure 8.4).

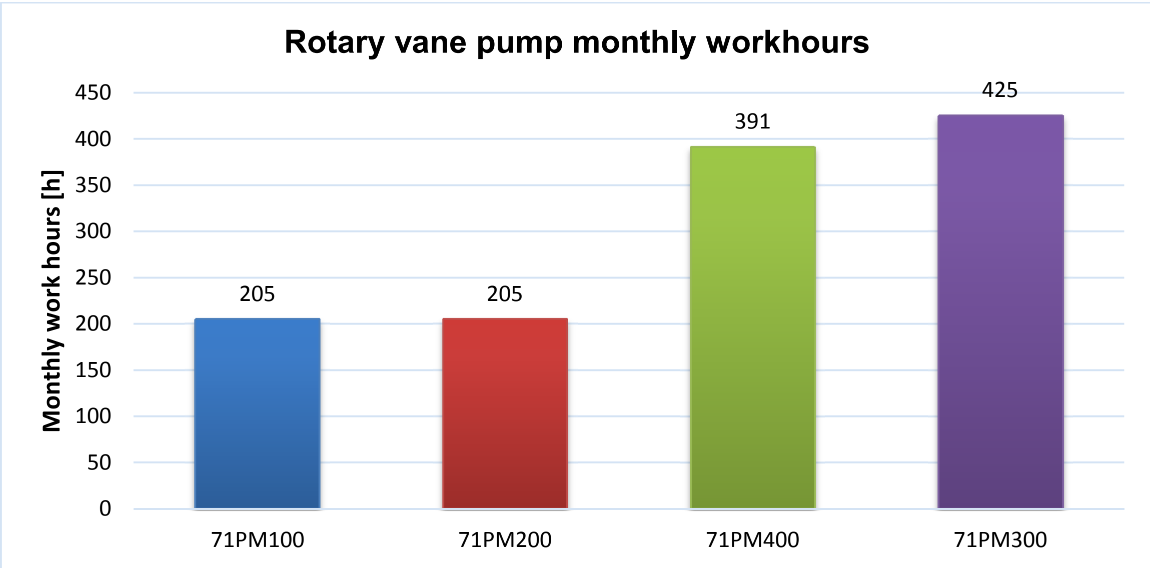


Figure 8.4 Rotary vane pump work hours

It appears that the pumps have an uneven workload, which was previously not confirmed. Pumps 71PM100 and 71PM200 work 47% less that pump 71PM400 and 52% less than pump 71PM300. Therefore, pumps 71PM100 and 71PM200 should also get fewer maintenances. The next chart (Figure 8.5 below) reveals that all the pumps get roughly the same amount of maintenances except for pump no. 71PM200, which has slightly less.

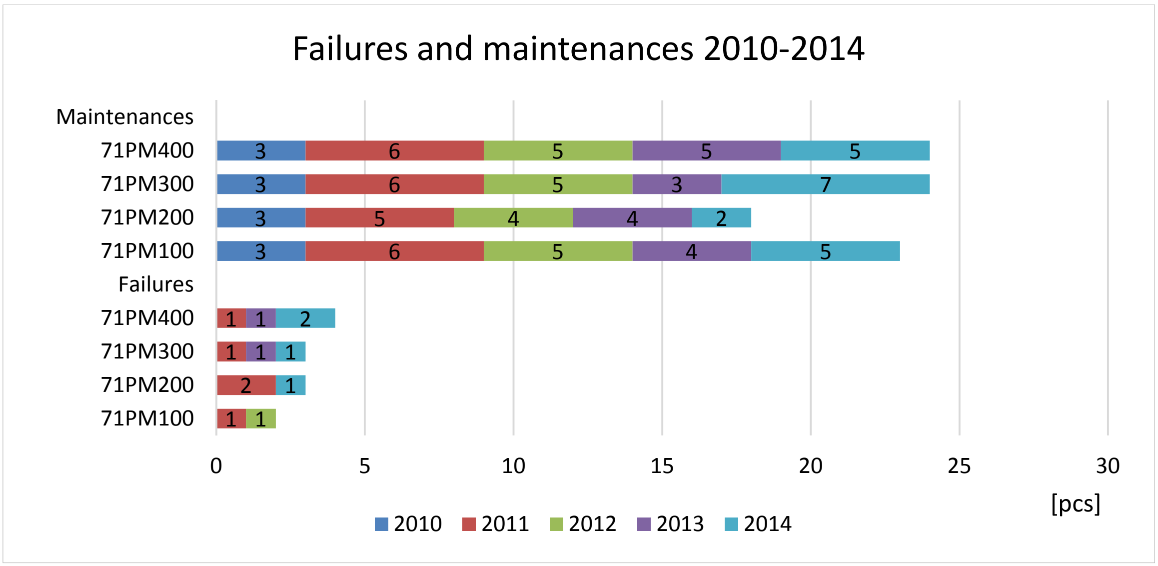


Figure 8.5 Failures and maintenances 2010 – 2014

If the baseline is set at 400 h as a monthly standard workload, all the 3-monthly inspections tasks can be converted to a 1200 h CBM inspection (see table 8.2 below). Using actual machine work hours instead of astronomical hours automatically rules out the chance of unequal maintenance on otherwise identical equipment. For more accurate baseline, the pumps' workloads need to be monitored at least throughout a 12 month period. The proposed maintenance plan is a forecasted version and needs to be adjusted according to future failures and equipment degradation.

8.1.3 Maintenance Plan For Rotary Vane Vacuum Pump

Applicable for:

- 71PM100 Vacuum pump – Busch
- 71PM200 Vacuum pump – Busch
- 71PM400 Vacuum pump – Busch
- 71PM300 Vacuum pump – Busch

Table 8.2 Proposed maintenance plan for rotary vane pumps

Trigger	Task	Description	Duration	Shut-down
Every 1200h	10	Oil and filter change. Oil type: LVO-210 (7L)	1:00	Y
Every 1200 h	20	Bleed separator water - valve 13.37	0:05	N
Every 1200 h	30	Check oil level. Check for oil leaks.	0:05	N
1500h or pressure >1 mbar	40	Change electrical valve filters. Check for loose connectors.	0:45	Y
1500h or pressure >1 mbar	50	Change exhaust filter. Filter type: SP-980	0:30	Y
Every 1200 h	60	Check the anti-suckback valve	0:30	Y
Every 1200 h	70	Check for air leaks in the pneumatic system	0:05	N
Every 1200 h	80	Check for leaks in the resin system	0:10	N
Monthly observation tour	90	Take pressure and hour counter readings, fill in the report	0:15	Y
Every 1200 h	100	Clean the ballast and dirt trap	0:05	Y
Every 1200 h	110	Check the condition of all sensors	0:15	Y
Every 1200 h	120	Clean the electrical motor housing and cooling coil	0:30	N
Every 1200 h	130	Check float valve after every exhaust filter replacement	0:30	Y
Every 1200 h	140	Check the safety switch.	0:05	Y
Every 1200 h	150	Ask operators for comments and tips.	0:10	N
Pump makes grinding noise, refuses to start or pressure > 1,4 mbar	160	Remove the pump from the system, prepare the assembly for transport, inform the VPI foreman, send pump to OEM or other qualified service provider.	1-4 weeks	Y

The tasks and trigger times in the maintenance plan above (Table 8.2) originate from OEM manuals, specialized service provider's documents and recommendations and from the experience of Quant's technicians and specialists.

8.1.4 Implementation costs

For rotary vane pump maintenance, two monitoring devices are used - Leybold Thermovac TTR 91 pressure sensor and digital hour counter. Four digital hour counters were purchased and installed (35 € each) and one pressure sensor with digital display unit is used to measure the pressure (1194 €). The total cost of equipment is 1334 €.

8.2 CBM PROFILE FOR TH-TOOLS INSULATION MACHINES

ABB EMF coil winding department holds four different types of insulation machines. Although some of the machines share common spare parts they still are different enough to require separate maintenance plans. The winding head assembly itself is complex and holds hundreds of parts, which means that the volume of spare parts is also significant. Therefore, any systematic improvement that allows the factory to reduce the amount of parts in stock or increase reliability is desirable. In this example, author focuses on the TH-Tools model no. XABB-804285 (Figure 8.6 TH-Tools insulation machine 42IM800).

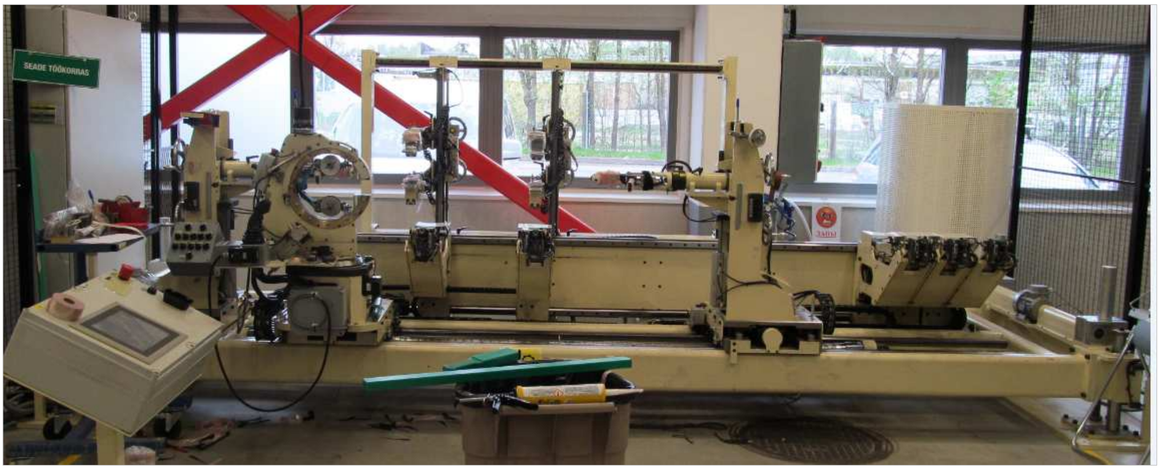


Figure 8.6 TH-Tools insulation machine 42IM800

8.2.1 Known Issues

Author chose this machine, because condition of the machine has seriously worsen in last four years. The frequent breakdowns (Table 8.3) are influencing the production and causing the client to fall behind its schedule. The reason behind the degradation might be the poor engineering work done in the development phase of the machines by which the parts are not able to bear such load. However, even in such extreme case the condition can be sustained by more frequent replacement of parts. The more likely reason for the deterioration is the fact that current maintenance plan is insufficient.

Table 8.3 TH-Tools insulation machine cause and effect list

Effect	Cause
Excessive noise or vibration	Support rollers wear out
Machine does not keep pace	Slack in mechanical assembly or brake fluctuations
Machine does not keep pace	Brake disks worn out
Braking force fluctuations	Dust in brake system
Braking force fluctuations	Overheated brake pads
Brake pads wear out	Abrasive dust on brake disks or pads
Braking force is too low	Brake pads are misaligned
Irregular rotational movement	Tooth belt worn out
Bronze dust on the assembly	Bronze ring is worn out
Bronze rings wears out	Overall play of the toothed wheel
Bronze rings wears out	Support rollers are worn out
Support rollers wear out	Wrong type of bearings of wrong method of installation
All support rollers wear out rapidly	Wrong rubber material type

The insulation head assembly (see Figure 8.7 (B) below) is a clockwork composed of hundreds of tiny parts. Two brake disks hold the tension on both tape spools. The rotating ring is held in place by 32 support rollers. The amount of small moving parts makes the maintenance of this machine very difficult and know-how extensive. The effect and cause list above illustrates that many parts wear out or overheat because of excessive friction. During inspections, technicians can notice these signs of wear as shiny spots on the metal surfaces or bronze dust scattered around the assembly. However, usually when these indicators appear the parts are damaged beyond repair. Thermography on the other hand, allows us to notice problems in an early stage and prevent the potential failure. The following figure (see Figure 8.7 (A) below) illustrates the normal working temperatures of the insulation head.

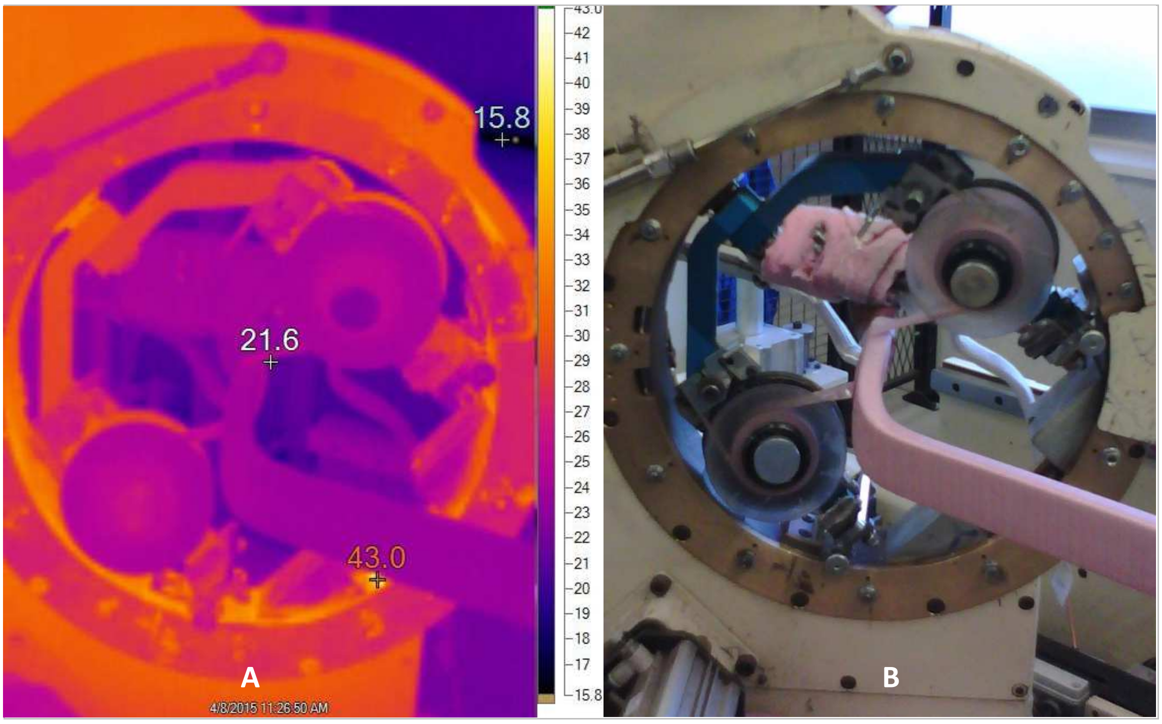


Figure 8.7 TH-Tools 2 winding head thermography

Opposed to the rotary vane pumps, which fail 1-2 times a year the insulation machines have a tendency to fail 50 times more often (see calculations below). Not all of those occurrences are breakdowns, they also include minor fixes and adjustments, but it shows the machine is unable to work without continuous interventions.

Table 8.4 Failure rate and mean time between failures

	42IM800	**42IM700**
No. of failures in 2014	$r_{2014} = 58$	$r_{2014} = 79$
Estimated No. of work hours in 2014	$T_{2014} \approx 2200$ (h)	$T_{2014} \approx 2200$ (h)
Failure rate (eq. 7.1)	$\lambda \approx 0{,}026$	$\lambda \approx 0{,}036$
Mean time between failures (eq. 7.2)	$\vartheta \approx 38$ (h)	$\vartheta \approx 28$ (h)

The calculations (Table 8.4) show that the 42IM800 is expected to fail after every 38 hours and 42IM700 after every 28 hours. Until the condition of the machines is not improved the service manager should plan the resources according to the MTBF, i.e. one technician should be planned to repair both of the machines at least once per week.

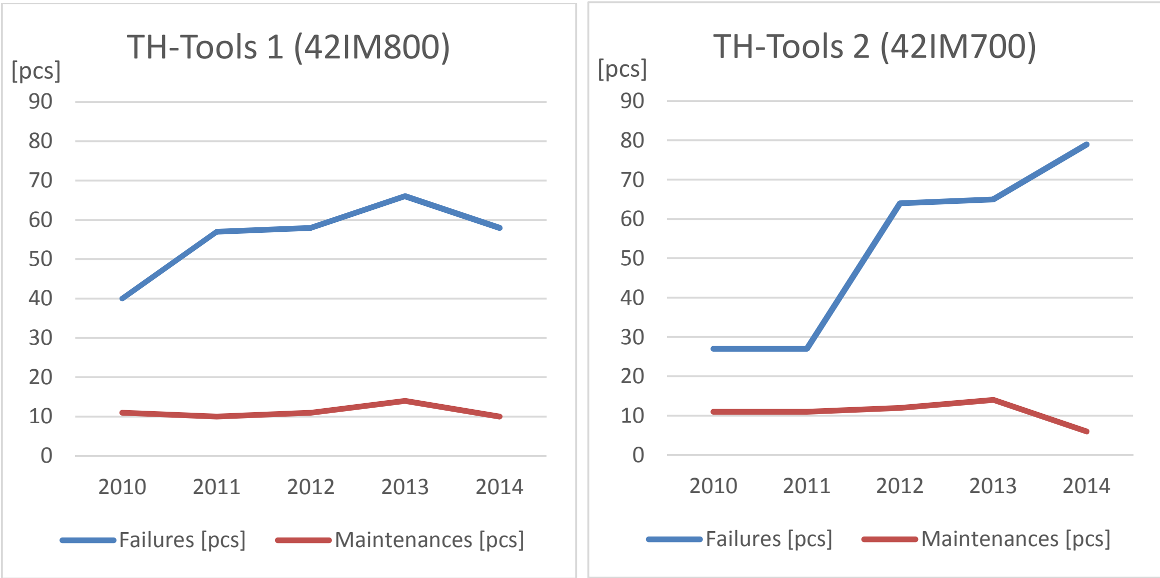


Figure 8.8 Failure and maintenance charts for 42IM800 and 42IM700

If we compare the two machines by number of failures and maintenances throughout past 5 years. (see Figure 8.8 above) then we can see that their condition is roughly the same. The 42IM800 has a more constant failure rate, whereas the 42IM700 shows serious degradation in past three years.

The insulation heads were completely retrofitted in August 2013 on both machines but show controversial effect on the failure charts. The reduction in 2014 failures on 42IM800 might be the result of the retrofit, but the 42IM700 shows a different trend probably because of the uncompleted maintenances. According to Quant's CMMS both machines have monthly, 6-monthly and yearly maintenances in their schedule. This means that the average number of maintenances should be at least 12 per year. In 2014 both machines were under maintained.

8.2.2 Maintenance Plan

The TH-Tools insulation machines do not have an hour counter. The work hours above are derived from a similar insulation machine running under similar workload. In order to implement the following maintenance plan (Table 8.5), hour counters have to be installed on both machines. The suitable hour counter type is ABB E-233 230 (see Figure 6.6).

Applicable for:

- TH-Tools 1 – 42IM800
- TH-Tools 2 – 42IM700

Table 8.5 Proposed maintenance plan for TH-Tools insulation machine

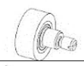
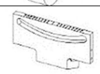
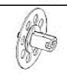
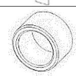
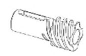
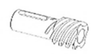
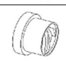
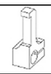
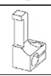
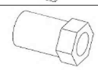
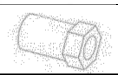
Trigger	Task no.	Description	Dura-tion	Shut-down
200h	10	Monitor machine work, listen for abnormal noise. Ask operator for comments.	0:05	N
200h	20	Test the all emergency stops and light barriers.	0:05	N
200h	30	Check the belt drive for bronze dust.	0:05	Y
200h	40	Check belt drive alignment. Measure gap distance	0:05	Y
200h	50	Check the bronze ring for wear.	0:05	Y
1000h	60	Empty the condensed water container (pneumatics system).	0:05	Y
1000h	70	Check the pressure in the pneumatics system (Norm. 6 bar)	0:05	Y
1000h	80	Lube the ball-joints in the taping ring assembly	0:05	Y
200h	90	Clean the surfaces, use dry cloth. Apply break-cleaner if necessary.	0:10	Y
200h	100	Clean the linear guides and lube again if needed.	0:10	Y
1000h	110	Check the fittings and plumbing for leaks (pneumatics system).	0:10	Y
1000h	120	Check the condition of the tooth belt. Replace or tighten if needed.	0:30	Y
200h	130	Check the condition of tapespool size levers.	0:30	Y
200h	140	Check the condition and alignment of the brake pads.	0:30	Y
200h	150	Clean the brake disks and adjust according to use.	0:10	Y
1000h	160	Clean the roller runways. Check for surface asperity.	0:05	Y
200h	170	Reset the brake tension.	0:30	Y
1000h	180	Check the support rollers with thermal camera. Replace rollers that are notably hotter than others. Repeat procedure on other side.	1:00	Y
4000h	190	Replace brake disks - M99097	0:30	Y
4000h	200	Replace brake pads PK1 - M99422	0:30	Y
4000h	210	Replace bushings SP1 - M07073	0:30	Y
4000h	220	Replace both consoles K1 - M99447	0:30	Y
4000h	230	Replace all rollers TR 1 - M09034	0:30	Y
4000h	240	Replace bushing P2 - M07072	0:30	Y
4000h	250	Replace both bronze slides LL1 – M02443	0:30	Y
4000h	260	Replace both spindles S1 and S2 – M99146/M99146	0:30	Y
4000h	270	Replace both spindle nuts SM1 and SM2 – M99137/M99136	0:30	Y
4000h	280	Replace size levers KH1 – M99341	0:30	Y
4000h	290	Replace both limiters P1 and P2 – M99442/M99443	0:30	Y
4000h	300	Replace both limiter nuts PM1 and PM2 – M99420/M99431	0:30	Y
2500h	310	Change PLC battery (follow Omron guidelines)	0:30	Y

The shortest trigger time is derived from monthly workload (rounded up to 200h). Trigger time is rounded, so that the hours are better observable and memorable. In OEM maintenance plan there is also a two-weekly inspection work-order, but it has not been fulfilled for years, because of resource deficiency. Therefore, some of the tasks from two-weekly inspection are transferred to the 200h maintenance (tasks no. 20 and 90 for example). The 1000h trigger time is derived from a 6-monthly maintenance job (rounded down to 1000h). A new CBM task (no. 180) was added to the maintenance plan and combined with a 6-monthly maintenance job.

In case of such complex assemblies the traditional maintenance tasks (lubrication, alignment, tightening of bolts) are expected to have little effect on the overall condition. Because the parts are small, they cannot be retrofitted and therefore need to be replaced (Table 8.6). The trigger time of 4000h is a first estimate, based on the retrofit done in July 2013 and the general condition of the winding head 20 months later, in April 2015, which indicated that many of the parts need replacement. Because the trigger cycle is so long, it is highly possible that the period needs adjustment after each retrofit.

8.2.3 Critical Spare Parts List

Table 8.6 TH-Tools critical spare part list

Part description	Image	Part No.	No. of parts consumed*
Bushing P2		M07072	83
Roller TR1		M09034	218
Console K1		M99447	N/A
Brake disk PK1		M99097	N/A
Brake pad PK1		M99422	N/A
Bushing SP1		M07073	16
Bronze slide LL1		M02443	18
Right spindle S1		M99146	22
Left spindle S2		M99145	32
Spindle nut SM1 (right)		M99137	22
Spindle nut SM2 (left)		M99136	23
Size lever KH1		M99341	N/A
Limiter P1		M99442	39
Limiter P2		M99443	18
Limiter nut PM1 (left)		M99420	59
Limiter nut PM2 (right)		M99431	42

* The No. of parts is not designated to a single machine. Some of the parts are common across several similar machines. Still it gives a rough estimation of the part turnover rate.

** In case of some parts the sum is unknown, because new spares are ordered without using the designated spare part code.

8.2.4 Implementation costs

Hour counters have to be installed on both machines, the initial cost is 60 €. The factory already owns a Fluke Ti125 thermal imaging camera, which is suitable for CBM operations. Therefore, the cost of the camera is not counted into the implementation costs. However, the cost of the spare parts in the list above (Table 8.6) sums up to 3800 € and is planned to be invested after every 4000 work hours.

8.3 VIBRATION MEASUREMENT TOUR

The condition of bearings is probably the hardest to evaluate. Because the bearing are usually installed in housings, which are located deep inside the machine, they are very hard to access and even harder to observe. The main causes for bearings failure are [33]:

• *Dirt*	*45.4%*
• *Misassembly*	*2.8%*
• *Misalignment*	*12.6%*
• *Insufficient Lubrication*	*11.4%*
• *Overloading*	*8.1%*
• *Corrosion*	*3.7%*
• *Improper Journal Finish*	*3.2%*
• *Other*	*2.8%*

Regardless of the cause, the result is always the same –increased friction. Friction leads to material wear, vibration and heat. These three are the indicators that can be detected before the ultimate failure. In case of uncovered bearings, material wear can be seen visually.

Vibration monitoring routine has to be set up differently from the equipment based maintenance plan. Because in ABB EMF it is financially wiser (see paragraph 6.4) to outsource the metering service, all the equipment has to be measured sequentially.

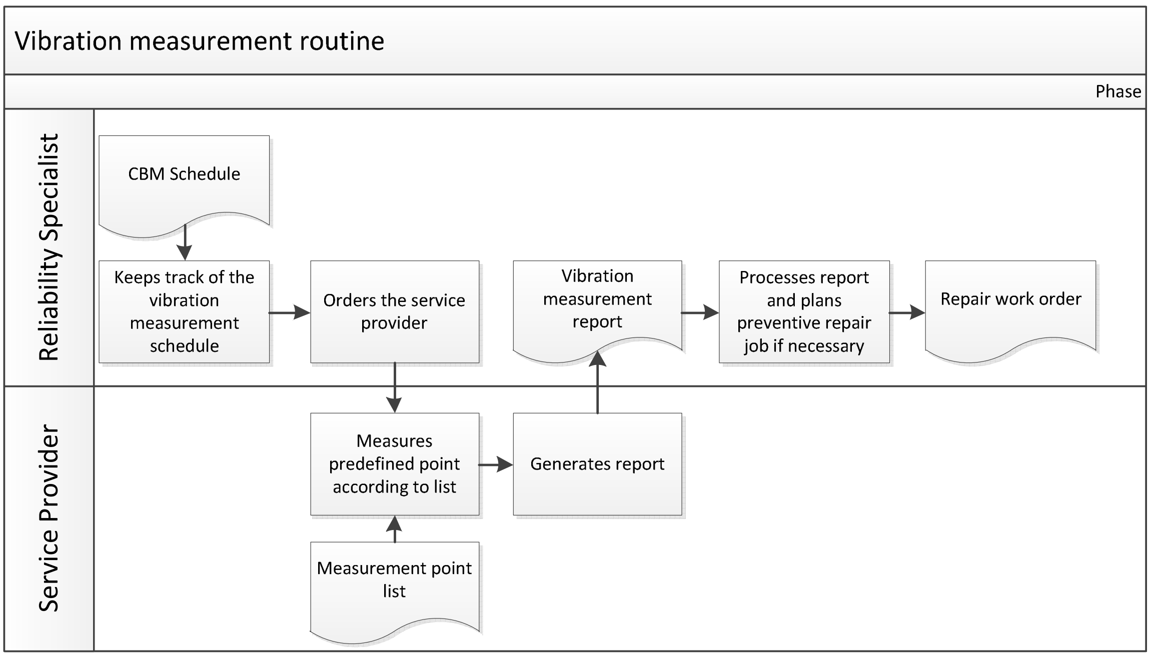


Figure 8.9 Vibration measurement routine flow chart

A measurement tour list (Table 8.7) is constructed to guide the service provider. Service provider presents both, numeric value and condition evaluation in its report. Later reliability engineer plans a preventive replacement or additional monitoring routine based on that report. It is the duty of the reliability engineer to record the data (Figure 8.9 above).

Table 8.7 Vibration measurement tour list

ID	Equipment description	Details	Equipment type	Location	Image
1	SP250: Hydraulic station main pump drive - ABB M2QA132M4A	7,5kW 1440rpm	Electrical drive	JTBP	
2	SP250: Hydraulic station auxiliary pump drive – ABB M2QA112M4A	4kW 1720rpm	Electrical drive	JTBP	
3	HD400: Hydraulic station auxiliary pump drive - Unitec S04965	3,5kW 1720rpm	Electrical drive	JTBP	
4	HD400: Hydraulic station main pump drive – Unitec ML6620L F001	11kW 1450rpm	Electrical drive	JTBP	
5	SP250: Press main drive - Siemens 1PH7137-7QD02-0ba0	22kW 1500rpm	Electrical drive	JTBP	
6	Danobat: Main drive – Siemens 1PH7224-2NC050FC3	55kw 700 rpm	Electrical drive	JT54	
7	Looping machine: Main drive – VEM 150137/0012H	15kW 1465rpm	Electrical drive	JT56	

Based on the recommendation of SKF (leading bearing manufacturer), the vibration measurement tour is planned four times a year. The first vibration measurement tour was made during this thesis in March 2015 (see Appendix 6 for results). Therefore, the subsequent tours are planned as follows (Table 8.8):

Table 8.8 Vibration measurement tour schedule

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
Outsourced measurement tour													
Additional measurements with CMAS 100-SL													

In order to achieve higher data consistency, Quant should try to gain vibration analysis knowledge. For that author makes a proposition to purchase SKF CMAS 100-SL Machine Condition Advisor. During the first year of vibration analysis Quant should make additional measurements in parallel with the professional service provider. Comparing the results helps to build a baseline with another device and set trigger values for future reference. Together with the purchase of the device, a basic training has to be purchased as well to rule out the chance of misusing the device and recording false data.

8.3.1 Implementation costs

The implementation costs of the vibration measurement routine include SKF CMAS 100-SL (1600 €) and initial training (600 €) – together roughly the cost of a new 22kW electrical motor. In addition the outsourced service - 560 €/year.

9 RESULTS

“CBM is not just a box you can buy to integrate onto your platform or system, but is a set of integrated technologies, processes, and capabilities that together enable CBM to be realized” [34]. As discussed in Complex System Maintenance Handbook, “CBM methods and practices have been continuously improved for the last decades: however, CBM is conducted at equipment level-one piece of equipment at a time, and the developed prognostics approaches are application or equipment specific” [35].

The most reliable results appear, if the information before the CBM implementation and after is compared in terms of failure rate, consumables consumption and maintenance costs. The information before the implementation describes the reliability of the machines with fixed term preventive maintenance system. The adequate time frame for failure analysis fits at least two independent breakdowns from similar or identical causes. In case of insulation machines in EMF the breakdowns tend to reoccur in 3-6 months. In stamping department the failures from similar causes reoccur much less often (1-5 years). The reason for that is possibly the larger dimensions of the parts which in general tend to last longer but on the other hand cause longer downtime and higher repair costs. Because the period for proper analysis is so long and does not fit into the time frame of this thesis, author can only forecast the possible savings from the next level maintenance system.

9.1 Monetary Factors

Cost of CBM

CMB seems to be more suitable for sites who have a lot of similar or identical equipment. Which allows a reliability engineer to focus more on a certain type of machine and the company to invest into a system that monitors several machines at the same time. This reduces the cost of implementation per machine and makes the CBM economically efficient.

Since CBM operates on a higher performance level than PM it is expected to increase reliability. Increased reliability results in improved technical availability and overall equipment effectiveness. From monetary point of view, production losses and repair costs are expected to decrease.

In ABB EMF, it seems that the initial cost of CBM per machine is similar to the replacement cost of the particular assembly or equipment. Although, for every next identical equipment the implementation cost is significantly lower, because the measurement devices are usually common. The break-even point for every measuring point is most probably the first prevented breakdown, because the cost of A-critical machine downtime supersedes most spare parts. Identifying the failing part in an early stage allows the reliability specialist to plan the replacement without production loss. The total CBM implementation investments proposed in this thesis sum up to 7400 € for the first initial year.

Oil sampling

The most eminent cost savings emerge with condition based oil change. The usual oil replacement interval on EMF's most loaded machines is 3 years. Suppose that the oil analyses extends the interval up to 5 years and most importantly, with incremental analyses the process is controlled and has no threat to other parts in the system.

When the average tank is 200L (one barrel of oil) and costs 450 € then with FTR (replacement interval of 3 years) the oil cost over 15 years is 2250 €, because the oil has to be replaced 5 times. Now when CBM allows us the extend the replacement up to 5 years then only 3 oil replacements are needed in 15 years and the oil management cost over the period is 1350 €. The oil analysis is free of charge, when Quant purchases the oil from a single supplier. In that case, the cost savings for that single tank are 900 €.

If we have roughly around 5000L of hydraulic oil in EMF then the cost difference per 15 years is estimated 22,5 k€. Condition based replacement can save up to 43% on oil costs (see Figure 9.1 below).

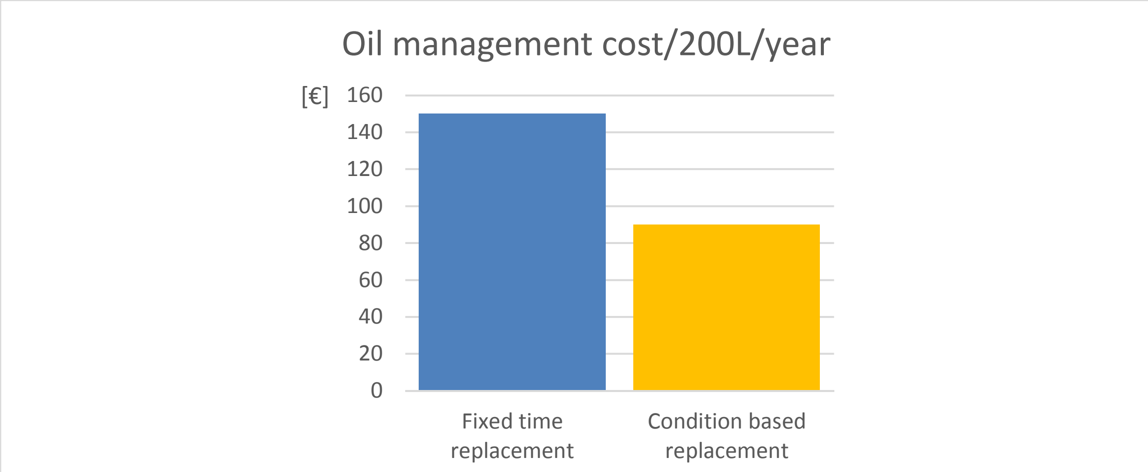


Figure 9.1 Oil management costs

9.2 Non-Monetary Factors

Under- and over maintenance

One of the best virtues of CBM is that is automatically rules out the chance of over and under maintenance. Out of which, the first is a pure waste of resources which can otherwise be used where needed most. Eliminating over maintenance helps Quant to overcome the labor resource deficiency problem and allocate technicians to further inspections. Removing under maintenance on the other hand, increases the reliability and safety of the machines.

Human Factor

The importance of human factor in CBM was underestimated in the planning phase of this thesis. It became obvious that the an experienced technician is the key to the CBM system and various measurement devices are just supportive tools. In the interest of the company and the maintenance system, the technicians need to insert all of their observations into CMMS for analysis and future reference. Incremental adjustment is the only way to develop a working maintenance schedule and it takes years for it to become truly reliable.

9.3 Future Work

The proposed maintenance plans are just the first steps towards a novel condition based system. In order to carry on the development process the following steps have to be executed in the next 2-3 years.

Remote data monitoring

For a CBM system to be truly efficient, the data monitoring process has to be continuous and remote. In case of remote monitoring, there is no need to visit the equipment, which saves more labor hours and in addition, the data is more reliable and automatically stored. The next step, in order to increase the CBM system efficiency, would be to add remote solutions to the monitoring methods proposed in this thesis.

CMMS improvement

A good CMMS program is essential for a working maintenance system and Quant has some shortcoming in that field. In order to improve the situation, it is recommended to hire a dedicated IT specialist to run the CMMS reengagement process. This is a project, which involves all the white and blue collars to start using the system properly and by the book.

Continuous adjustment of CBM plans

For the proposed maintenance plans to become more reliable, further work needs to be conducted by the reliability specialists. In case of any changes in the machine work (environment, workload, product, speed, etc.) the maintenance plan has to be updated accordingly.

10 SUMMARY

The hereby thesis is written in relation with Quant Estonia OÜ and is addressed to ABB's Electrical machine factory in Jüri. Quant Estonia OÜ provides maintenance services to the aforementioned ABB factory and is responsible for the upkeep of all their machinery. The purpose of this thesis is to develop and launch a more effective condition based maintenance system.

The first part of this thesis (Chapters 1-5) describes the current state in the factory. Electrical machines factory produces electrical motors and generators, mostly for windmills and maritime purposes. A detailed overview of Quant's maintenance operations explains its relationship with ABB and brings out the possible strategies in maintenance business. Chapter 3 discusses the possible downsides of the current time based maintenance system. Author finds that the current maintenances plans are superficial and do not contribute to outdated equipment. This statement is also proved by the increasing failure rate of researched equipment.

The second part of the thesis (Chapters 6 and 7) explains the theory behind condition based maintenance and possible condition monitoring solutions. CBM suitability for ABB Electrical machines factory is researched and in this study author focuses on five monitoring methods: vibration analysis, pressure monitoring, temperature metering oil sampling and hour counting. Maintenance schedule that is based on actual machine hours, rather than astronomical hours, is more proportional to the rate of wear and is therefore more reliable. The other four metering methods are applied to equipment, where they are most efficient.

In the third part of the paper, (Chapter 8) author proposes novel condition based maintenance plans, oil analysis routine and a vibration measurement tour for a selection of equipment. Two sets of machines (rotary vane pumps and TH-Tools insulation machines) are analyzed thoroughly, based on their previous breakdowns and maintenances. The results indicate that the current time based maintenance system inevitably involves a chance of uneven maintenance on otherwise identical equipment. Furthermore, because of a weak computerized maintenance management system many of the equipment is under-maintained.

The newly proposed maintenance plans are based on actual working hours and measureable data, which rules out the chance of uneven maintenance. In other terms, the new plans have more efficient labor utilization and follow both the propositions of Quant’s technicians and the guidelines of original equipment manufacturers. Furthermore, author proposes two outsourced monitoring routines. Vibration metering for a set of critical motors and an oil sampling routine for lubrication and hydraulic systems. Both of those routines where implemented during the research and received good feedback. Condition based oil change is expected to give up to 43% cost saving effect immediately.

Condition based maintenance implementation is a process rather than a project. This research paper is the initial step towards a more advanced maintenance system in ABB electrical machines factory. Even though it takes years of continuous improvement to develop maintenance plans that truly support the condition of the machines, this thesis shows that also with limited data and a short period of time, it is possible to to bring CBM methods into effect.

11 KOKKUVÕTE

Käesolev töö on välja töötatud Quant Estonia OÜs ja suunatud ABB Elektrimasinate tehase tootmisseadmetele. Quant Estonia OÜ pakub ABB tehasele täiskorrashoiu teenust ja on vastutav sealse masinapargi töökorra eest. Magistritöö eesmärk on välja arendada ja kasutusele võtta uus ja tõhusam seisukorrapõhine hooldussüsteem.

Töö esimene osa (peatükid 1-5) kirjeldab ABB tehase hetkeolukorda. Elektrimasinate tehas toodab elektrimootoreid ja generaatoreid, peamiselt tuulegeneraatorite ja laevade tarbeks. Järgneb peatükk, mis kirjeldab Quant Estonia OÜ hooldustegevusi, selgitab viimase seotust ABB Elektrimasinate tehasega ja toob välja erinevad hoolduse tüübid tööstusmasinate valdkonnas. Hetkel kasutusel oleva, kalendripõhise hooldussüsteemi nõrgad küljed on üles loetletud kolmandas peatükis. Autor leiab, et praegused hooldusplaanid on pealiskaudsed, ega toeta üha vananevate masinate seisukorda. Seda väidet tõendab ka uurimisaluste masinate rikete sageduse tõus viimaste aastate vältel.

Töö teine osa (peatükid 6 ja 7) kirjeldab seisukorrapõhise hoolduse tagamaid, võimalikke seisukorra hindamise meetodeid ja hindab seisukorrapõhise hooldussüsteemi sobivust ABB elektrimasinate tehasele. Käesolevas töös on autor välja valinud viis seisukorra hindamise võimalust: vibratsioonianalüüs, rõhu mõõtmine, temperatuuri mõõtmine, õlianalüüsid ja töötundide lugemine. Masina tegelikel töötundidel põhinev hooldusplaan vastab täpsemalt seadme seisukorra muutumisele kui kalendripõhine hooldusplaan ja on seetõttu ka usaldusväärsem.

Magistritöö kolmandas osas (peatükk 8) pakub autor valitud seadmetele välja uudsed seisukorrast lähtuvad unikaalsed hooldusplaanid ning õlianalüüside ja vibratsioonimõõtmiste programmi. Autor analüüsib kahte erinevat masinate komplekti (vaakumpumbad ja isoleerimismasinad TH-Tools), võttes aluseks eelmised rikked ja tehtud hooldused. Analüüsi tulemusena selgub, et kalendripõhise hooldusplaani kohaselt saavad muidu identsed masinad paratamatult erineva tihedusega hooldust. Lisaks selgub, et ebakorrektselt täidetud hoolduste infosüsteemi tulemusena on paljud seadmed plaanitust vähem hooldatud.

Seisukorrapõhise hooldusplaani puhul on ülevaatuste intervallid sätitud masina tegelike töötundide järgi, mis garanteerib kõikidele sarnastele seadmetele ühesuguse hooldusintensiivsuse. Peale selle pakub seisukorrapõhine hooldus efektiivsemat tööjõu kasutust ja võtab arvesse nii Quant Estonia OÜ enda tehnikute, kui ka seadmete tootjate korrashoiualaseid soovitusi. Autor pakub välja allhankijatelt tellitava vibratsioonimõõtmise teenuse elektrimootoritele ja laboratoorse õlianalüüside teenuse olulisematele määrde- ja hüdrosüsteemidele. Mõlemad eelpool mainitud meetodid võeti kasutusele töö tegemise ajal ja andsid peagi positiivseid tulemusi. Seisukorrapõhine õlivahetus säästab prognoosi järgi kuni 43% õlivahetamise kuludelt.

Seisukorrapõhise hooldusprogrammi juurutamine on pigem pikaajaline protsess. Käesolev uurimustöö on esimene samm tõhusama hooldussüsteemi rakendamise suunas. Vaatamata sellele, et toimivate hooldusplaanide väljatöötamiseni võib kuluda aastaid, näitab antud töö, et ka piiratud algandmete ja lühikese aja jooksul annab rakendada seisukorrapõhise hoolduse meetodeid ja tõsta masinate töökindlust.

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APPENDIXES

1 APPENDIX – WORK ORDER EXAMPLE

QUANT

Work Order Details

Work Order: EE1640470 61WR200 - WR - ROBOTKEEVITUS hooldus

kontrollida lekkeid

Parent:		Status:	INPRG
Site:	Electrical Machines Factory EE - EMF	Priority:	7
Location:	JT54 - Väikeste rootorite ja staatorite südamike valmistamine	Work Type:	PM
Loc.Cust.Code:	JW54	Failure Class:	
Asset:	61WR200 - WR - keevitusrobot	Problem Code:	
Eq.Cust.Code:	200181	Drawing Number:	
GL Account:	8140-S - Full Service Contract	Asset Type:	
		Serial Number:	

Target Start:	7.03.15 2:00	Target Finish:	7.03.15 2:00	Work Duration:	00:00
Sched Start:	19.02.15 8:30	Sched Finish:	19.02.15 12:00	Est.Downtime:	00:00
Actual Start:	19.02.15 7:46	Actual Finish:			

Reported By:	AEEAIKO - AEEAIKO	Report Date:	Feb 19, 2015 7:44 AM
On Behalf Of:			
Supervisor:	AEERAAR - Arrosaar, Raigo	Fin.Ctrl.ID	
Lead:		Contract:	
Person Group:		Service:	
Classification:		Vendor:	

Site:

Plans

PM: **10027 - 61WR200 - WR - ROBOTKEEVITUS hooldus**
Job Plan: **10038 - 61WR200 - WR - ROBOTKEEVITUS - 3KSR**

Task ID	Description	Duration	Date	Measurement Point	Value	Status
10	Kaitseseadiste korrasoleku ja kinnituste kontroll.	00:00			0	In Progress
30	Avariilülitite funktsioneerimise kontroll	00:00			0	In Progress
40	Elektrisüsteemi funktsioneerimise, kaablite ja pistikute kontroll	00:00			0	In Progress
50	Õhufiltri vahetamine, mõõdud 54*65 cm	00:00			0	In Progress
60	Õlilekete puudumise kontroll roboti juures	00:00			0	In Progress
70	Jahutussüsteemi torustiku ja liitmike lekkekontroll	00:00			0	In Progress
80	Jahutusvee vahetus	00:00			0	In Progress

Date Signature Supervisor

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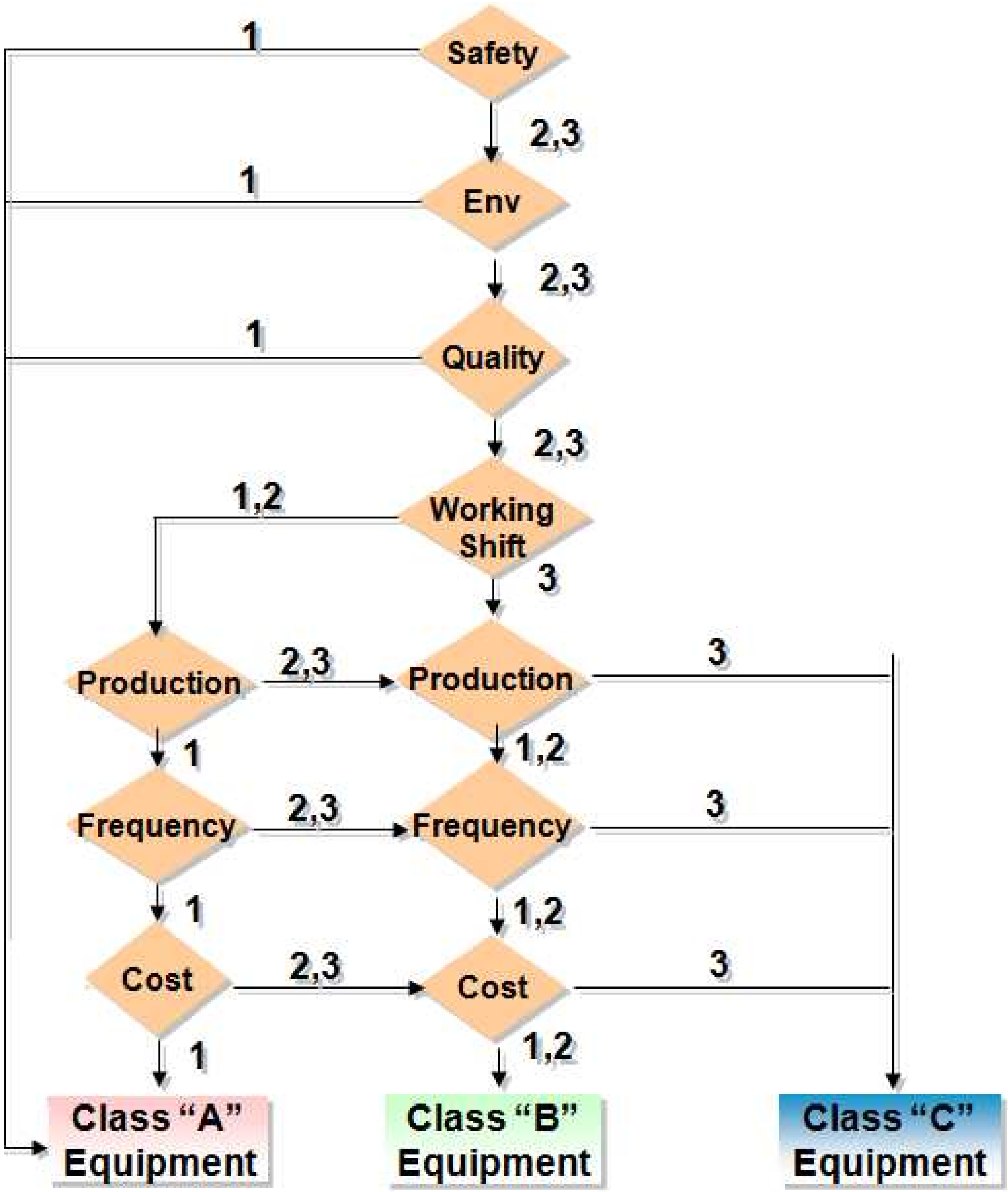
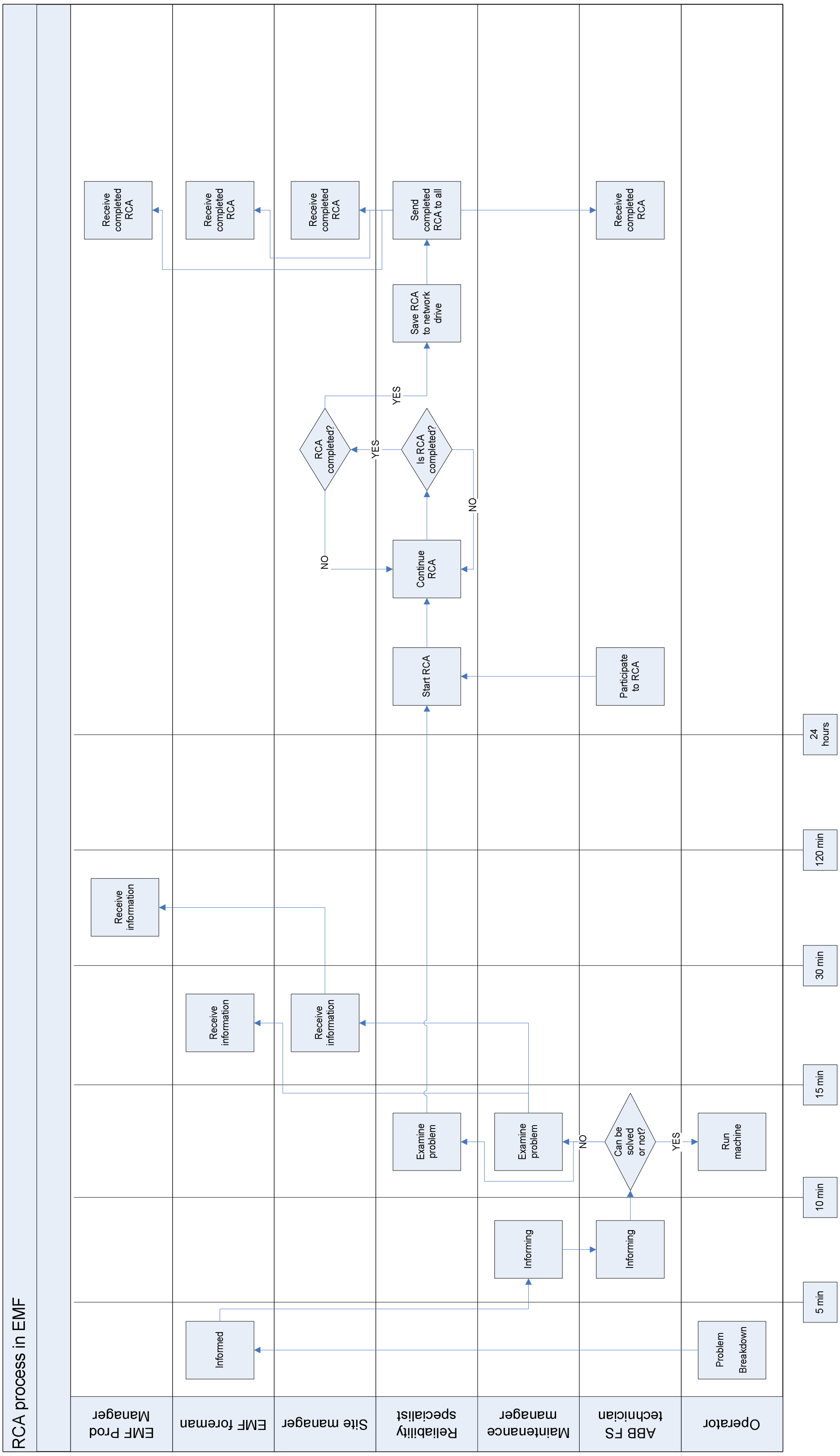
2 APPENDIX – CRITICALTY ASSIGNEMENT TOOL



[1]

3 APPENDIX – RCA FLOWCHART



4 APPENDIX – OIL ANALYSIS REPORT

ALcontrol Laboratories

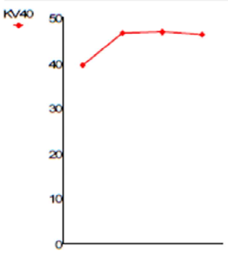
ALcontrol Laboratories
Conwy
LL32 8FA
United Kingdom
Tel: 01492 574750
Fax: 01492 574778

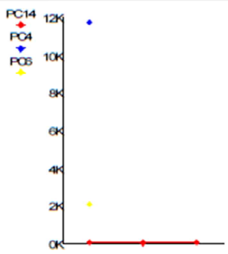
Make:	VERTIKAAC TREIPINK	Sample No:	4939664
Model:	VTC175/210	Location:	JURI TEHAS
Serial No:	3022827	Client:	ABB AS
System:	HYDRAULIC	Form No:	AN24507
Brand:	PETRO CANADA HYDREX AW	Job No.:	6/15
Grade:	46	Sampled:	08/01/15
Unique No.:	4013749	Received:	03/02/15

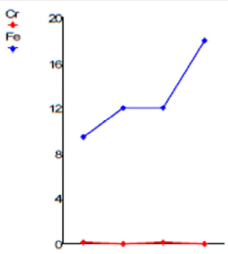
Diagnosis Key: Normal | Caution | Serious — Diagnostician: Team

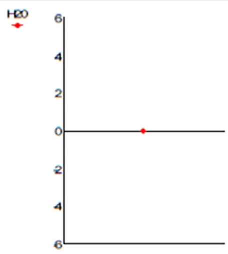
Wear appears satisfactory. No significant contamination. Advice : Monitor at the recommended sampling period.

Results		Current Sample	Historical Samples		
Sample No		4939664	4575176	4488914	4456344
Status		✓	✓	✓	
Sampled		08/01/15	12/12/13	05/09/13	01/08/13
Fluid Age		1000	750	600	400
Unit Age					
Fluid Condition					
Viscosity @ 40 °C	mm²/s	46.3	46.8	46.6	39.5
Appearance	-	Clear & Bright	Clear & Bright	Clear & Bright	Debris Present
Neut No.	mg KOH/g	0.60			
Additives					
B (Boron)	mg/kg	1.1	0.5	0.3	0.1
Ba (Barium)	mg/kg	0.3	0.0	0.0	0.1
Ca (Calcium)	mg/kg	144	141	140	138
Mg (Magnesium)	mg/kg	0.1	0.0	1.4	0.9
P (Phosphorus)	mg/kg	256	237	241	240
S (Sulphur)	mg/kg	782	764	639	609
Zn (Zinc)	mg/kg	378	356	356	347
Contamination					
ISO Code	-	19/17/12	19/17/13	19/16/13	21/18/14
Water	%	<0.1			
Na (Sodium)	mg/kg	5.6	0.8	4.2	6.5
K (Potassium)	mg/kg	1.0	1.2	0.9	0.3
Si (Silicon)	mg/kg	3.3	2.0	2.0	1.9
Li (Lithium)	mg/kg	0.0	1.0	0.1	0.1
Wear Metals					
PQ index	-	10			
Al (Aluminium)	mg/kg	0.0	0.4	0.1	0.0
Sn (Tin)	mg/kg	0.0	2.4	0.0	0.0
Pb (Lead)	mg/kg	0.1	0.8	0.0	0.0
Cu (Copper)	mg/kg	0.3	0.0	0.1	0.1
Fe (Iron)	mg/kg	18	12	12	9.4
Cr (Chromium)	mg/kg	0.0	0.1	0.0	0.1
Mo (Molybdenum)	mg/kg	0.0	0.6	0.4	0.0
Ag (Silver)	mg/kg	0.0			
Ni (Nickel)	mg/kg	0.0	0.2	0.0	0.2
Mn (Manganese)	mg/kg	0.5			
Ti (Titanium)	mg/kg	0.0	0.0	0.0	0.0
V (Vanadium)	mg/kg	0.0	0.0	0.0	0.0
Cd (Cadmium)	mg/kg	0.0			









F.A.O. JANNO SIITAN, KONETEX GRUPP OÜ, T-HE 127, TARTU 50113, ESTONIA, 50113, janno@konetex.ee

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5 APPENDIX – PRESSURE MONITORING CHART

71PM100 – Pump 1		
Date	Pressure (mbar)	Action
17.05.2014		1500h oil and filter change
19.05.2014	0,7	
27.05.2014	0,6	
6.08.2014	0,6	
22.09.2014	0,6	
21.10.2014	0,7	
27.11.2014	0,8	Planned maintenance
9.12.2014		Oil and filter change
6.01.2015	0,7	
2.02.2015	0,53	
11.03.2015	0,49	

71PM200 - Pump 2		
Date	Pressure (mbar)	Action
11.04.2014		Unplanned inspection
17.05.2014		1500h oil and filter change
19.05.2014	0,4	
27.05.2014	0,4	
6.08.2014	0,49	
22.09.2014	0,39	
21.10.2014	0,42	
27.11.2014	0,5	Planned maintenance
6.01.2015	0,54	
2.02.2015	0,34	
11.03.2015	0,49	

71PM400 - Pump 3		
Date	Pressure (mbar)	Action
18.02.2014		Oil and filter change
19.05.2014	1,7	
27.05.2014	1,4	
30.06.2014	0,78	Planned maintenance
6.08.2014	0,64	Planned maintenance
22.09.2014	0,71	
21.10.2014	0,7	
27.11.2014	0,7	Planned maintenance
6.01.2015	0,7	Oil and filter change
4.02.2015	0,87	
11.03.2015	0,97	

71PM300 - Pump 4		
Date	Pressure (mbar)	Action
18.02.2014		Oil and filter change
19.05.2014	1,8	
27.05.2014	0,7	Planned maintenance
30.06.2014	0,74	
6.08.2014	1,1	
22.09.2014	1,5	
21.10.2014	1,3	
27.11.2014	0,51	Planned maintenance
6.01.2015	0,63	Oil and filter change
4.02.2015	1,2	
6.03.2015	1,3	
11.03.2015	1,5	Repairs (Alas-Kuul)
31.03.2015	0,33	Repairs (Koliseva)

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6 APPENDIX – VIBRATION MEASUREMENT REPORT

Company:	Quant Estonia OÜ	Department:	KNFP
Customer:		Engineer:	
Order Date:	18.03.2015	Measurement Date:	23.03.15

Used devices: Microlog GX; SKF Stethoscope TMST 3; SKF Machine Condition Advisor CMAS 100-SL.

DE – Drive-end bearing

ODE – Opposite drive-end bearing

No.	Equipment	Type	Comments and recommended actions
1	SP250: Hydraulic station main pump drive - ABB M2QA132M4A	Electric motor	Vibration 6,45mm/s. Out of balance.
2	SP250: Hydraulic station auxiliary pump drive – ABB M2QA112M4A	Electric motor	Not measured
3	HD400: Hydraulic station auxiliary pump drive - Unitec S04965	Electric motor	ODE bearing makes cracking noise. Bearing inner vibration 0,24gE. Bearing replacement recommended.
4	HD400: Hydraulic station main pump drive – Unitec ML6620L F001	Electric motor	Bearings in good condition.
5	SP250: Press main drive - Siemens 1PH7137-7QD02-0ba0	Electric motor	Bearings in good condition.
6	Danobat: Main drive – Siemens 1PH7224-2NC050FC3	Electric motor	Bearings in good condition.
7	SP250: Hydraulic station main pump drive - ABB M2QA132M4A	Electric motor	Bearings in good condition.

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