CHALMERS

Critical equipment classification and cost reduction within professional maintenance

Master of Science Thesis in Production Engineering

ALEXANDER BÖRJESSON
ADAM SVENSSON

Department of Product and Production Development
Division of Production Systems
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ADAM SVENSSON

Examiner: Johan Stahre
Department of Product and Production Development
Chalmers University of Technology
SE-412 96 Göteborg
Telephone: +46 (0)31 – 772 10000

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Abstract

This project, conducted at Volvo Trucks, aims at finding an appropriate method to determine equipment criticality in order to help the maintenance department prioritize among work orders and to increase equipment availability. Work routines for how to perform maintenance and for how to control spare part inventory is also being suggested. An explorative, qualitative research methodology was used to interpret data information collected using literature study, semi-structured interviews, seminars and workshops. Maintenance within different types of businesses have been assessed in order to strengthen the validity of the report and to gain knowledge.

The project reveals an inability to learn from past events and that a complete problem solving methodology is missing in the daily work in the maintenance department. This means that much of the prerequisites for equipment classification are missing and that the model presented has great potential in helping the department develop its work methods.

To improve the prerequisites and to be able to base the classification on facts, a data collection tool is presented. The tool, called emergency work order (EWO), helps the department collect information about a failure and to analyze it. The classification model bases its classification on the documented events and prioritizes using cost comparison. The classification model is, because of this approach, reactive as it will classify equipment based upon past events. This project concludes that this will help the maintenance department to increase equipment availability by continuously learning from failures and in turn, move towards a more proactive maintenance approach. The spare part routines presented is also based upon the usage of data in combination with qualitative evaluations of the parts importance.

Keywords: equipment classification, critical equipment, maintenance, strategy, spare parts management, reactive maintenance, preventive maintenance, proactive maintenance.

Acknowledgement

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We would also like to thank all organizations and persons contributing with knowledge, experience and material, especially but not exclusively Magnus Wallmander (Volvo Powertrain), Jan-Eric Fagerlind (Volvo Powertrain) and Patrik Falk (Volvo Construction Equipment).

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Göteborg, May 2011

Alexander Börjesson
Adam Svensson

Table of Contents

Abbreviations

The following abbreviations are used in this report.

ABC	Always better control
AGV	Automatic guided vehicle
EWO	Emergency work order
HERCA	Human error root cause analysis
KPI	Key performance indicator
KRI	Key result indicator
MTBF	Mean time before failure
MTTR	Mean time to repair
OEE	Overall equipment efficiency
PI	Performance indicator
RCM	Reliability centered maintenance
TPM	Total productive maintenance
TPS	Toyota production system
VCE	Volvo construction equipment
VDM	Value driven maintenance
VED	Vital essential desirable
VPS	Volvo production system
VPT	Volvo powertrain
WCM	World class manufacturing

1 Introduction

1.1 Background

When Henry Ford in the year 1896 finished his first car nobody could imagine what he would achieve during his life and even less how his work would influence the industry in general. As the founder of Ford Motor Company, Mr. Ford revolutionized transportation in year 1908 by introducing the Ford Model T. The car became a huge success and to own a car was now affordable for a wide range of citizens. As the demand for the Model T increased Mr. Fords biggest concern was to increase production capacity. Thanks to the process innovation, a new factory and a decrease in production time he managed to produce a significant number of cars each day (Ford Motor Company, 2011). What Mr. Ford achieved in terms of productivity gain, waste reduction and streamlined production is what many producers tries to imitate even today.

Today, the need for productivity gain and waste reduction is not entirely related to a huge demand of products that Mr. Ford tried to meet. Rather the need is about surviving in a constantly increasing competition. Globalization and increasing product customization forces truck producers such as Volvo to constantly improve their production system. The approach to productivity gain has, just like the reasons for it, evolved. Instead of constantly forcing the workers to do more in less time, technical aids and automation are used to increase the productivity and reduce heavy, monotonous and hazardous work. However, as the production system complexity and level of automation increases more resources needs to be focused on maintaining and developing the system. This results in constantly increasing competence requirements and forces organizations to reconsider the distribution of resources (Frohm, 2008).

1.2 Problem description

Currently, a substantial part of the maintenance work at Volvo Trucks is done as a reaction to unexpected events. This leads to a quick fix mentality where the maintenance staff acts more like firefighters rather than continuously improving the production system. Working unstructured obviously does not solve all problems in an optimum way; the problem is fixed for now but the probability of it is necessarily not reduced. The maintenance mechanics rely almost entirely on their experience. Even though the maintenance mechanics in general are very experienced and therefore able to solve the problems this is not a satisfying situation. Working in a structured way with clear work procedures and good documentation would be beneficial. It is important that all fixes, regardless of it is a quick fix or a permanent solution, are evaluated, documented and standardized as a way of minimizing the risk of reoccurrence.

For driven production lines like the ones at Volvo Trucks the economic gain of correct maintenance is obvious. A breakdown that causes the whole factory to stop does not only affect the total output and deliverability but also costs in terms of work in progress (WIP), unused manpower and reduced equipment utilization. Lowering the number (and length) of production stops can therefore be seen as a direct way of lowering the cost and increasing the capability of the system. If the knowledge about critical equipment can be continuously improved and documented, downtime and consequences of breakdowns can probably be minimized.

As implied earlier, even the most advanced and powerful machinery needs at some point maintenance and spare part replacement. This means that all equipment in a modern factory, regardless of its technical level and age, needs maintenance and supervision. As the number of systems (and their complexity) increases maintenance will play a bigger role. This project tries to find new methods for increasing the performance of the production system by focusing equipment classification and maintenance.

1.3 Purpose

The purpose of the thesis is to increase the capability of the maintenance department by establish easy to use, yet powerful methods for identifying and classifying critical equipment in the factory. This will make it possible to make appropriate prioritizations within maintenance. The work routines and factory mentality within the maintenance department as well as surrounding departments will be analyzed and aims to increase understanding for maintenance work and the importance of maintenance and continuous improvements. Both the method for classification of equipment and the suggested work methods shall be compatible with the current production system in use. The project also aims to establish spare part management principles.

1.4 Aim

This thesis work aims to develop an easy to use, yet powerful classification method for critical equipment in order to be able to prioritize work tasks within maintenance. It also aims to develop better work routines for the maintenance department to increase its effectiveness. A framework for spare part management will be presented.

The project can be summarized in the following three questions:

- How can the equipment criticality be classified at Volvo Trucks?
- What work methods should be used to support the classification method?
- How should spare parts be managed?

1.5 Delimitations

When evaluating the work methods and company culture, focus will be on the maintenance department and the departments that either is influenced by the maintenance department or influences the maintenance department. Focus will be on how breakdowns are handled, reported and prevented from reoccurring. Company culture and mentality will play an important role in the analysis and will therefore be evaluated, but because of the complexity in changing these aspects the project will not present any implementation strategies concerning this matter.

1.6 Company description

Volvo Trucks is a Swedish trucks manufacturer within the Volvo Group. Volvo Trucks is the second largest heavy-duty truck brand in the world and sells trucks in more than 140 countries with production all over the world. This project is carried out at the Tuve factory in Gothenburg, Sweden. The Tuve factory produces the models FM, FH and FH16 and also supplies all the other factories with truck frames.

The engineering and maintenance department is a supporting function in the factory. The maintenance branch is responsible for preventive and reactive maintenance to ensure equipment availability. The engineering branch supplies the factory with technical competence regarding tools, equipment, balancing etc. and is responsible for new equipment investment.

2 Methodology

The project methodology aims to help understand the current state of the maintenance department and surrounding functions in the factory. The information collection was done using mainly interviews and observations (i.e. a qualitative approach) and follows the methodology proposed by Prasad (1993). Information was also collected using seminars and workshops (see Chapter 2.1.3).

This thesis is explorative in its nature and the knowledge about what information that is needed to solve the problem evolved during time. There is no precise method to grasp a problem like this more than trying to understand the present situation. Therefore, in the case of this thesis, the qualitative research approach is appropriate. Qualitative research is often used as a way of generating new hypotheses in contrast to quantitative research which often is used to verify that these hypotheses are correct (Bryman & Bell, 2007).

The qualitative research approach emphasizes words rather than actual numbers and stresses the importance of a deeper understanding of the situation (Bryman & Bell, 2007). This means that the project has focused on general principles rather than detailed activities and tools. During factory visits attention was on an aggregated level. Actual work tasks were not investigated, rather the general philosophy and objectives was discussed.

As Burgress & Bryman (1999) observes there are no precise definition of a how to conduct a qualitative research. Bryman & Bell (2007) elaborates around multiple possible methodologies for conducting qualitative research. The method chosen in this project was first used by Prasad (1993) when conducting a research within the health-care organization. The methodology proposed by Prasad (1993) (visualized in Figure 2.1) is appropriate for the research part of this thesis thanks to its iterative layout. It is therefore applicable to a wide range of research projects regardless of their size and scope.

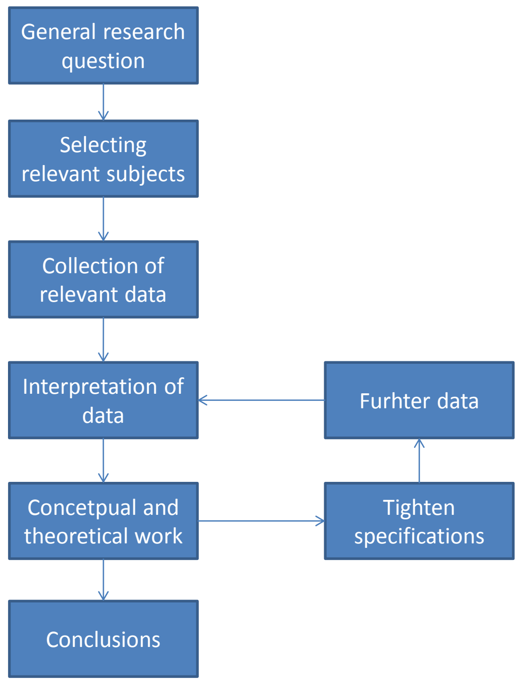

Figure 2.1: The iterative research methodology (Prasad, 1993).

2.1 Methodology description

2.1.1 General research question

The general research questions form the base upon which all further work is being done. The question used is the same as in the aim of the project. The questions need to be investigated and answered in order to fulfill the purpose of the project. The next step involves widening these questions into several subjects.

- How can the equipment criticality be classified at Volvo Trucks?
- What work methods should be used to support the classification method?
- How should spare parts be managed?

2.1.2 Selecting relevant subjects

When selecting relevant subjects it is important not to focus on the consequences of problems or to strictly answer the research questions. Instead this step involves trying to find the actual cause that leads to a specific answer, i.e. it is not only of interest to answer how the organization looks today but also why and to investigate peoples opinion about it. The following questions were initially selected as important to be able to fully understand the situation.

- What is the role of the maintenance department?

- How is the maintenance department organized today and why?
- What is the goal of having a classification model and why?
- How is the classification of equipment performed today and why?
- What is lacking in the current work principles for problem solving?
- How is the maintenance department contributing to organizational learning?
- What KPIs is used today and how do they contribute to the continuous improvement culture?
- How does the department divide its work between different types of maintenance?
- How is the spare part inventory managed today?
- What are the objectives of the current spare part principles?

All these questions were then transformed into a list of relevant theories and subjects which was later evaluated. In addition to these subjects the following aspects was considered relevant.

- What is maintenance?
- What is classification?
- How should the maintenance strategy support the production system?
- Are there any frameworks for maintaining a production system available?
- How do these frameworks treat spare parts management?
- How can production equipment be classified using these frameworks?

2.1.3 Collection of relevant data

Data was collected using literature studies, workshops, meetings and observations. Best practice within Volvo Group was analyzed with aid from the Volvo Production System (VPS) Academy and by factory visits. Databases and journals served as a base for the literature study. Keywords were selected to fit the relevant subjects defined above. Semi-structured interviews and meetings with operators and group leaders, from both production and maintenance, were the main sources of information regarding the present situation. By analyzing data log files extracted from ERP-systems the finding regarding the present situation has been strengthened.

In semi-structured interviews the questions are formulated in advance, but the interviewer is allowed to rephrase the questions during the interview (Merriam, 1994). The interviewer is also allowed to ask more questions during the interview as a way of creating a better discussion (Bryman & Bell, 2007).

This approach makes the data analysis straightforward as the interviewees are asked almost the same questions. However, important issues and unexpected topics may be missed due to the predefined questions (Bryman & Bell, 2007). Because of this, semi-structured interviews were combined with observations. This is, according to Bryman & Bell (2007), a good way of capturing unexpected events.

The first days of the project were spent in the factory performing non-participant observations. This refers to observations done by an observer not participating in the work (Bryman & Bell, 2007). The observation was also unstructured, i.e. no schedule or plan was used during the observations. In connection to the observations, unstructured interview was used to ensure correct interpretation of the situation. Maintenance mechanics (day and night shift) and senior maintenance mechanics was interviewed. The information collected was documented continuously and analyzed at the end of the day.

Following these first days, the project performed semi-structured interviews and literature study concurrently. At this stage, the literature study was used to get a basic understanding of maintenance and the task of the project. Maintenance engineers and managers from several fields of interest were interviewed, such as production lines, frame side manufacturing and assembly. This was done to ensure the whole organizations perspective. The knowledge gained during this process was continuously verified by the project supervisor and documented.

2.1.3.1 External seminars and study visits

The project has conducted two factory visits and has participated in a World Class Manufacturing (WCM) audit at Volvo Powertrain Skövde. The global maintenance manager at Volvo Powertrain introduced, prior to the audit, the maintenance strategy and provided contact information.

The WCM audit was held by the WCM manager in Skövde and constituted of result presentations from different functions. Each presentation was followed by questions from the global WCM coordinators present. During this audit, the project had the ability to acquire and document information.

The factory visits were arranged by the maintenance department of each factory visited. During an initial meeting the agenda for the day was introduced. Topics of interest were discussed and later shown in the factory. A round trip was performed and the arranger had the opportunity to show what was believed to be good practice within maintenance. Questions were asked during the round trip to increase the understanding of their system. The information was documented and later analyzed at the closing meeting.

To get a broader view of maintenance a fire station and a nuclear power plant was also evaluated in terms of maintenance and critical equipment. This was done using semi-structured telephone interview and e-mail conversation. The businesses were selected using discussion and the aim was to find businesses in which consequences of equipment failure is severe.

2.1.4 Data interpretation

This step involves categorizing and classifying the data to make it more tangible. Prasad used the approach of creating "concept cards" proposed by Glaser & Strauss, a common method within grounded theory (Bryman & Bell, 2007). Concept cards are created by categorizing pieces of information (referred to as elements) such as events and (parts of) conversations into categories. The category is then given a meaningful common denominator (label) which is used as the title of the concept card.

This project used a file structure to categorize and classify data. The following three main categories, derived from the project aim, were used (these can be seen as main concept cards).

- Equipment classification
- Spare part management
- Work principles

Notes from workshops, meetings and factory visits was then broken down to information elements and placed in the corresponding category. During this process, sub-categories were also introduced to create better structure.

2.1.5 Conceptual and theoretical work

Theory and empirical findings was then analyzed in order to be able to understand the present situation and to be able to suggest improvements. The data interpretation phase led to a number of hypotheses which was then further analyzed. Brainstorming sessions, discussions and the knowledge as upcoming Master of Science Engineers was later used to confirm or reject the hypotheses. To be able to confirm them, further analysis was conducted. This is described in the next paragraph.

2.1.6 Tighten specifications & further data

During this process, new meetings and more data collection was conducted to be able to confirm the hypotheses. This also required refined information searching. This step was done in several iterations which are proven to be a valid way of strengthening once interpretation (Bryman & Bell, 2007).

More literature study was conducted to gain theoretical knowledge in fields acquired during factory visits and the WCM audit.

2.1.7 Conclusions

The conclusions, consisting of confirmed hypotheses and relevant data were then turned into facts which were used to answer the research questions. The confirmed hypotheses were combined with data and explanations to convince the audience about its credibility and significance (Bryman & Bell, 2007).

2.2 Validity of qualitative research

Guba and Lincoln (1985) propose a method for determining the validity of the qualitative research by looking into trustworthiness and authenticity.

2.2.1 Trustworthiness

Trustworthiness can be acquired by conforming to the following parameters.

- **Credibility**
  Credibility can be guaranteed by ensuring that the research is performed under the use of good practice, but also by submitting the research to other of interest to confirm the findings. It is also of importance that the people that contributed with data confirm their information even though it might result in less edge due to personal reputation implications. The credibility reflects how the study corresponds with the reality (Bryman & Bell, 2007).

- **Transferability**
  Qualitative studies tend to be unique for the studied context and are often concerned with a small range of data. Transferability refers to the extent that the study can be generalized and transferred to different contexts (Bryman & Bell, 2007).

- **Dependability**
  Guba & Lincoln (1985) propose to establish a method to ensure that all records from different parts are stored. Data and information from problem formulation, selection of research participants, fieldwork notes, transcripts, brainstorming session decisions and so on should be kept accessible.

- **Conformability**
  Guba & Lincoln (1985) propose that establishing conformability should be one of the objectives of the roles as auditors even though it is impossible to be fully objective. Trying to reduce the impacts of personal values is very important when trying to obtain conformability (Bryman & Bell, 2007).

2.2.2 Authenticity

In addition to trustworthiness the criteria of authenticity is used to obtain data validity (Lincoln & Guba, 1985). This aspect raises a wider set of issues concerning the political impact of the research. Authenticity includes factors such as fairness. Fairness represents to what extent the different viewpoints represent members from different levels in the hierarchy (Bryman & Bell, 2007).

3 Theoretical framework

3.1 Production system

A production system is often symbolized by a complex structure with dependencies between functions, core values and departments. These relationships must be clarified to get all instances to work towards a common goal which in turn enables the company to succeed in its context. Toyota Production System (TPS), often associated with the power behind Lean production, is probably the most well-known production system (Lindström, 2010). TPS has shown to be successful for many years, turning a poor quality Japanese automotive company into the company today often referred to as world class when it comes to quality and safety (Liker, 2004). Often inspired by Toyota, companies formulate their own production system as a way of reaching their goals. A production system represents the actual way of working (Maylor, 2010). To continuously improve the knowledge is a necessity. A well formulated production system makes it possible to benchmark factories and data to continuously improve towards operational excellence (Liker, 2004). A defined production system within a global company aims to makes it easier to work in a standardized way towards the goal of the company.

A great example from a standardization point of view is the world's largest supplier of home products namely, IKEA. Stores all over the globe look more or less the same and by having a standardized layout and a standardized way of working, it is easier to transfer knowledge and to make both customers and employees understand the philosophy of IKEA.

3.1.1 Volvo Production System

VPS was first introduced in 2007 as a way to continuously improve quality, delivery and productivity. VPS is the Volvo Way in actions – how Volvo goes from words to action. It contains practical tools that when used correctly, helps the organization to work towards its shared goal (Persson, 2008). VPS has five core principles which are thought to assist and guide the organization towards its goal (see Figure 3.1). The principles are listed below.

- Teamwork creates an efficient organization where all employees are involved and committed to the continuous improvement work. This way, all employee contribution to the overall goal of the organization, everyone's experience, knowledge and creativity is captured (Lindström, 2010).
- Only by establishing deep knowledge and understanding a stable process can be created. This means reduced variation and waste which makes the process predictable and efficient (Lindström, 2010).

- Doing things right the first time is referred to as built-in quality. Conforming to a built-in quality philosophy means fixing problems as they occurs which in turn helps the organization to move towards a zero-defect production (Lindström, 2010).
- Just-in-time means producing and delivering what is needed, when it is needed in the quantity needed. In other words, a pull strategy helps the organization to produce only what the customer want in the shortest lead-time possible (Lindström, 2010).
- Apply continuous improvements. It will require a long term approach but are at the same time the driving force in the organization (Lindström, 2010).

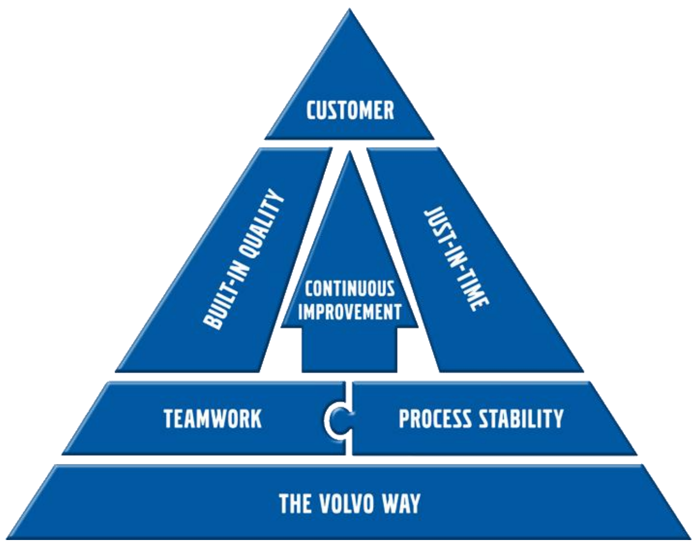

Figure 3.1: VPS core principles.

3.1.2 VPS Maintenance System

Maintenance system (MS) is found within the process stability element and consists of a number of tools for ensuring equipment effectiveness and efficiency. This is done by establishing a system for preventive maintenance which involves all departments related to the equipment. VPS MS also involves all levels of the organization (Persson, 2008).

Some key elements within VPS MS are:

- Autonomous and professional maintenance (see Chapter 3.3)
- Preventive maintenance
- Early equipment management
- Visualization

The aim of VPS MS is to reduce the amount of un-planned maintenance work as well as decreasing the amount of reactive maintenance. Shop floor employees and managers, maintenance staff and equipment acquisition personnel should all be involved to liberate resources and knowledge, to work with preventive maintenance (Persson, 2008).

According to Persson (2008) the vision of MS is to have a situation where:

- 90% of all maintenance work is preventive
- Poor Overall Equipment Efficiency (OEE) should initialize maintenance activities
- Operators and maintenance specialists work together to continuously increase equipment availability
- Operators are educated and trained in maintenance, they can quickly discover abnormal machine behavior and perform basic preventive maintenance
- Professional maintenance focuses on more complex maintenance tasks, e.g. condition based maintenance and improved preventive planning
- Early equipment management is used to facilitate future maintenance

3.1.2.1 Availability and OEE

Traceability is a prerequisite to measure progress. VPS proposes measures such as mean time to repair (MTTR) and mean time before failure (MTBF) to ensure traceability (Lindström, 2010), (Freivalds, 2008).

OEE is a total performance measurement for equipment concerning availability, efficiency and quality (Freivalds, 2008).

Equation 3.1: OEE is a common performance measurement.

$$OEE = Availability \times Efficiency \times Quality$$

OEE should according to VPS be calculated for strategic machines or machines with high demand, e.g. for bottlenecks and where equipment utilization needs to be high due to high investment costs. In order to be able to calculate OEE, data must be collected (Lindström, 2010).

3.1.2.2 Early equipment management

Early equipment management considers failure causes and the maintainability of equipment. Life cycle cost analysis is used to choose the optimal equipment, using the experience from improvement activities and the knowledge of a cross functional team. Early equipment management aims at tracking all maintenance problems back to its root causes to eliminate them as early as possible. The key aspect is to get a better possibility to foresee the risks of actions and decisions (Productivity Inc., 2008), (EMS Consulting Group, 2011).

3.1.3 Spare parts management

VPS maintenance system includes guidelines for spare parts management. These guidelines are divided into 5 different levels from basic to world class. These are written as statements that must be satisfied to fulfill each level.

- **Level 1:** The most basic level demands that the following actions should be conducted for a pilot machine.
    - Unnecessary items has been removed using separation
    - All spare parts have been classified based on whether they are used within preventive maintenance or not
    - Spare parts have been put in order in a clean and dust free environment (especially important for sensitive parts)
    - Quantities and replenishment levels has been defined

- **Level 2:** The next level demands that all level 1 activities are carried out for all AA (highest criticality class) and A (second most critical) equipment. Visual management has also been introduced for all parts to aid a strict FIFO (first-in-first-out) principle.

- **Level 3:** When all level 1 and level 2 activities are carried out for all equipment, one conforms to level 3 within spare parts management. Quantities of spare parts should also be synchronized with preventive maintenance activities.

- **Level 4:** This level is reached when a management system for automatic reordering of spare parts is introduced. Spare parts are standardized between equivalent equipment.

- **Level 5:** World class level is reached when high standardization of spare parts is introduced. Continuous improvement of the spare parts management system is also being conducted.

3.2 Lean production

Lean production focuses of continuously reducing waste, improving quality and increasing customer value to lowest cost. The philosophy has much in common with TPS and many of the core concepts are therefore described using Japanese terms.

Three of them, *muda*, *muri* and *mura* symbolizes waste, overburden and unevenness respectively. These three wastes should be reduced (Liker, 2004).

Lean production is often described using a pyramid consisting of four levels. Each level represents a core value within Lean production and only by achieving all four core values a successful lean implementation can take place. The lean framework is by Liker (2004) defined as 14 principles of management which, if implemented and complied with, helps the organization to do more with less resources. The 14 management principles spans from concrete tools to more philosophic approaches.

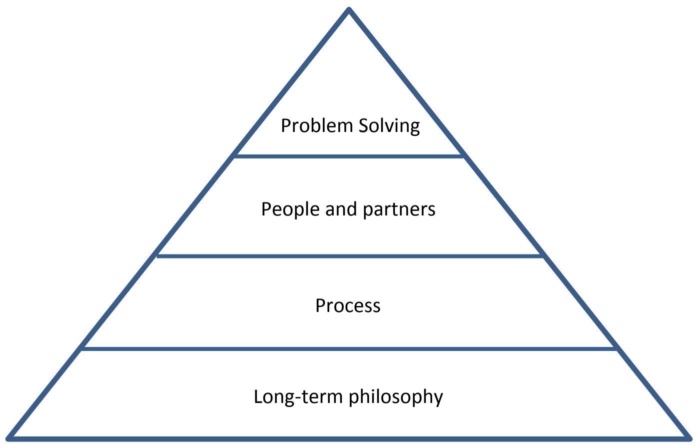

Figure 3.2: The four levels within Lean production visualized using a pyramid (Liker, 2004).

Level 1. Long-term philosophy

a) Base management decisions on long term philosophy instead of short term financial goals

Level 2. The right process will produce the right results

a) Create a continuous process flow. Don't hide problems by using buffers
b) Using the pull-principle will help you avoid overproduction
c) Level your production instead of producing using a start and stop approach
d) Build a culture of stopping to fix problems directly to ensure correct quality
e) Standardize all task as it is a prerequisite for improvements
f) Use visual indicators so that everybody can discover problems
g) Use technology that supports the people, not replaces them

Level 3. Add value to the organization by developing its people and partners

a) Grow leaders inside the company that thoroughly understands the system
b) Create a strong culture that develops people aligned with the philosophy and beliefs
c) Challenging targets for your partners allows them to grow

Level 4. Continuously solving root problems drives organizational learning

a) Go and see for yourself to thoroughly understand problems
b) Avoid mistakes by making decisions slow and implementing them fast
c) Become a learning organization by relentless reflections and continuous improvements

3.3 Maintenance

In the context of production engineering, maintenance refers to the technical, administrative and managerial actions taken to ensure that a physical asset continue to do what the users want them to do, with respect its initial function and specification (SIS, 2000). Maintenance can also contain the supervision of equipment (SIS, 2000). Different approaches on how to apply maintenance to physical assets exists.

3.3.1 Reactive maintenance

The maintenance that is required to restore the state of a physical asset to its initial state once it has failed is defined as corrective or reactive maintenance (SIS, 2000). Reactive maintenance is the purest approach to maintenance and was the only approach used until the mid-1900s (Moubray, 1997). The main reason for this was the low level of mechanization and the fact that downtime was not regarded as an issue. Reactive maintenance can also be referred to as breakdown maintenance.

3.3.2 Preventive maintenance

During World War II the demands on the industry grew at the same time as labor left the factories for the army. This led to a dramatic increase in mechanization, higher equipment complexity and the factories became dependent on the machines. Suddenly, downtime was regarded as waste and the idea of preventing failures was born.

Preventive maintenance, at this time, referred to maintenance performed on fixed intervals (Moubray, 1997). Today, preventive maintenance is somewhat wider and includes both planned maintenance and condition-based maintenance (SIS, 2001).

3.3.2.1 Planned maintenance

Planned maintenance refers to the activity of replacing and inspecting parts and materials on a regular basis following a predefined schedule (SIS, 2000). This schedule is often defined by merging the suppliers' recommendations with legal regulations as well as in-house experience (Kelly, 2006). Planned maintenance is used to improve equipment life and to avoid unplanned maintenance activities (Wireman, 2008). Planned maintenance is in literature also referred to as scheduled maintenance; time based maintenance or planned preventive maintenance.

3.3.2.2 Condition-based maintenance

Condition-based maintenance means maintenance tasks being carried out when needed. This is often determined by monitoring the equipment performance and condition (Kelly, 2006) (SIS, 2001). For example, vibrations, sounds or surface roughness of the product can be monitored.

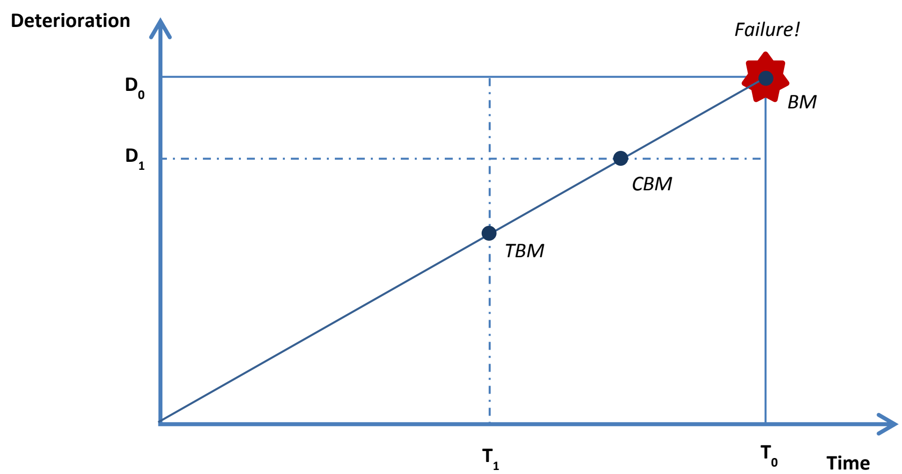

Figure 3.3: Time Based Maintenance (TBM) introduces a risk of changing the part too often but reduces the risk of having unexpected failure. Breakdown Maintenance (BM) never changes a part that does not need replacement and is therefore in that sense cost efficient. Condition Based Maintenance (CBM) is the most complex method of the three requiring knowledge and deep process understanding.

3.3.3 Proactive maintenance

Proactive maintenance refers to not only preventing failures but to eliminate the possibility of the failure, i.e. to work proactively means to foresee possible failures and eliminate the possibility of them by for example redesign (Nationalencyklopedin, 2011), (Sasaya, 2009). This is the third and most complex maintenance approach requiring large amount of resources since all possible failure modes needs to be defined before a failure can be eliminated.

3.3.4 Autonomous maintenance

Maintenance tasks carried out by the machine operator rather than special maintenance staff is referred to as autonomous maintenance (Levitt, 2008), (Lindström, 2010). The task can be both reactive and preventive in its nature. The aim of autonomous maintenance is to avoid small production stops and to ensure equipment availability. It often takes several years to introduce autonomous maintenance in a factory as it requires education, training and commitment (Nord, Pettersson, & Johansson, 1997), (Levitt, 2008). To be properly educated is also a prerequisite for understanding why the maintenance is being performed. The responsibility of autonomous maintenance will increase the job satisfaction, which in turn improves the commitment (Rubenowitz, 2004).

Autonomous maintenance in its simplest form consists of 5S and lubrication. The level of complexity then increases (often visualized using a staircase) into inspections and later also repair actions (Ljungberg, 2000), (Lindström, 2010).

Autonomous maintenance is a way of ensuring that the operator understands the equipment, can discover unusual behavior and feels commitment to the equipment. Autonomous maintenance is effective since it is impossible for the maintenance department to cover all equipment at all time and to have expert knowledge about each equipment. Even if the maintenance mechanics had the time required to check all equipment every day they are not likely to find the symptoms that may lead to a breakdown since they do not know how the equipment is used to sound, smell or behave. This makes it impossible to notice malfunction or deviation. This is however knowledge every operator has since he/she is using the equipment on a daily basis (Nord, Pettersson, & Johansson, 1997).

3.3.5 Professional maintenance

All maintenance tasks carried out by staff within the maintenance department is referred to as professional maintenance. Tasks requiring much time and special knowledge are often not feasible within autonomous maintenance and are therefore assigned to the maintenance department (Lindström, 2010), (Ljungberg, 2000). Professional maintenance also refers to a lot of actions not directly connected to repairing and ensuring the availability of the equipment. These actions is rather used to ensure efficient and effective maintenance and covers planning, economy, spare part management etc. See Figure 3.4.

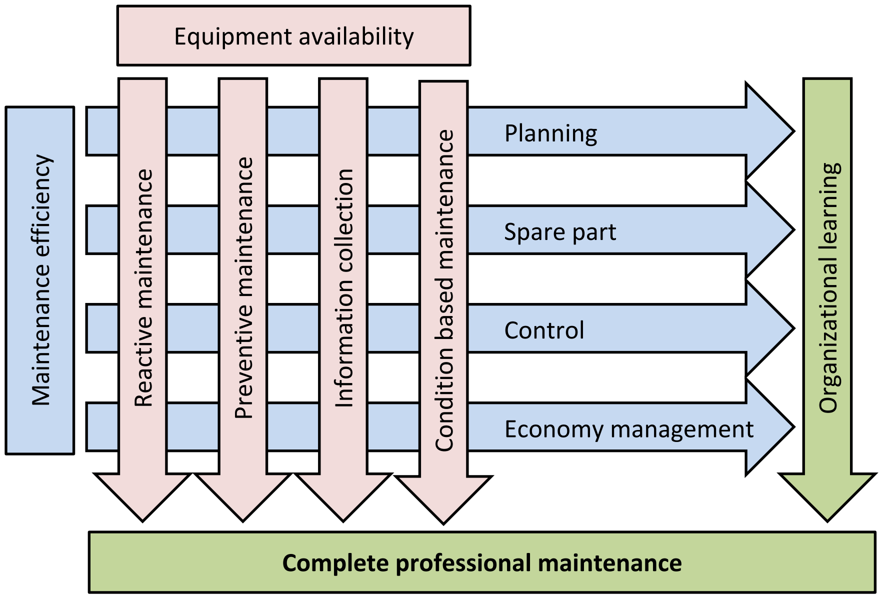

Figure 3.4: Professional maintenance consists of both equipment availability and maintenance efficiency and drives organizational learning (Nord, Pettersson, & Johansson, 1997).

3.4 Total Productive Maintenance

Total Productive Maintenance (TPM) refers to a big number of principles and tools used for maintenance. The tools and principles have evolved during many years and the focus has shifted from reactive maintenance to preventive maintenance and lately proactive maintenance (Chan, Lau, Ip, Chan, & Kong, 2003), (Nord, Pettersson, & Johansson, 1997).

TPM is a complete philosophy to maintain and improve the efficiency of a production system. The core concept is collaboration between different functions and departments within the company and mutual understanding. It's an ongoing process that needs constant attention and commitment (Ljungberg, 2000). Implementing TPM project wise will most certainly make you fail. TPM can be divided into three cornerstones described in Chapter 3.4.1 - 3.4.3 (Ljungberg, 2000). If not all cornerstones are implemented and maintained the execution will fail. The cornerstones are described below.

TPM relies in shared information between departments where one works to satisfy the customer. Trying to implement TPM in an organization that is strictly top-down controlled where managers can keep information for themselves to control the workers is not likely to be successful (Nord, Pettersson, & Johansson, 1997).

TPM wants to overcome the often present barrier between production and maintenance by working in kaizen groups and with autonomous maintenance. It is also important that the maintenance department is involved when new equipment is procured. It is likely that they are the ones with the highest practical knowledge about similar equipment and the weaknesses in the current equipment (Ljungberg, 2000).

3.4.1 Cornerstone 1: Production follow-up

Cornerstone 1 in TPM emphasizes the analytic work that results in data and knowledge about the process and the equipment. The ability to maintain the equipment and to continuously improve it is reduced if no data exists. MTBF and MTTR are two common ways of how to monitor a process (Ljungberg, 2000). Selecting the appropriate performance measures can be troublesome but is of great importance. Faulty selected measures may be counterproductive and reduce the effectiveness of the maintenance department (Parmenter, 2007). See also Chapter 3.11.

3.4.2 Cornerstone 2: Autonomous maintenance

The ideal way of performing equipment maintenance is that the operators maintain their equipment themselves. They are probably the ones with most knowledge about equipment failures and therefore the ones with highest probability of solving the problem quickly (Ljungberg, 2000), (Nord, Pettersson, & Johansson, 1997).

Historically, maintenance has been regarded as unnecessary, resulting in loss of production. With this mentality it is not likely that operators will care about the equipment. Hence, maintenance will not be regarded as something positive, contributing to the welfare of the company. This philosophy forms, together with TPM, two different alternatives. Either you prioritize short-term time savings or you choose long-term stability. You cannot force employees to care about equipment if top management does not care about maintenance (Ljungberg, 2000).

Several autonomous maintenance programs are described in literature. According to Ljungberg (2000) the following key factors for success are the most common.

- **Management support**
  This is the most important factor for a successful TPM implementation. Management should not only encourage the operators to maintain their equipment but also provide the right knowledge and follow up the work.
- **Initial education, training and practice**
  Education and training in autonomous maintenance tasks as well as TPM in general is crucial. Without the knowledge, the work becomes both impossible and meaningless.

- **Collaboration between departments**
  The core principle of TPM should also be present within autonomous maintenance. Professional maintenance should always support the operators.
- **Continuous improvements groups**
  The autonomous maintenance needs continuous attention and improvements. Kaizen teams are also present as a separate cornerstone in the TPM framework.
- **Time**
  Give the operators the time required to learn, perform and check all actions. Rushing through the actions will cause errors and will not allow the operators to reflect and develop their work.

3.4.3 Cornerstone 3: Kaizen teams

TPM provides a set of tools to organize people in groups to work with continuous improvements, knows as kaizen teams or improvement teams. Their work is not a project with a clear goal and time definition. The objective is instead to continuously improve the process. Working in these groups is mandatory within TPM and is included in the daily work. The aim of this is also to change the perceived role of the operator. Instead of being paid only for assembling trucks; you are paid to improve the company (Ljungberg, 2000).

3.5 World class manufacturing

WCM is a production system philosophy evolved from the post World War II era within Japanese manufacturing industry. WCM uses methods, tools and techniques from concepts such as:

- Total quality control (TQC)
- Total productive maintenance (TPM)
- Total industrial management (TIM)
- Just in time (JIT)

The main focus of WCM is continuous improvements in the fields of quality, cost, lead time, flexibility and customer service. It is hard to determine a precise definition of WCM since many consulting firm sells their own interpretations using the name WCM (Sasaya, 2009).

The concept of WCM is visualized by a house built upon a foundation. The house constitutes of ten pillars each representing a focusing area. The foundation consists of principles that should be regarded throughout the pillars. Each pillar has its own methodology divided into seven steps to reach “world class” within its specific area.

In order to reach world class for the whole organization the last step in each pillar must be fulfilled. See Figure 3.5. WCM emphasizes the importance of working strategically within all pillars (Sasaya, 2009).

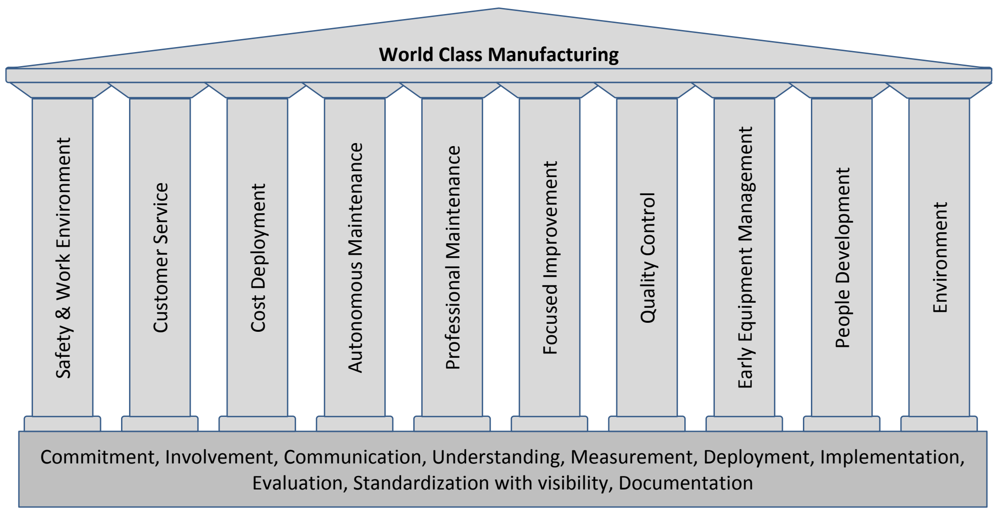

Figure 3.5: The house of WCM constitutes of 10 pillars and a foundation of 10 principles.

Most of the pillars in the house are used within different production philosophies. In the case of this project it is however interesting that several pillars concerns maintenance. All pillars will not be evaluated in this project. Instead, a brief overview of the pillars of interest in the context of this project will follow (Sasaya, 2009).

The heart of WCM is focused improvements and the source of decision making is Cost Deployment which uses systematic analyses to address costs to losses. The ambition is to be able to address all losses to a specific issue or type of issue as a way of facilitating correct prioritizations. Since the limits of responsibility are strictly defined in WCM, addressing all losses to a specific issue will also determine the pillar responsible for each loss. The magnitude of each cost enables each responsible function to do prioritizations within its own area of responsibility (Sasaya, 2009).

WCM strives at finding the root causes of the problems, as a way of working away from treating symptoms. This strive influences every decision taken within the organization. The problem solving process is extensively described and is paid a lot of attention. To keep track of improvements, methods such as PDCA are used (Sasaya, 2009).

3.5.1 Cost deployment

Cost deployment was developed to visualize the connection between actions and cost reduction. The goal is to cover all costs. Cost Deployment enhances visualization, encourages stratification and enables prioritization. The cost deployment pillar is often regarded as the compass within WCM as it always points in the right direction. The result of the Cost Deployment work is a Pareto chart stratifying all costs. Typically, the costs are divided per pillar but can also be done differently. If stratification is done per pillar each pillar can then further stratify the data. See Figure 3.6.

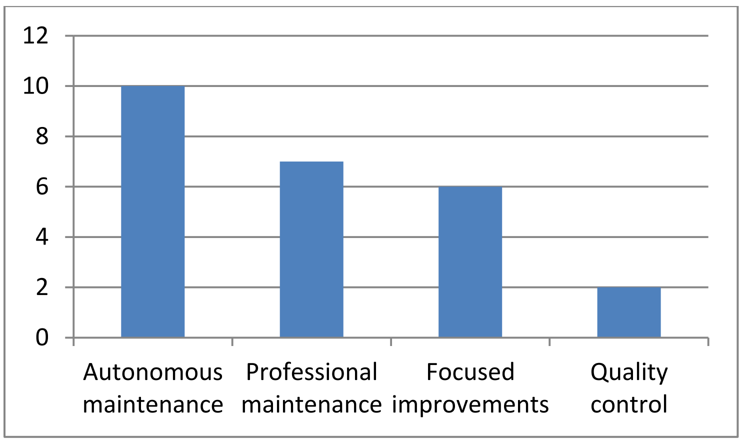

Figure 3.6: The result of the Cost Deployment clearly shows each pillars costs associated with its work.

3.5.1.1 Define losses

The first step in the Cost Deployment staircase aims at dividing the factory into several areas or processes. All possible losses in connection to each area are then defined. This is done in a matrix form which may look like in Table 3.1. The color symbolizes big, medium and small loss (Sasaya, 2009).

Table 3.1: Losses defined per process in a matrix.

Loss/Process	Casting	Welding	Assembly	Shipping
Op. waiting	● (green)		● (red)	● (red)
Breakdown	● (orange)	● (green)	● (red)	
Re-work	● (orange)	● (red)	● (green)	● (orange)
Scrap		● (green)		● (red)

According to WCM this work is often conducted by production personnel and requires approximately 10 hours. One suggested method is to let each person do his/her own matrix which is then compared and discussed until consensus is reached. As a rule of thumb, the division between high, medium and low losses should follow a standard ABC-classification (Sasaya, 2009).

3.5.1.2 Divide losses

Once this is done, all losses should be divided into causal and resultant losses according to the definitions below.

- **Causal loss**
  A loss caused by the problem or equipment itself is said to be causal. This type of loss can always be reduced by different activities. Causal loss can be seen as the root loss which may cause further losses
- **Resultant loss**
  A loss of material, manpower, energy or similar surrounding effects is classified as resultant loss since it is a result of a causal loss. Resultant losses cannot be reduced by activities. Rather they are reduced by elimination (or reduction) of causal loss.

Since a causal loss often has resultant losses it is important that the correlation between all losses is clearly defined. Since a loss can be causal for one failure but resultant for another failure all possible combinations needs to be documented. Using a matrix it is possible to define all resultant losses in each process given a specific causal loss in any process. For example, a machine breakdown (causal loss) in a casting process may result in waiting (resultant losses) in the hardening process.

3.5.1.3 Calculate cost

The step aims at transforming all losses into costs. This step is often conducted by financial staff and requires a lot of time. To calculate the cost of a certain event all available losses needs to be found and quantified. Table 3.2 shows how a machine breakdown in the welding process can be quantified. All losses are converted into hours of production. Equation 3.2 - Equation 3.5 are examples of how to determine costs in WCM (Sasaya, 2009).

Equation 3.2: Cost of down time due to machine breakdown.

$$Down\ time\ cost = N.of\ people\ waiting * Down\ time * Manhour\ cost$$

Equation 3.3: Cost of machine repair due to breakdown.

$$Machine\ repair\ cost = N.of\ people\ repairing * Repair\ time * Manhour\ cost$$

Equation 3.4: Cost of spare parts used when repairing the machine.

$$Spare\ parts\ cost = \sum_{0}^{n} (Unit\ price * unit\ cost)\ for\ n\ different\ parts$$

Equation 3.5: Cost of rework as a result of a machine breakdown.

$$Production\ rework\ cost = N.of\ people\ reworking * Rework\ time * Manhour\ cost$$

Table 3.2: Example of quantified losses for a breakdown in the welding process.

Loss category	Machine losses
Loss type	Breakdown
Process regarded	Welding

Casual loss	Lost machine time per breakdown/stop event	Hours	1.5
	No of events		23
	Total time stop/downtime	Hours	**34.5**
Resultant losses	Machine start up-time following any stoppage per event	Hours	0.5
	Number of start-ups		23
	Total time for start ups	Hours	**11.5**
	Unproductive machine time during re-work	Hours	1
	Number of events		0
	Total unproductive time	Hours	**0**
	Total lost machine hours	Hours	**46**

When the time of each loss is defined the cost can be calculated using the equations. The sum of all costs for a particular failure type is then stratified on a per process basis.

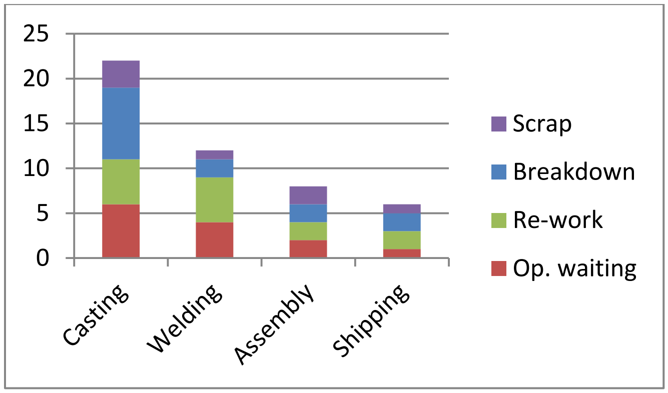

Figure 3.7: All costs during a certain period is stratified on a per process and loss type basis.

3.5.2 Autonomous maintenance

WCM concludes that autonomous maintenance is applicable and suitable in all environments where breakdowns occur due to lack of basic conditions (see Chapter 3.5.3.2) and operators are present (Sasaya, 2009).

Autonomous maintenance can, as all other pillars, be divided into seven steps. The steps spans from simple reactive actions to more demanding, preventive and proactive actions. Table 3.3 describes what actions that needs to be put in place before world class autonomous maintenance can be achieved. The table shows how operator and system development must take place side by side.

Table 3.3: Automonous maintenance activityes and requirements.

Step	Actions	Operator requirement
1	**Perform initial cleaning:** Eliminate dirt and dust to expose abnormalities and defects. Small problems are fixed directly. Unused tools are removed so that problems are more easily detected.	**Process understanding:** To understand the process and its properties to such extent that it can be performed correctly.
2	**Address contamination sources:** Ease the cleaning process by eliminating things that makes the cleaning and checking cumbersome. Lubrication and check points need to be accessible for a successful AM implementation.	
3	**Establish standards:** Formulate work standards that help to maintain cleaning, lubrication and tightening. Introduce visual control to aid the operator.	
4	**General inspection:** Conduct general equipment inspection and modify the equipment if needed. Provide the operator with the knowledge and skills needed to perform the inspection.	**Product understanding:** To understand the product and its properties to such extent that adjustments can be made to the equipment to suit the product.
5	**Process inspection:** Provide the operator with knowledge about how to handle abnormalities and write instructions on how to adjust and measure the process.	
6	**Systemize:** Achieve safety and quality be establishing clear routines for how to conduct the inspections and adjustments. Introduce self-management to spare parts and tools.	**Detect abnormalities:** To be able to detect abnormalities and perform basic emergency actions to limit its consequences.
7	**Full self-management:** Practice full self-management through standards in line with the vision of the organization reduce waste be continuous improvements. Improve performance by systematic data analysis (MTBF etc).	**Detect signs of abnormalities:** To be able to detect signs of abnormalities and to perform periodical overhaul of the equipment.

3.5.3 Professional maintenance

Equipment will break down even if it is designed to be reliable and even if world class autonomous maintenance is performed. For this reason professional maintenance is required. Professional maintenance is responsible for preventive maintenance, equipment classification and for economical justifications of maintenance systems (Sasaya, 2009).

The aim of the PM pillar is thus to maximize the equipment availability at an economical cost, to eliminate unplanned maintenance and to reduce the number of production stops to zero. According to Sasaya (2011) approximately one third of all maintenance tasks should be assigned to PM.

WCM concludes that several aspects of maintenance need to be considered before world class can be reached. The following bullets represent the first steps within the professional maintenance pillar and can be seen as prerequisites and preparations. These are to a very large extent also a part of the autonomous maintenance pillar. This shows the importance of having both autonomous and professional maintenance and that production department commitment must be obtained to reach world class professional maintenance (Sasaya, 2009).

- Prevent deterioration by having a correct process without human errors.
- Obtain basic standards for cleaning (5S).
- Lubrication should be performed on a regular basis.
- Continuous tightening according to predefined schedule.
- Keep maintenance records.
- Measure deterioration by daily and periodic inspections.
- Predict deterioration by performing minor service activities when event occurs and correctly report all abnormalities.
- Assists when maintenance mechanic repairs the equipment.

The maintenance department should assist the production department by developing easy autonomous maintenance standards, build and maintain a system for error reporting, provide tools and other equipment as well as continuously develop new methods for equipment maintenance.

Professional maintenance is responsible for recording all stops over ten minutes and for finding the root causes. The Emergency Work Order (EWO) described below is a powerful tool for doing this. This data is used within the cost deployment and serves as a decision basis for all pillars. Within professional maintenance, the data can be used to determine equipment criticality classification. This enables the professional maintenance to select an appropriate maintenance strategy, prioritize among improvement projects and to obtain a reasonable spare parts strategy.

3.5.3.1 Emergency work order

The EWO is a template for documenting a failure. It holds predefined fields for all information needed to perform an “on the site”-analysis (Sasaya, 2009). The EWO is filled out by the maintenance mechanic together with the operator. It is used to ensure data collection and constitutes the input data in Cost Deployment. A EWO is powerful since it enables the maintenance mechanic to immediately catch the required information. It also starts the problem solving process. A complete EWO contains the following information (see Appendix D).

- Contextual information about the equipment and failure
- Failure description
- Detailed analysis using 5 Why's and 5W+1H
- Possible root causes
- Definite root cause and appropriate root cause category
- Countermeasure suggestions
- Unique EWO number
- Etc…

The EWO is a very important part within WCM. Without the EWOs the system will not be able to continuously monitor the business and address it to costs. Each EWO is then transferred into a database for further analysis.

3.5.3.2 Categorization of failures into root cause categories

As stated above, each EWO concludes the definite root cause of the failure. In addition to this, the failure is also categorized into one of the predefined root cause categories. This categorization is of great importance since it makes it possible to address the failure to its appropriate pillar. Stratification is then used within each root cause category for further visualization and for obtaining increased level of detail. The following six root cause categories exist within WCM (Sasaya, 2009). Within each category several different root causes can be found.

- **Lack of basic conditions**
  If equipment fails due to lack of basic conditions, a lack of prerequisites to fulfill its given function during its intended lifetime has occurred. Each equipment requires its own basic conditions.

- **Failure to observe operating conditions**
  When equipment is in use there are always conditions and/or parameters that are changing. If a parameter is changing out of specification the operator must be able to discover the new state and take actions accordingly. If the machine fails to inform its operator that a particular parameter has changed it should be categorized as a failure to observe operating conditions.

- **Failure to restore or eliminate wear**
  If the failure occurs due to age, deterioration or wear (given that the basic conditions are fulfilled) it is classified into this category of root causes.

- **Human error**
  Human errors can be divided into the three subgroups; human error of operator, human error of maintenance mechanic and human error of craftsman. The philosophy in WCM is to never blame an operator when a failure has occurred. Instead the error is broken down into different categories for further analysis. A suitable tool to find a tangible root cause used in WCM is the Human Error Root Cause Analysis (HERCA).

- **Design weakness**
  There exist two different types of design weaknesses. The first type is the result of inherent strength, resulting in a component that is not able to fulfill its task. The second type is rather related to an improper design that creates failures somewhere else, i.e. the component is sufficient but it creates failure in another function.

- **External influence**
  This category holds all sources of failures affecting the equipment from the outside. Therefore the solution will never be found within the equipment. Instead external factors need to be evaluated. Examples of external influences are:
    - Weather conditions
    - Objects and components interfering with the equipment
    - Environmental conditions within the factory
    - Central IT-systems failure

Different type of root causes often occurs during different part of the equipment lifecycle. Bergman & Klefsjö (2010) concludes that the bathtub curve can used to visualize different failure patterns (described in Chapter 3.10.1) during a life cycle.

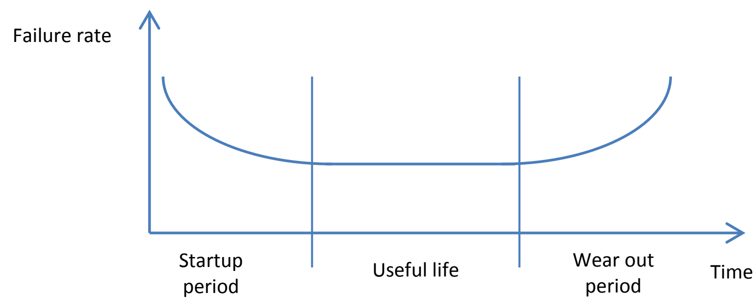

Figure 3.8: Typical correlation between failure pattern and life time.

Table 3.4: The correlation between failure patterns and life time makes it possible to predict the when a certain type of root cause category is likely to occur.

	Startup period	**Useful life**	**Wear out period**
Lack of basic conditions	**X**	**X**	**X**
Failure to observe operating conditions	**X**	**X**	**X**
Failure to restore or eliminate wear			**X**
Human error (operator)	**X**	**X**	
Human error (maintenance)	**X**		
Human error (Craftsman)	**X**	**X**	**X**
Design weakness	**X**	**X**	
External influence	**X**	**X**	**X**

3.5.3.3 Category owner and further stratification

Once all EWOs are categorized upon root cause category the information can be handed over to the appropriate pillar owner. This way, WCM ensures that the correct function gets the responsibility for the costs associated with its area of responsibility. Within each function, the costs can then be further categorized and stratified. This visualization makes it easy to see the costs of different events and prioritize among them. Each pillar is responsible for reducing its own costs using appropriate tools. The professional maintenance pillar is responsible for the following categories:

- Failure to restore or eliminate wear
- Human error of maintenance crew

Autonomous maintenance is responsible for:

- Lack of basic conditions
- Failure to observe operating conditions
- Human error of operators

This means that all EWOs in categories other than “Failure to restore or eliminate wear” and “Human error of maintenance crew” leave the professional maintenance for its appropriate owner. The ones kept within professional maintenance can now be further analyzed.

3.5.3.4 Further stratification and prioritization of equipment

The EWOs must now be further stratified to be able to conclude what equipment or activity that is causing the highest costs. The stratification can be done with regards to several parameters such as equipment, area, consequence etc. A high level of detail in the EWO enables a better accuracy of the stratified data, i.e. it becomes easier to find and implement the correct countermeasure (Sasaya, 2009).

If the data is stratified with regards to equipment and total cost, an equipment classification can easily be obtained. WCM proposes four different classes of critical equipment, AA, A, B and C. These different classes can be assigned different routines regarding inspection, spare parts management etc. General maintenance countermeasures often found suitable for each criticality class is presented in Appendix A.

3.5.4 Focused improvement

The focused improvement pillar consists of a number of tools and techniques used to attack large identified costs. Any pillar may use these tools to reduce its own biggest cost. The pillar is characterized by thorough analysis and comprehensive results that are proven to be economically worth implementing (Sasaya, 2009).

Projects are started by a cross-functional group where members are recruited by competence (all personnel is classified according to competence). The team work according to the project methodology visualized in Appendix D. The project often lasts several months.

3.6 Reliability-centered Maintenance

Reliability-centered maintenance (RCM) is an approach used to determine the maintenance requirements of a system, machine or equipment. According to Moubray (1997) RCM refers to the process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context. It was developed during the mid-1970s when higher availability and reliability, greater safety and quality were discovered as important keys to success (Moubray, 1997). RCM has successfully been used both within civil aviation as well as within military organizations.

The heart of the RCM process has its roots in answering seven questions covering the following aspects respectively.

3.6.1 Function

At first, the functions of the system must be defined as a way of ensuring that all instances of the organization have a common view of the equipment. The function can be defined as a specification or as a performance measurement. It is also important to investigate if the system is capable of doing what the users want it to do, i.e. to avoid trying to achieve something beyond performance specification (Moubray, 1997).

An equipment functions can be primary or secondary. A primary function is the function it must fulfill, i.e. a function it is acquired to fulfill. Secondary function is what the asset is expected to fulfill beyond its primary function, i.e. expectations on protection, safety, compliance with environmental regulations etc. (Moubray, 1997).

3.6.2 Functional failures

A functional failure occurs if an asset is unable to fulfill a function to the extent of the performance standard. The analyst should define all possible functional failures for each function. A failure is the only event that can stop the function from delivering as expected. Therefore all possible failures need to be identified. This can be done in two ways (Smith & Hinchcliffe, 2003), (Moubray, 1997).

- By asking what events that can cause the system to enter a failure mode.
- By identifying what circumstances that results in a failure mode.

3.6.3 Failure modes

This step aims at identifying all possible events that are reasonably likely to cause each failed state, the failure modes. A reasonably likely event is an event that has occurred on the same or on similar equipment in the same context. Failures that are regularly prevented and failures that have not happened yet but are possible should also be regarded. This list should also include potential failures caused by human error, not only the ones that are caused by usual wear and tear (Smith & Hinchcliffe, 2003), (Moubray, 1997).

3.6.4 Failure effects

This step aims at listing failure effects which describes what happens when each failure mode occurs. These failure effects can be listed in multiple ways. The following questions can be used as guidance (Moubray, 1997).

- Is there any evidence that the failure has occurred?
- How does the failure pose a threat to safety?
- How does it affect production or operations?
- What is the physical damage?
- What must be done to get the asset delivering its functions again?

3.6.5 Failure consequences

The failure effects identified in step 4 will affect the organization in different ways. This step focuses on finding the consequences of each failure effect. It is the magnitude of the consequence that reveals where to start.

Within RCM, the consequences can be classified as:

- **Hidden failure consequences**
  Have no immediate impact which makes them very hard to determine, but have often catastrophic outcome.
- **Safety and environmental consequences**
  It has safety consequences if it can injure someone and it has environmental consequences if it could violate environmental standards.
- **Operational consequences**
  If the failure affects outcome, quality, operating costs etc. it has operational consequences.
- **Non-operational consequences**
  Failures that do not affect safety nor production, but still involves the cost of repair falls into this category.

3.6.6 Preventive/Proactive tasks

This step describes how the consequences of a certain failure should be avoided by avoiding that particular failure mode. Moubray (1997) suggests the following three tasks to be evaluated.

- **Scheduled restoration task**
  To overhaul a component before it has been worn out either after a certain age or before a certain point in time.
- **Scheduled discard task**
  To replace a component before it has been worn out either after a certain age or before a certain point in time.
- **Scheduled on-condition task**
  This type of task relies on the fact that equipment gives a warning of that a failure is about to occur. Equipment is kept in use on the condition that it continues to meet the performance standards, therefore the name on-condition.

3.6.7 Default tasks

Preventive tasks can only be applied if it is technically feasible. If no preventive task is feasible, default actions must be used. Moubray (1997) suggests the following alternatives for default actions:

- **Failure-finding**
  This action implies checking for hidden failures periodically to determining if a failure has occurred.
- **Redesign**
  This is a one-off action to change the built-in capability of the system. In other words, this action eliminates that particular failure mode.
- **No scheduled maintenance**
  This default action suggests doing nothing until a failure occurs. In other words, these failures are allowed to happen.

The RCM approach concludes that for

- **Hidden failures**
  Proactive tasks are worth doing if it can reduce the risk of multiple failures. If such an action is not possible then failure finding is appropriate. If the problem cannot be found, i.e. it is not possible to neither prevent nor find it; redesign of the equipment must be done.
- **Safety and environmental consequences**
  Proactive tasks are only worth doing if it can reduce the risk of the failure to low level, given that the consequences are critical resulting in high costs or injury. If such a task cannot be found, then the equipment must be redesigned.
- **Operational consequences**
  Proactive tasks is only worth doing if the cost of the consequence exceeds the cost of repairing the failure. Otherwise it is worth running-to-failure.
- **Non-operational consequences**
  Proactive tasks is only worth doing if the cost of the consequences of the failure exceeds the costs of repair over a certain period. For high repair costs, consider redesigning the equipment. For low repair costs run-to-failure is appropriate.

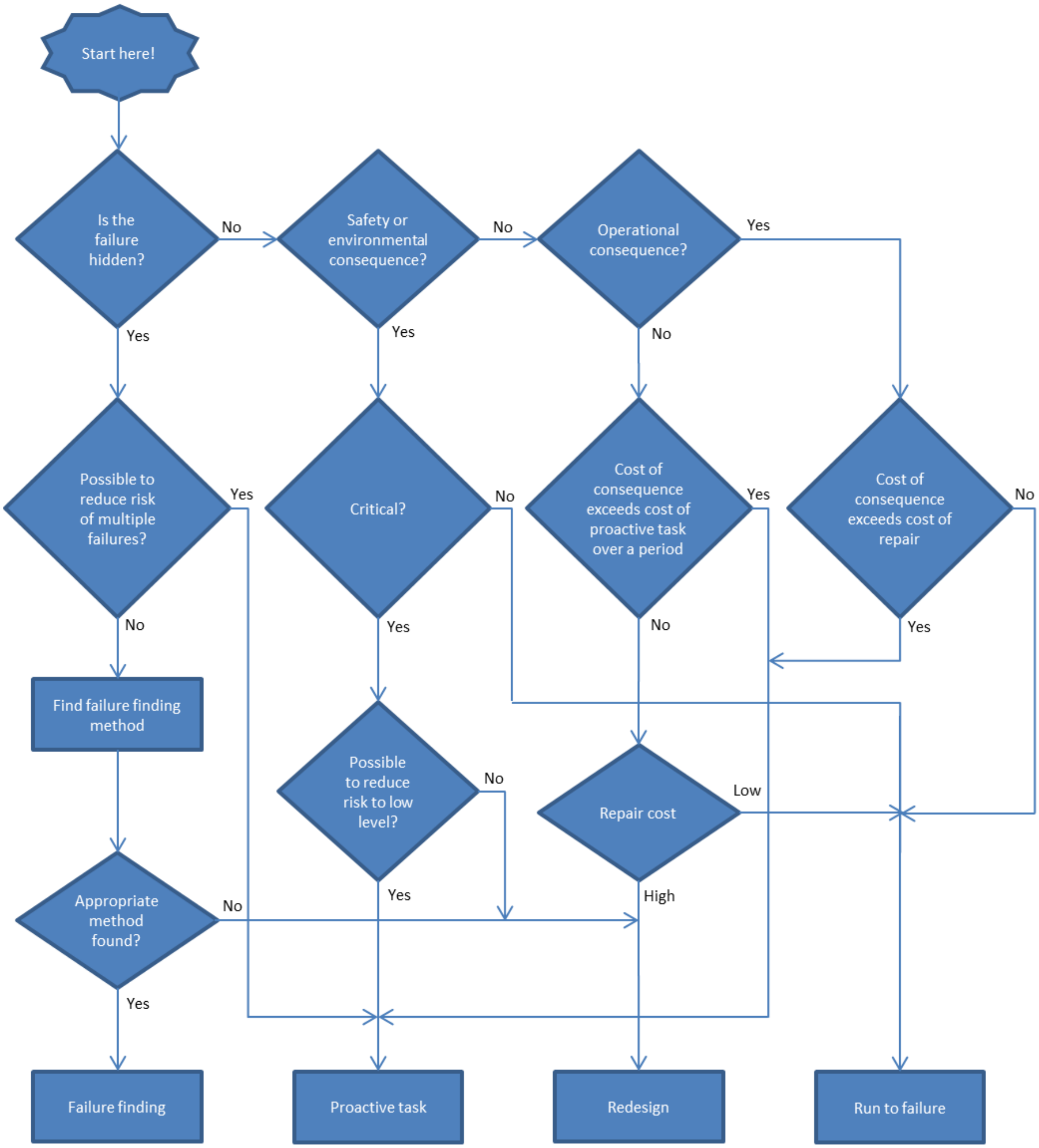

Figure 3.9: Flowchart for simplified task selection given typical failure types.

3.7 Value driven maintenance

Value driven maintenance (VDM) was developed as a way to visualize that maintenance in fact can bring value to an organization. By linking together the traditional maintenance thinking with economics and the concept of value adding, VDM tries to avoid the often used assumption that the economic operating result can be improved by reducing the maintenance budget (Haarman & Delahay, 2004).

Haarman & Delahay (2004) describes that VDM tries to bridge the gap between maintenance and economics and pinpoints the challenge of explaining and financially proving that maintenance does in fact add value.

3.7.1 Value drivers

VDM defines four value drivers that maintenance affects and that contributes to the value of a business (Haarman & Delahay, 2004).

- **Asset utilization**
  This first value driver adds value by increasing the availability of the equipment since this makes it possible to produce more items which can then be sold. In other words, increased asset utilizations bring more income while the investment cost remains fixed.
- **Safety, health and environment**
  By increasing safety, health and environmental aspects of the business value can be added in two ways. The business minimizes the risk of charges and penalties due to law interference and minimizes the risk of losing its license to operate the business.
- **Cost control**
  By controlling the costs associated with maintenance the budget can be reduced which in turn creates value for the business. This is achievable by for example development of smarter and more cost efficient maintenance programs.
- **Resource allocation**
  Whilst cost control is about controlling the consumption of resources this value driver is about mange the resources in a good way. VDM specifies the following four types of resources: personnel, spare parts, contractors and knowledge. By applying smart management to any of these four types will create value.

To aid the process of defining a complete value of the four drivers combined, Haarman & Delahay (2004) proposes a VDM formula shown in Equation 3.6.

Equation 3.6: VDM formula (Haarman & Delahay, 2004)

$$PV_{maintenance} = \sum \frac{F_{SHE,t} \times \left(CF_{AU,t} + CF_{CC,t} + CF_{RA,t} + CF_{SHE,t}\right)}{(1+r)^t}$$

Where:

$PV_{maintenance}$ = present value potential

$F_{SHE,t}$ = Safety, health and environment factor for year t (0 to 1, prob. of losing license)

$CF_{AU,t}$ = future free cash flow in year t from Asset utilization

$CF_{CC,t}$ = future free cash flow in year t from Cost control

$CF_{RA,t}$ = future free cash flow in year t from Resource allocation

$CF_{SHE,t}$ = future free cash flow in year t from safety, health and environment

r = discount rate

3.7.2 Value driver analysis

Using the formula above, a potential value of the maintenance department can be obtained and by performing sensitivity analyses it will become obvious how changes affects the total value of the maintenance department.

Value driver analysis can then be used to, with the sensitivity analysis as a base, define the dominant driver. This can be done using performance measuring and benchmarking for example. By improving the dominant value driver the maintenance organization will develop towards the most valuable maintenance organization.

3.8 Classification

Classification refers to the assignment of classes or categories to items according to their properties. It can be performed in many different ways and any information can be classified or categorized. For example, the human being has classified more or less all known living species and materials on the earth. One big advantage of classification is that the obtained class emphasizes characteristics of the set of elements, e.g. all clothes have something in common, as well as all cars. Classification is used to remove redundancy and to structure information (Fontoura Costa & Marcondes Ceasar Jr., 2001).

The human being has by subjective criteria created most of the categories in the universe. Different situations will occur while classifying objects (event, products, subjects, data units, entities etc.). It is normally easy to classify and categorize, as in the case of determining whether a person is glad, sad, angry or happy. However, situations exist where these subjective interpretations are not very likely to be appropriate. According to Fontoura Costa and Marcondes Ceasar Jr. (2001) three different patterns for classification exists.

3.8.1 Imposed criteria

The imposed criteria approach is related to a practical problem. The classification criteria are in this case clearly stated initially, i.e. to classify the criticality of equipment exceeding a specified cost. Therefore, in order to measure the features, appropriate measuring methods needs to be defined. This is the easiest pattern for classification (Fontoura Costa & Marcondes Ceasar Jr., 2001).

3.8.2 Supervised criteria

Supervised classification refers to classification based on comparisons with a predefined prototype. One can for example develop a strategy for determining equipment criticality by comparing the properties (normally related to features, characteristics, measurements, attributes and scores) against the corresponding property of highly critical equipment. This pattern is more complex than imposed classification and the prototype needs to be defined prior to classifying the equipment.

3.8.3 Unsupervised criteria

Unsupervised classification refers to the classification of objects where insufficient or no data exists. Neither prototypes nor criteria exist in this approach. This can be referred to as the situation when it cannot be assured whether an object conforms to a certain class or not, e.g. when a baby classifies objects, this cannot be based on any criteria since no information about relevant criteria exists. The classification criteria and features are instead defined through continuous learning and evaluation where new concepts are created and new relationships between objects are identified. This is the most complex classification pattern and will result in a categorization considered suitable given the current population of objects.

3.9 Spare parts management

3.9.1 Introduction

Inventory refers to all resources within an organization that is kept to fulfill a present or upcoming need. Inventories are thus resources used to provide service to customers. Investment in inventory often represents more than 25% of the total assets of the company. Therefore, it is essential to continuously improve spare parts management. The costs of maintaining the inventory must be compared to the benefits gained from store keeping, determining an optimal level. The total cost should be kept close to its minimum (Gupta, 2009).

Lean principles emphasize warehouse optimization to reduce the amount of inventory; both as a way to reduce the amount of tied up capital but also to reduce material handling. It is however important to reduce the inventory wisely since the saving from inventory reduction seldom exceeds the costs of production loss when a spare part is missing (Levitt, 2008).

3.9.1.1 Replenishment

The total life of the resource becomes the measure to use for replenishment decisions (Gupta, 2009). Finding a replenishment pattern will be troublesome if no life cycle data exists. Preferably, preventive maintenance should also be regarded. Other factors influencing spare parts management is limited warehouse space, limited budget available for inventory, degree of management attention, customer service level etc.

3.9.2 Inventory cost

According to Gupta (2009) four different costs together forms the total inventory cost C. The total inventory cost is typically calculated over a period of time, i.e. one month.

Equation 3.7: Total invetory cost.

$$C = Purchase\ cost + Ordering\ cost + Carrying\ cost + Shortage\ cost$$

3.9.2.1 Purchase cost

The purchase costs consist of the price for procurement and can be described by the following formula (Gupta, 2009).

Equation 3.8: Purchase cost.

$$Purchase\ cost = (Price\ per\ unit) \times (Demand)$$

3.9.2.2 Ordering cost

All administrative work to settle the order including employee costs for telephone calls, invoicing, payments etc. constitutes for the ordering cost. It is not dependent on the order size and is a fixed cost (Gupta, 2009).

Equation 3.9: Ordering cost.

$$Ordering\ cost = (Cost\ per\ order) \times (Number\ of\ orders)$$

3.9.2.3 Carrying cost

The carrying cost includes costs related to warehouse space allocation, management of material, insurance, interests, risk of obsolescence and capital costs. The carrying cost is described by the following formula (Gupta, 2009).

Equation 3.10: Carrying cost.

$$Carrying\ cost = (Cost\ of\ carrying\ one\ unit) \times (Avg\ no.over\ the\ period)$$

3.9.2.4 Shortage cost

The shortage cost concerns costs due to the inability to deliver to customer in time. Two possibilities related to shortages of spare parts needs to be mentioned here. If a breakdown occurs that has an immediate impact on the output, the system will not be stable until the spare part is replaced and the cost of the inability to deliver will be high. Shortage of items that do not cause an immediate loss will not contribute to the shortage cost as these can be back ordered. Only if the back ordered part does not arrive before the present one break down a shortage cost will apply. The following formula describes the calculation of shortage cost (Gupta, 2009).

Equation 3.11: Shortage cost.

$$Shortage\ cost\ =$$

$$(Cost\ of\ lacking\ one\ unit) \times (Avg\ no.\ of\ units\ short\ over\ the\ period)$$

3.9.3 Spare parts statistics

In order to find suitable warehouse level and reorder point the demand of a certain spare part must be determined. This can be done deterministically or stochastically. The demand is said to be deterministic if future demand can be predicted with a defined level of certainty. If the demand varies with time and needs to be described with a probability distribution function it is stochastic (Gupta, 2009).

In order to be successful within the highly competitive market, having the correct spare parts is essential as it ensures reliable equipment and customer satisfaction. On the other hand, having too many parts in stock will increase inventory and tie up of capital. It is therefore essential to accurately forecast the number of spare parts required in a certain point in time. Different theories are proposed to ensure that spare parts are at hand when needed (Kennedy, Patterson, & Fredendall, 2001), (Tadj, Ouali, & Soumaya, 2011). The methods proposed assume that components will experience failures over time and that the possibilities of failures can be modeled with statistical distributions. Reliability approaches has been developed along with new technology to predict systems and equipment (Werner, Niggeschmidt, & Lanza, 2009), (Tadj, Ouali, & Soumaya, 2011).

3.9.3.1 System reliability and failure probability

Reliability can according to Mannan (2005) be defined as "*The ability of an item to perform a required function under stated conditions for a stated period of time*" or as "*The probability that an item will perform a required function under stated conditions* *for a stated period of time*". The latter definition brings out at least one aspect, namely probability.

Probability can be modeled in multiple ways. Mostly it is not a matter of calculating equally likely and mutually exclusive outcomes like when throwing a die. The probability of getting a 4 is always 1/6 since there is only one outcome out of 6 possible that matches the hypothesis. Personal probability is a proven probability theory and has gained legitimacy during recent years. It has the power to regard more information than what is included in pure data (Mannan, 2005).

The probability of a failure can be modeled by different failure distributions. The following three distributions are commonly used.

- **Exponential distribution**
  Used when the failure rate is constant over time, and is often used when failure data is lacking (Mannan, 2005). See plot E in Figure 3.10.
- **Weibull distribution**
  A widely used distribution within reliability engineering since it handles dynamic failure rates. It is applicable to all applications where the failure rate is changing over time, e.g. for wear-out components such as bearings. Weibull distribution can also be used to model infant mortality by altering the β parameter. If $\beta = 1$ the Weibull distribution equals the exponential distribution (Moubray, 1997), (Mannan, 2005).
- **Poisson distribution**
  This distribution is used to model rare events. It is used to determine demand during a certain period given an expected value. Examples of rare events are accidents per person, number of breakdowns per year, number of inhomogeneities etc. (Mannan, 2005), (Gupta, 2009).

3.9.3.2 Expected demand for rare events

Gupta (2009) describes a classification method for management of rare spare parts that uses the Poisson distribution. The distribution is however only valid when the following two assumptions are fulfilled.

- Failure events for all components in the system follow the Poisson distribution. In other words, the times to failure are exponentially distributed; and
- For each component, there exists only one failure mode.

The events must also occur with a known mean time to failure and must be independent of the time since the last event. This ensures that the collected data is from the same population and thus make it possible to make statistical determination from the data. The probability of failure is then used to determine the demand C_2 for the next period t_2, given the previous demand C_1 during period t_1 using Equation 3.12 (Gupta, 2009).

Equation 3.12: Expected demand for rare events.

$$C_2 = C_1 \times \left(\frac{t_2}{t_1}\right) \pm Z \sqrt{C_1 \times \left(\frac{t_2}{t_1}\right) \times \left(\frac{t_1+t_2}{t_1}\right)}$$

Z = appropriate percentile of the normal distribution

3.9.3.3 Ordering replacement model

Pham (2003) proposes a ordering replacement model that takes five different parameters into account, the expedited ordering cost c_e, the regular ordering cost c_r, the system down (shortage) cost per unit time k_f, the operation cost per unit time w, and the salvage cost per unit time s. The expected cost per unit time O_c, can be defined as in Equation 3.13 (Pham, 2003). The model assumes regular order in t_0 with a lead time L_r, but if a breakdown occurs prior to t_0 the regular order is dismissed and an expedited order is placed immediately. The numerator holds all costs associated with the order and the denominator holds the time period. Depending on whether the breakdown occurs prior to or after the regular ordering point t_0 some factors will be omitted. This makes the model suitable for both scenarios. The probability mass function $F(t)$ can be estimated or modeled using statistical distribution fitting.

Equation 3.13: Expected cost per unit time.

$$O_c(t_0) = \frac{V_c(t_0)}{T_c(t_0)}$$

$$V_c(t_0) = c_e F(t_0) + c_r \bar{F}(t_0) + k_f \left[(L_e - L_r) F(t_0) + \int_{t_0}^{t_0+L_r} F(t)dt \right] + w \int_0^{t_0+L_r} \bar{F}(t)dt + s \int_{t_0+L_r}^{\infty} \bar{F}(t)dt$$

$$T_c(t_0) = (L_e - L_r) F(t_0) + L_r \int_0^{t_0} \bar{F}(t)dt$$

L_r = Lead time to get spare part
L_e= Lead time if spare is ordered immediately after failure
$\bar{F}(t) = 1 - F(t)$

The model function is continuous and requires integration over time. Assuming that $\dot{V}_c(0)/\bar{F}(t_0) < 0$ *and* $\dot{V}_c(\infty)/\bar{F}(\infty) > 0$ the minimal cost can be obtained by finding the minimum of the function by differentiation. This point represents the optimal order replacement time.

3.9.4 Classification of spare parts

Both qualitative and quantitative methods can be used to classify spare parts as a way of applying different principles to them. Three different methods are described below.

3.9.4.1 ABC-classification

Always Better Control (ABC) analysis aims at separating inventory into three categories, namely A, B and C. The separation can be made upon annual total inventory cost. Commonly used separation figures are shown in Table 3.5. It is however possible to use other parameters that fits the pattern (Gupta, 2009), (Freivalds, 2008).

Table 3.5: Typical ABC-classification.

Category	Percentage of items	Percentage of inventory value
A	10-20	70-85
B	20-30	10-25
C	60-70	5-15

3.9.4.2 VED-classification

VED-classification is a qualitative method for categorizing inventory into the three categories vital, essential and desirable (Gupta, 2009). Vital items are items needed to ensure a fully operational process. Essential items are needed to ensure an efficient process. Missing an essential part will reduce operational efficiency. Desirable items neither stop nor reduce efficiency, but may increase efficiency and reduce failures if available. VED-classification is appropriate for rare items can be used together with quantitative methods such as ABC.

3.9.4.3 Statistical classification

Spare parts can also be classified with regards to their expected demand described in Chapter 3.9.3.2 or with regards to its failure pattern.

3.10 Failure modeling and failure patterns

A failure stops equipment from performing as intended, which thereafter cannot meet the performance requirements (SIS, 2000) (SIS, 2001). The requirements are often set as a range of acceptable performance (Narayan, 2004). Failure is the event corresponding to the state fault (SIS, 2000). Failures can, according to Narayan (2004) be categorized into the following four categories.

- **Critical and degraded failures**
  This type of failure might totally eliminate the systems function, e.g. if a water pump that supplies sprinklers with water fails when there is a fire, the building will most probably be destroyed.
- **Evident failures**
  Failures that can be predicted by performance monitoring are evident, e.g. if a bearing is worn out the performance deviations will be possible to monitor. If the conditions are known the bearing can be replaced.
- **Hidden failures**
  These failures are unknown to the operator during normal conditions. Hidden failures can be observed with additional instrument, e.g. if the fire alarm is not working when the fire occurs it is a hidden failure. Inhomogeneity within material is also subject to hidden failures.
- **Incipient failures**
  When equipment is concerned with deterioration, incipiency is the point in time when the failure becomes detectable. A functional failure occurs as the deterioration has forced the equipment out of acceptable performance. The incipiency interval is the time from detectability to functional failure. If failures are evident and incipient it is possible to predict them.

Gupta (2009) proposes an alternative approach for categorizing failures using different objectives. One or several of the following objectives are suggested.

- **By cause:** appropriate categorizes might be stress-related failure, misuse failure, inherent weakness failure, wear-out failure and maintenance induced failure.
- **By suddenness:** appropriate categories might be immediate failure and gradual degradation failure.
- **By degree:** appropriate categories might be catastrophic failure, intermittent failure and partial failure.
- **By definition:** appropriate categories might be applicable to the specification and not applicable.
- **By result:** appropriate categories might be critical failure, major failure and minor failure.

3.10.1 Failure pattern

Some of these failure types can be addressed to different failure patterns. Failure rates can be plotted against time to determine its failure pattern. Nowlan & Howard (1978) studied an airline company where failures were categorized into six different patterns.

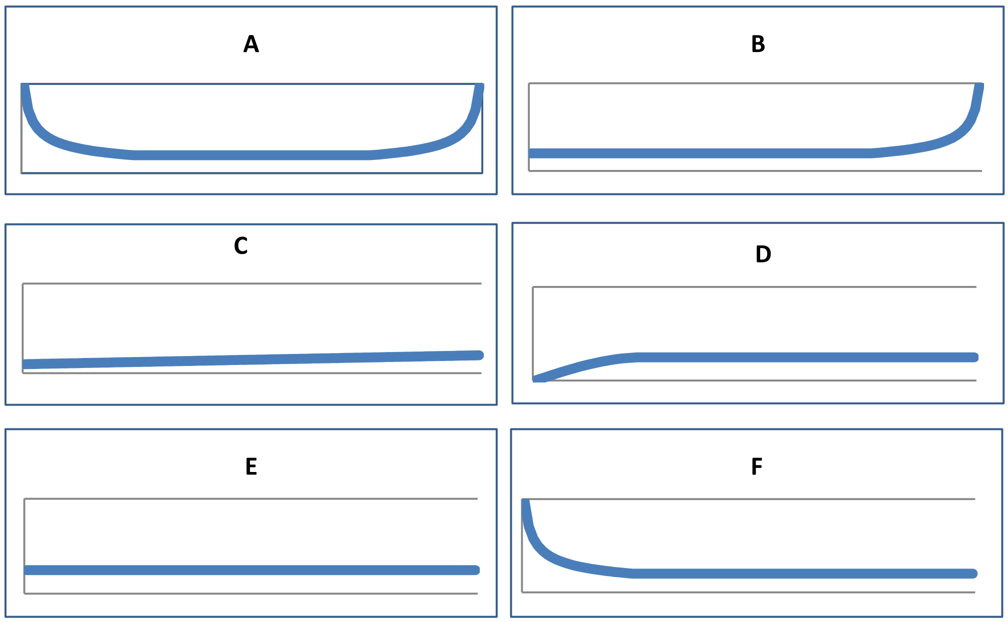

Figure 3.10: Failure patterns.

Failures concerned with deterioration and aging is in general believed to be predictable and preventable using extensive records. The airline company study revealed that this belief of predicting was not possible to the extent expected (Nowlan & Howard, 1978). The graphs in Figure 3.10 show conditional probability with regard to age for mechanical and electrical components. Pattern A shows the well-known bath-tub curve starting with a high conditional probability followed by a constant or slowly increasing probability, ending with a wear-out zone. Pattern B shows constant or slowly increasing conditional probability ending with a wear-out zone. Pattern C shows slowly increasing conditional probability. Pattern D shows a low conditional probability when the component is brand new followed by a rapid increase to a constant level. Pattern E shows a constant level of conditional probability (random failures). Pattern F starts with high conditional probability, known as infant mortality and decreases to a constant level. Infant mortality can be the result of poor design, incorrect operation, poor, incorrect installation, or unnecessary maintenance (Moubray, 1997).

Wear-out failures, caused by corrosion, oxidation, friction wear, shrinkage, fatigue etc. are normally characterized by an increasing failure rate. Infant mortality or other early failures are normally characterized by decreasing failure rate. Constant failure rate is applicable to random and stochastic failures (Gupta, 2009). These three scenarios is present is several graphs in Figure 3.10 and it is therefore in general terms not possible to determine which graph a particular failure conforms.

Table 3.6: Correlation between different failure patterns and failure conformability (Moubray, 1997).

Pattern	A	B	C	D	E	F
% of failures	4%	2%	5%	7%	14%	68%

The result from the airline study showed the correlation between patterns and number of failures as described in Table 3.6. Similar results were presented in a study for the oil offshore industry (Narayan, 2004).

Aware of these facts, some organizations have abandoned proactive maintenance. This may be a correct decision for equipment with minor consequences, but for equipment with extensive failure consequences (critical and degraded failures) preventive action may still be needed (Moubray, 1997).

3.10.2 Types of failures

3.10.2.1 Sporadic failure

A failure occurring without clear warning is regarded as sporadic. Since it happens infrequently it is very hard to predict and prevent. On the other hand, sporadic failures often derive from a single cause making it easy to find and restore (Kunio, Kaneda, & Kimura, 1990).

3.10.2.2 Chronic failure

In contrast to sporadic failures, chronic failures derive from complex cause and effect relationships. Finding these causes may require more resources but since the cause is tangible, it is always possible. According to Kunio, Kaneda & Kimura (1990) people often try to eliminate chronic failures without understanding the causes. Only by complete understanding persistent improvement can be made. As seen in Figure 3.11, two different types of chronic failures exist (Kunio, Kaneda, & Kimura, 1990).

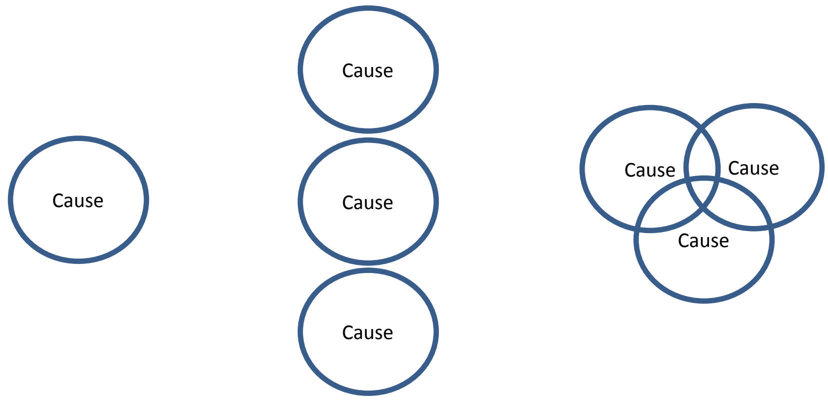

Figure 3.11: Different types of failures. From left: sporadic failure with one cause, chronic failure with interchanging cause, chronic failure derived from multiple concurrent causes. (Kunio, Kaneda, & Kimura, 1990)

3.10.3 Swiss cheese model

To describe the interrelation between failures, system weaknesses and consequences the Swiss cheese model, also known as Reason's model, is often used. A system's defense against failures is represented by layers of Swiss cheese. The holes in the layers represent flaws of the system or active failures conducted by the operator. Hazards for failure is present everywhere but only if a trajectory of consecutive holes is found, a failure will occur (Akselsson, 2008).

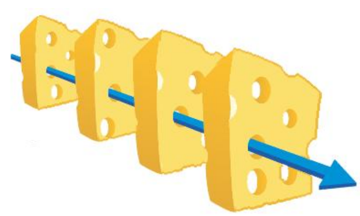

Figure 3.12: Failure occurs only if a hazard can pass all safety barriers by finding consecutive flaws or mistakes (Akselsson, 2008).

3.11 Performance measurement

To be able to understand a process or a business, performance measurements are required. Performance measurements can be divided into three general types with different levels of complexity. See Figure 3.13 (Parmenter, 2007).

- Key result indicators (KRIs) give a perspective view on the performance
- Performance indicators (PIs) shows the overall performance during last period
- Key performance indicators (KPIs) indicate what actions to perform to increase performance.

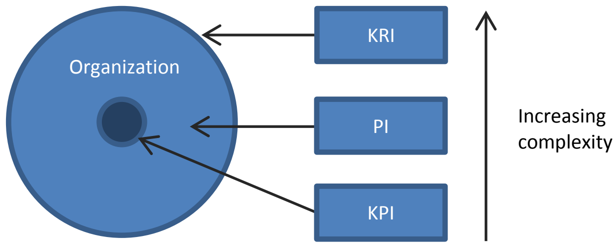

Figure 3.13: The relationship between different performances measurements is by Parmenter (2007) described using a schematic picture.

3.11.1 Key result indicators

The most obvious characteristic of a KRI is that multiple actions influence it. Because of this, a KRI don't provide a clear picture of what to improve. Rather, it shows whether the business is moving in the right direction. Since multiple factors affect the KRI these are best suited for the board of the company, not the daily management team. KRIs are often mistakenly regarded as KPIs (Parmenter, 2007).

KRI examples:

- Customer/Employee satisfaction
- Net profit before tax
- Return on capital

3.11.2 Performance indicators

Performance indicators are more tangible than KRIs but are still more troublesome to grasp than pure KPIs. Performance indicators should be a complement to the KPIs and provides more contextual information about the organization than pure KPIs (Parmenter, 2007).

Performance indicator examples:

- Profitability of the top 10% of customers
- Net profit on key product lines
- Percentage increase in sales with top 10% of customers

3.11.3 Key performance indicators

KPI is a measure focusing on the most critical process for the organization. According to Parmenter (2007) a typical KPI has the following characteristics:

- A nonfinancial measurement, monitoring performance aspects relevant for the whole organization. KPIs should be chosen in such way that all employees sees the benefit of it, not as a tool for managerial control as this often result in distrust and lowered employee commitment.

- The ultimate KPI is measured continuously or at least daily showing future and current performance. A KPI measured monthly or quarterly cannot be a key to the business since it is too late to improve. For example, measured number of planned travelers' upcoming week is a better KPI than number of travelers last week for a train operator. (Often regarded as lead and lag KPIs).

- Actions required to influence the KPI should be known to all employees. In contrast to KRI all employees should be able to affect the KPI on a daily basis. The KPI should of course also reflect the goals of the organization. Taking actions upon a KPI should push the organization in the right direction.

- The responsibility of a KPI should be to assign a specific department, team or individual. Since the KPIs have constant attention from the top management it must always be possible to take actions upon them. Without clear responsibilities the innovative and productive strive may be weak. For this reason, measurements such as "return on capital" will never be a KPI.

- A positive change of the KPI should affect all other performance measurements in a positive direction.

As symbolized in Figure 3.14 proper performance measurements is defined according to the mission and vision of the business. If this is not achieved, striving for improving the performance measurement may make the business develop in a direction not in correlation with its mission.

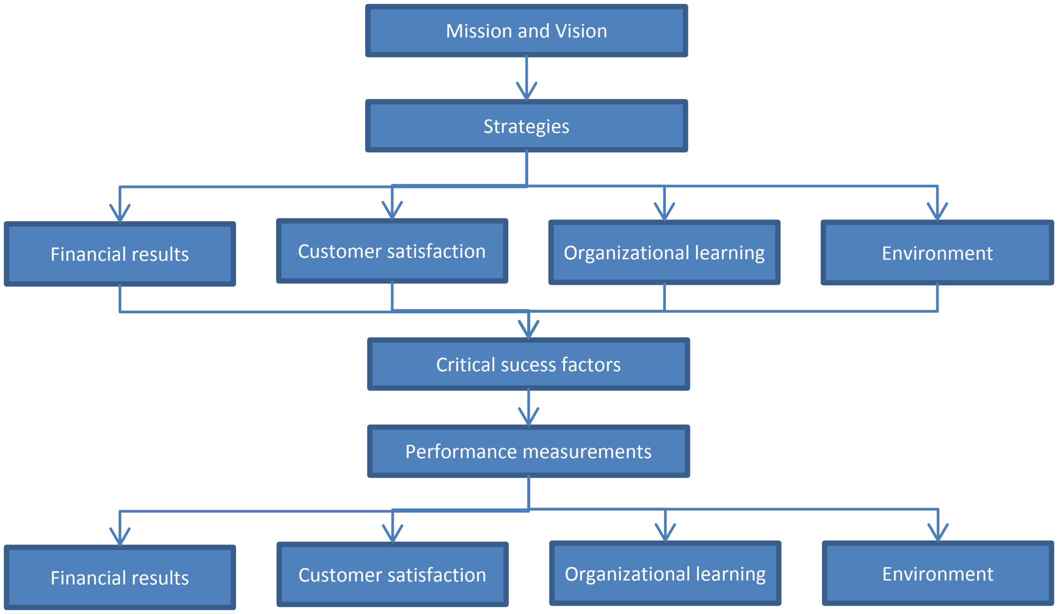

Figure 3.14: Performance measurements should be chosen with respect to mission and vision.

4 Empirical findings

4.1 Volvo Powertrain Skövde

Volvo Powertrain (VPT) is working according to the WCM philosophy described in Chapter 3.5. The organization is currently in step 3 within both professional and autonomous maintenance which means no breakdowns longer than 10 minutes exists. Extensive records of failures are kept with the aid of EWOs and Microsoft Excel databases. The work of implementing WCM was started about four years ago. However, not until recently, full understanding and commitment was gained.

The EWOs are discussed during daily EWO meetings and changes are made either during the meeting or by the operator afterwards. EWOs describing small failures (i.e. low cost) are treated within the team as small improvements. Bigger issues are handed over to a project team. The team then analyses the EWOs more thoroughly and starts a major improvement project.

Equipment classification is determined on a per root cause category basis and uses cost for prioritization. This way, each responsible function has its own critical equipment that needs attention.

The maintenance department uses IS for maintenance reporting and SAP for economic aspects such as invoicing etc. At VPT the maintenance department is organizationally arranged as an individual function that is reporting directly to the plant manager with participation in their steering committee. The manager of Professional Maintenance is participating in a network with other managers from the same position from factories within VPT worldwide. The maintenance mechanics are divided per competence rather than area which ensure that the correct competence always treats the corresponding failures.

During the audit in Skövde, the WCM coordinators emphasized that implementation however must start within some pillars or in a smaller area of the factory and that it is impossible to implement everything at once. The coordinators also made it clear that even if WCM aims at changing the whole culture in the organization this should not take focus from the small, practical daily changes and improvements.

4.2 Volvo Trucks Umeå

The classification model used within Volvo Trucks factory in Umeå is a slightly reworked version of a model developed at Volvo Construction Equipment (VCE) in Arvika. The model classifies production equipment relatively with regards to the equipment's criticality. The model is based upon the definition of risk stated in Equation 4.1.

Equation 4.1: Defintion of risk.

$$Risk = Consequence \times Probability$$

The classification is performed by assessing approximately 20 statements about the equipment. The statements are divided into the five main categories listed below.

- Safety hazard
- Quality and environmental hazard
  - Quality
  - Environment
- Probability for disturbance
- Consequence of disturbance
- Maintenance safety

Each category contains between three and five statements regarding the status of the equipment. Each statement has predefined answers and a score for each answer is assigned accordingly. This way, the qualitative answer is converted into a quantitative measure. The next paragraph describes one of the categories in detail in order to explain the model.

4.2.1 Example of category

The environmental sub-category contains the statements, answers and scores presented in Table 4.1. The result for the environmental sub-category, R(E), is then calculated using the formula below.

Equation 4.2: Equation for result calculation within the environmental sub-category.

$$R(E) = Environmental\ impact \times (Process\ security + Discoverability)$$

The final result of the "Quality and environmental hazard" category is derived by comparing the environment result with the result of the quality sub-category. The biggest value constitutes the category result. A sample of a category is shown in Figure 4.1.

Table 4.1: Part of classification model. The table shows three statements from the environmental sub-category with corresponding answers and scores.

Statement	**Answer**	**Score**
Environmental impact	***No impact:*** The equipment contains nothing that could jeopardize the environment.	0
	Impact: Events in the equipment can have some environmental impact.	8
	Big impact: Events in the equipment can have big environmental impact (i.e. big leakages, heavy metals)	16
Process security	***Very seldom:*** Less than 1 incident per year	1
	Seldom: More than 1 incident per year	2
	Frequent: Incidents are frequently reoccurring (more than 1 incident per year)	4
Discoverability	***Discovered immediately:*** Failures are discovered immediately by frequent/continuous control or by frequent/continuous supervision.	1
	Can be immediately discovered: Failures can be discovered if the process in controlled. Controls are performed using samples/interval.	2
	Cannot be discovered immediately: Failures in the process cannot be discovered without advanced testing equipment and thorough analysis.	4

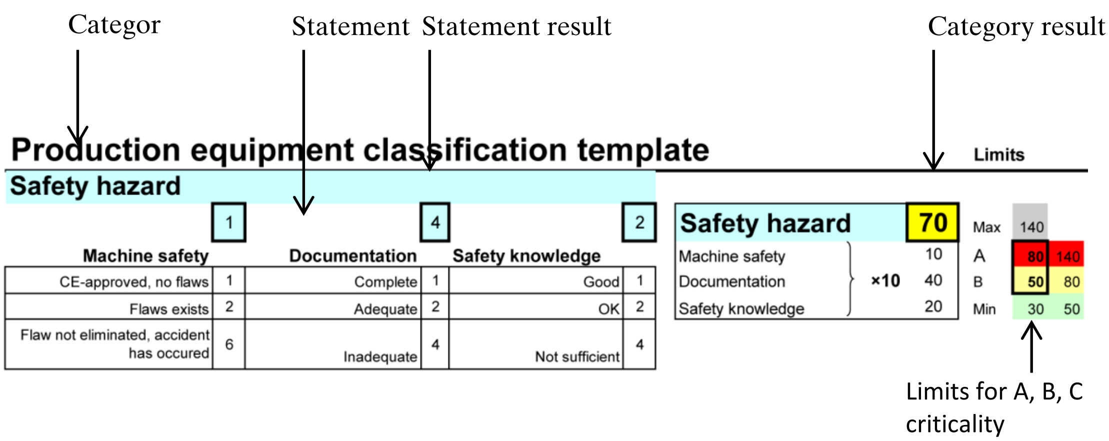

Figure 4.1: Example of classification category template.

Each category has its own limits for A, B and C criticality (80, 50, and 30 respectively in the figure above). The overall criticality is defined by the highest criticality among the categories. Apart from the individual category results the sum is also regarded. The values in Table 4.2 are used to determine whether the criticality should be changed.

Table 4.2: Criticality class limits for overall points.

Criticality class	Points in total
A	≥100
B	10-99
C	1-9

4.3 Volvo Construction Equipment Eskilstuna

4.3.1 Reactive maintenance

VCE uses a central maintenance system called Avantis. The system handles all failures related to any equipment and creates work orders when the operator reports an equipment failure. The orders can be followed in the system from failure to implemented countermeasure. Orders are assigned unique IDs and documents can be attached to a specific order. When a failure is reported into the system, mandatory, predefined input fields such as machine type and failure category needs to be filled in. It is also possible to in detail describe the phenomenon in plain text. This information helps the maintenance department to ensure a correct categorization and to find countermeasures. Once the work order is reported into the system a maintenance mechanic is responsible for solving the problem and for adding follow up information. Reactive maintenance is carried out using standardized work methods based on the information from the central maintenance system Avantis.

Statistical information can be collected from the database to generate graphs, pie charts and stratifications. This enables prioritization, cost reduction and planning. In other words, Avantis helps the maintenance department to base its decisions on facts and to monitor its performance in an easy manner.

4.3.2 Proactive maintenance

VCE follows the VPS guidelines and is assessed accordingly. During the last audit VCE performed poorly because of their inability to fulfill the requirements for the first level. In order to perform better a proactive classification method was created.

The classification model used to determine equipment criticality considers the parameters redundancy, utilization, quality impact, and equipment age. The parameters are assigned a quantitative value between 1 and 4 (1 is most critical). By comparing these parameters in a decision tree the criticality of equipment is determined. Classifying one machine requires approximately two hours and two persons. The decision tree is visualized in Figure 4.2. The parameters are explained in the table below.

Table 4.3: Explanation of the paramters and corresponding value.

1	**2**	**3**	**4**
Equipment redundancy			
No redundancy in the cell. A breakdown will cause immediate production stop in the cell	Redundancy within the cell exists. Requires more than 2-shifts due to long setup time.	Redundancy within the cell exists. Does not require more than 2-shifts.	Redundancy within the cell without setup time exists.
Equipment utilization			
More than 85%	85 – 81%	80 – 50%	Less than 50%
Quality impact of the equipment			
Very tight tolerances. Heavily increased the risk of customer impact.	Tight tolerances. Increased the risk of customer impact.	Normal tolerances but still risk of customer impact.	Large and/or no tolerances. No risk of customer impact.
Equipment age			
Equipment is older than 12 years	12 – 9 years	8 – 5 years	Less than 5 years

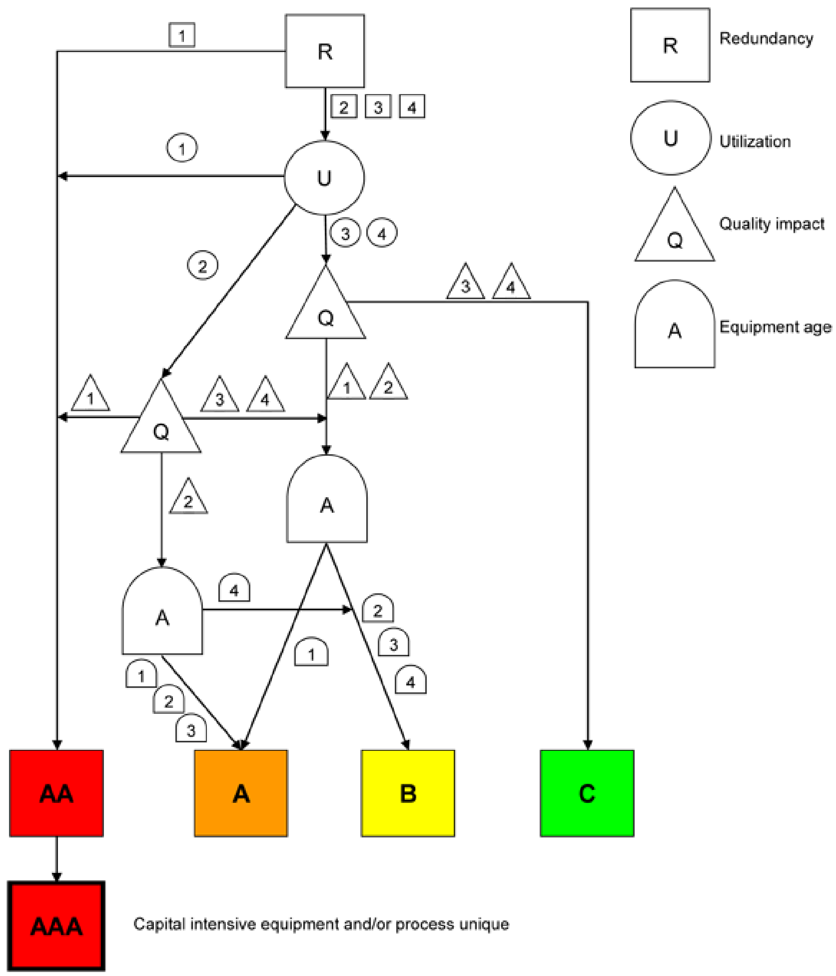

Figure 4.2: Classification decision tree from VCE.

The classification results in the following five classes.

- **AAA** – Cell that stops production and is process unique and/or is capital intensive.
- **AA** – Cell that stops production or an entity with very high level of utilization and has high quality impact.
- **A** – Entity with redundancy capabilities within the cell, with high level of utilization and/or quality impact.
- **B** – Entity redundancy within the cell, with low utilization or quality impact.
- **C** – Entity with redundancy within the cell, low level of utilization and low quality impact.

The classification is done upon the assumption that the facility is performing at full capacity and only equipment which is considered strategically important have been evaluated. This equipment has been selected using qualitative analysis and discussion. There are no standards for how and when to perform a reclassification.

Apart from this proactive way of classifying equipment a separate approach is used to prioritize on a daily basis. This approach is more of a reactive nature since it bases its decisions on actual events.

4.3.3 Spare parts management classification

VPS triggered the development of a spare part classification method at VCE. The classification method concerns the following six parameters.

- Delivery time
- Price
- Replacement frequency
- Quantity in warehouse
- Local suppliers
- Perishable
- Production impact

The spare part management principle is based on the assumption that spare part shortage should never occur since it is considered too costly. Therefore, the carrying cost and the shortage cost is not considered in the classification model. Because of this assumption, all spare parts tend to be critical since the factory is arranged as a serial flow. An algorithm creates a criticality value with the input from the parameters. Using predefined limits, spare parts can be divided into different classes. Unique spare part management principles can then be applied to each class.

Before actually obtaining all spare parts, the result is compared with historical demand and supplier recommendations. The aim is to find the optimum spare part solution considering all three alternatives and the economic consequences of each of them. (The list of recommended spare parts is in some cases too extensive, possibly because suppliers want to make money, or it can be inadequate as a way of making an impression of the equipment having higher quality than actual.)

4.4 Gårda fire station

4.4.1 Autonomous maintenance

Almost all maintenance is according to the manager carried out as preventive actions by the operator. If equipment fails during a rescue mission the organization has no ability to fix it on site. However, during daytime, staff for heavier maintenance tasks is available. Because of the fact that no urgent reactive maintenance is available, redundancy is used to a large extent.

4.4.2 Preventive maintenance

The preventive maintenance schedule is defined as a combination of the suppliers' recommendations and experience from similar equipment. The goal of the preventive maintenance is always to ensure the safety of the equipment user in regards to chemicals, smoke and water.

The preventive maintenance is monitored on daily, weekly and monthly basis to ensure that correct actions are taken and that the equipment performs as intended.

If equipment failure occurs this is treated in two ways:

- The user or his team leader writes a standardized failure report which is then submitted to the appropriate manager. The manager is then responsible for evaluating the event and decides whether the event was caused by human error or by equipment malfunction. Depending on the result of this evaluation countermeasures are taken (for example redesign of preventive maintenance schedule or education of the staff).
- The user may also bring the issue to discussion during debriefing meetings after each mission. In this forum, the issue can be discussed among the fire fighters and managers.

Since almost all equipment used by the fire fighters is there to protect them, there seems to be no difficulties in motivating the operators to raise issues or to discuss failures and solutions. According to the workshop manager this is of great importance for the organization and it helps the fire station to develop it routines continuously. For this reason, there is no need for a classification model since all activities are based on preventive schedule or user proposal.

4.5 Oskarshamn nuclear power plant

4.5.1 Organization

The maintenance organization is organized in a separate department directly under the CEO of the plant. The department is divided into six units which are responsible for different type of tasks (see Figure 4.3). All maintenance is carried out by the maintenance department, no autonomous maintenance is present.

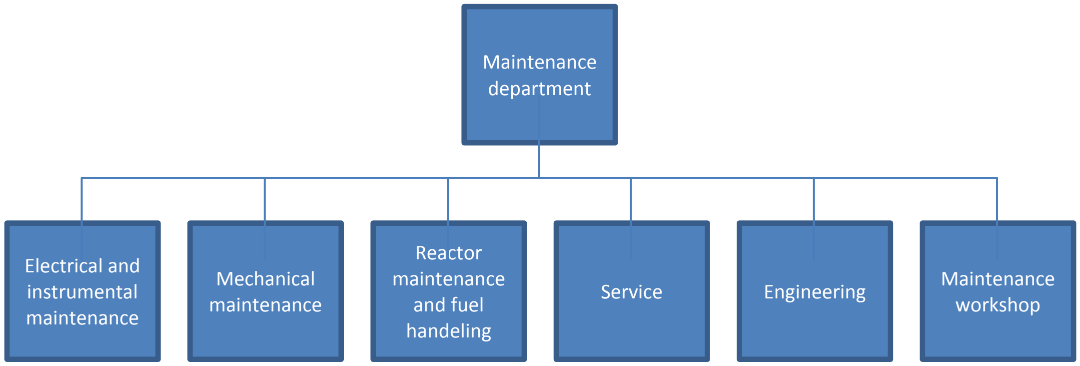

Figure 4.3: Oskarshamn nuclear power plant maintenance department.

The four leftmost functions work mainly with preventive and reactive maintenance within each area of responsibility. Each function works both with short and long term objectives. The staff is further specialized in different areas such as calibration, vibration or turbines. The engineering function works with more advanced maintenance tools such as RCM and performs life cycle cost analyses. This function also works with quality improvements in quality circles. Five specialists within the maintenance department are used as a support function within the whole organization. These specialists can be consulted by other departments.

4.5.2 Preventive maintenance

Preventive maintenance is carried out according to the suppliers' recommendations, external and internal competence as well as experience and in house analyses. All preventive maintenance is documented in an ERP-system. The power plant is also obeying any legal requirements concerned with maintenance.

Preventive maintenance is planned by responsible engineer and a list of tasks to be performed is generated by the maintenance schedule. The tasks are carried out by the engineer himself or by other maintenance mechanic. All maintenance performed is documented in the ERP-system. Several tools are used to aid the departments work. Apart from the ERP-system, IT-tools for planning, follow-up and calibration are used.

4.5.3 Corrective maintenance

Any malfunction is reported by the use of separate routines. All reports are entered into the ERP-system and are classified according to a number of objectives including security. The maintenance department is responsible for troubleshooting and countermeasures. The countermeasures are planned and implemented by the engineer or maintenance mechanic. All activities are documented in the ERP-system and statistical analysis is carried out on the data.

4.5.4 Continuous improvements

Head of each function is responsible for obtaining new knowledge within each area of responsibility. The organization is continuously working to spread knowledge between different units of the plant. Knowledge can also be obtained through the national network NUMEX.

4.5.5 Equipment classification

All equipment within the power plant is classified according to security, quality, risk of leakage and electrical function. Each class then specifies how certain activities should be carried out. The plant is currently working on a new classification method to better support its maintenance department. This method will classify equipment with security and reliability as main objectives. Each class contains routines for aspects such as:

- To what extent preventive maintenance should be carried out
- To what extent knowledge and experience should be kept in house
- To what extent the equipment should be analyzed using for example RCM
- To what extent spare parts should be kept in stock
- How documentation and checklists should be designed

5 Results

5.1 Current state description

5.1.1 General

The Volvo Trucks Tuve factory is divided into the following units which will be used throughout this report.

- **Frame factory:** Produces frame sides for the global market using a highly automated process
- **Pre-assembly:** In the pre-assembly area different modules of the truck is prepared
- **Cab assembly:** Prepares the cab for final assembly on the truck
- **Engine assembly:** Prepares the engine for final assembly on the truck
- **Axle assembly:** Prepares the axles for final assembly on the truck
- **Chassis lines:** Assembles frame sides into chassis using automated guided vehicles (AGVs)
- **Driven assembly lines:** All other assembly is done on two parallel driven assembly lines.

The frame factory constitutes the first of two core functions. It manufactures frames for both this factory and other factories within Volvo Group. The second core function is all the assembly operations assembling trucks.

Maintenance is a part of the Engineering and Maintenance department. The department is organizationally arranged with a Professional Maintenance Manager reporting to the manager of Engineering and Maintenance who reports to both the Tuve Plant Manager and to the General Manager of European Manufacturing and Engineering. The Manager of Engineering and Maintenance is participating in the steering committee.

5.1.2 Frame factory

The frame factory is characterized by high level of automation and has been working according to TPM principles for about 6 years. The journey was started with the help of TPM consultants. All stops are documented in a database and Pareto charts are used to locate the most frequent errors. Cross functional improvement teams consisting of machine operators, mechanics and engineers are used in the department. All stops longer than two hours are analyzed and root causes are documented in the database. The analysis follows a standardized procedure and all steps are documented in the quality assurance system called QULIS.

The commitment within the workforce is believed to be high and operators not involved in a particular improvement team but with knowledge about a failure may still assist the team by performing 5 why analysis etc. This way, the improvement teams and the operators work together towards improving the KPIs.

Instead of hiring engineers when needed, the frame factory has engineers permanently employed. This way, the frame factory will have the resources necessary to improve the existing equipment continuously. The engineers are present in improvement teams and develop preventive maintenance. Autonomous maintenance is performed on a regular basis. All operators are properly educated. Owners are also appointed for each machine in the frame factory. The owner has more responsibility for the machine and is usually the one performing the autonomous maintenance on that particular machine.

Within the frame factory no breaks are scheduled. Instead operators are allowed to have stopover for meals. This means that the operators themselves plan the breaks in such way that the production never stops (i.e. all operators cannot leave the factory at the same time). This requires mutual understanding and seems to work well. This way of working results in flexible operators that is willing to use unplanned downtime for meals and the operators understands the importance of having a continuously running production.

The frame factory is not using the CMMS-system provided by the maintenance department (SAP) for scheduling preventive maintenance (see Chapter 5.1.4.3). The reasons for this are multiple. For example, there is no easy way to include tasks not assigned to equipment. Because of this, the engineers use a separate Microsoft Excel spreadsheet with all tasks that should be performed. This reduces administration and results in a more intuitive task list.

5.1.2.1 Classification of equipment

Classification of equipment is performed according to the following two parameters within the frame factory.

- **Deliverability assurance**
  The last buffer in the frame factory consists of a high storage area. If the high storage area fails the production of trucks needs to be stopped within approximately one hour. For this reason, the high storage area is classified as critical. The department uses KPIs directly connected to the deliverability as a way of constantly monitoring the performance of the high storage area.

- **Bottleneck analysis**
  The frame factory consists of several machines with buffers in between. This means that a machine breakdown not necessarily stops all other machines directly. It is however one machine that, despite buffers, always will affect the total output – the bottleneck. The bottleneck will always be critical for the overall production and is therefore classified accordingly.

5.1.2.2 Performance measuring

The frame factory uses KPIs to monitor its process. OEE is used as a way of ensuring deliverability. If the OEE goes beyond a certain point for any machine this indicates that capacity to produce in the correct pace to meet customer demand is missing. Therefore OEE is a measure used to ensure capacity requirements rather than trying to maximize it. Scrap rate and customer complains is also monitored.

5.1.3 Assembly

The truck assembly has a majority of hand-tools and the products are transported using driven assembly lines. Prior to the driven lines, self-navigating automatic guided vehicles (AGVs) was used. Going from decoupled AGVs, controlled by pace, to driven assembly lines has put new demands on the maintenance organization since there are no buffers in the driven lines.

No autonomous maintenance is performed within the assembly but the operators are supposed to report equipment malfunction. It is today not possible to add responsibilities such as autonomous maintenance directly to an operator since his role is already defined. If more tasks and responsibilities are added to the group, the group leader is the only person that these can be assigned to. The production department works towards introducing balance owners. When this is done, tasks and responsibilities can be assigned to the balance owner. Operators are allowed to solve issues that do not require special knowledge. The group leaders report stop times into a Microsoft Excel spreadsheet. These stops are later analyzed by the maintenance department.

Assembly does not have any kaizen groups continuously working with improvements. Equipment that is put into production by the production engineering department should be maintained by the maintenance department. This division of responsibility creates an inadequate situation since the maintenance department may need to put a lot of efforts into problems caused by the production engineering department.

5.1.3.1 Classification of equipment

No method for classification of equipment is currently used within production. However, a list of equipment considered critical divided into five classes of criticality exists. The classes are defined by its production consequence. This should rather be seen as a static categorization of equipment. The list was compiled several years ago, when a paced production line was used. The list is therefore outdated, containing equipment already scrapped. The list of consequences also needs a certain time before actually becoming a consequence since it was created before installing a driven line.

Table 5.1: Criticality classes and corresponding consequence.

Class	**Consequence**	**Criticality**
1	Immediate loss of production	Very high
2A	Loss of production at supplier	High
2B	Extensive quality deviation	Medium
3	Production disturbance	Low
4	Other consequences	Depends on consequence

The list can be used to focus preventive actions towards a specific class of equipment. Since it does not regard aspects other than production output it is not suitable for addressing other problems (such as for example operator safety and ergonomics). It does not regard the number of actual failures, i.e. it is a pure proactive model classifying equipment according to a worst case scenario. It does not help the maintenance department to increase equipment availability. The consequences are also very vaguely described, making it hard to determine the actual criticality of certain equipment.

5.1.4 Maintenance Department

5.1.4.1 Maintenance mechanics

The maintenance mechanics are responsible for taking actions required to keep the equipment in a condition that corresponds to the performance specification and to continuously improve the reliability of the equipment by performing for example 5 why’s analyses. They are not responsible for improving the performance of the equipment. If a failure occurs that cannot be solved during production time, the maintenance mechanic is responsible for creating a work order which is to be carried out during non-production time.

The maintenance mechanics are organized in four shift (morning, afternoon, night, off duty). Each team consists of 8 persons divided into four pairs. Each pair is located in a specific area of the factory according to Table 5.2. In addition to these, four extra mechanics (whereof two seniors), always working during the day, are located by the driven lines. The reason for this is the extensive amount of problems in this area. The two mechanics located in the workshop each shift can be moved to any area if bigger problems occur. When this is not the case, the mechanics conduct maintenance work on hand-held tools.

Table 5.2: Shift allocation for different parts of the factory.

	Frame factory	**Pre-assembly**	**Driven lines**	**Workshop**
Senior mechanics	-	-	2 (daytime)	-
Mechanics	-	-	2 (daytime)	-
Shift mechanics	2	2	2	2

The maintenance mechanics are not involved in procurement of new equipment and feels that equipment sometimes is procured without concerns to its afterlife. The mechanics believes to have high knowledge regarding the maintainability of the equipment and should therefore be involved in this phase.

5.1.4.2 Maintenance engineers

The maintenance engineers are responsible for issues with higher complexity that needs more thorough analysis. The aim is to reduce the risk of the failure reoccurrence. The maintenance engineers are also responsible for continuous improvements of preventive maintenance activities. If existing equipment is worn out and needs to be replaced, the maintenance department is responsible to address this issue to the production engineering department. The maintenance engineers work tasks are well defined, but personnel from other departments may not share the same view. The communication between maintenance engineers and maintenance mechanics is often performed in an ad-hoc, insufficient manner. The maintenance engineers are involved in procurement of new equipment.

5.1.4.3 CMMS

Volvo trucks are using SAP as ERP-system. Therefore the maintenance department uses an economic module within SAP to track resource utilization, invoicing and failure analysis. The maintenance mechanic also uses Teamplace, a web based community, to describe failures as a way of documenting the work for future (similar) issues. WinCC is a system that monitors multiple PLC-systems and visualizes failure codes for the maintenance mechanics. The maintenance mechanics can, thanks to WinCC, sometimes discover a problem before the customer realizes it. Since not all equipment is connected to WinCC an alarm operator is always present to receive failure reports by phone. As mentioned before, the assembly operators use a Microsoft Excel spreadsheet to store data about production stops. This data is neither connected to SAP nor to WinCC.

When a breakdown occurs the group leader calls the alarm central operator and explains the problem briefly. The alarm operator creates a work order in SAP and enters the time of the failure, area, equipment ID and failure description. The alarm operator then calls any of the maintenance mechanics currently on duty in the particular area. Once the maintenance mechanic has solved the issue, the solution is documented in SAP. In addition the maintenance mechanic sometimes describes it in Teamplace. The complete procedure for receiving and processing a failure alarm is shown in Figure 3.9.

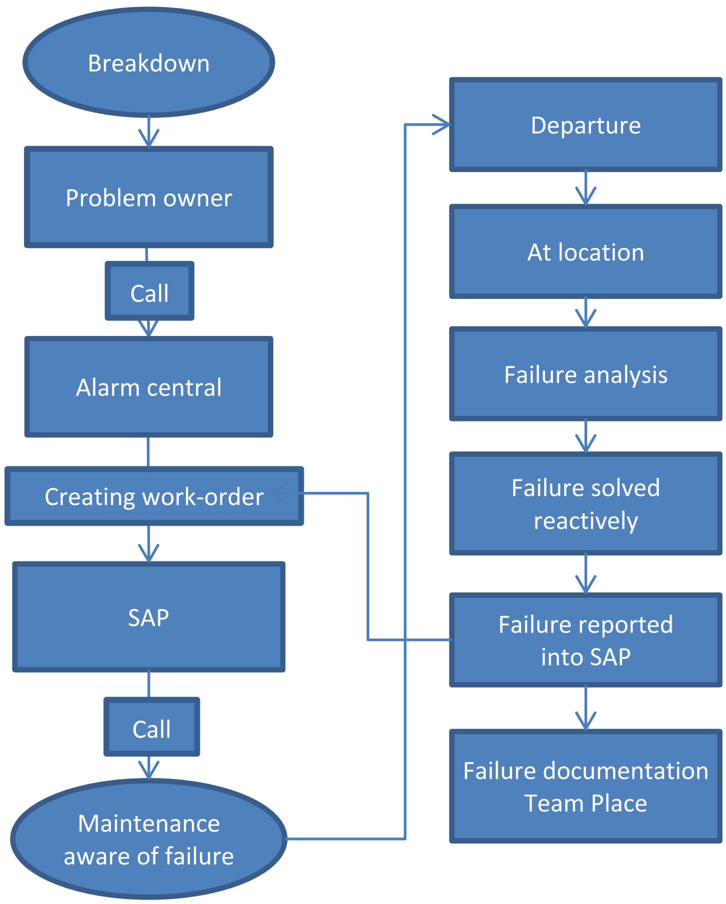

Figure 5.1: Flowchart visualizing the processing of a failure report.

5.1.5 Spare parts management

When new equipment is procured, spare part recommendation is also obtained. The responsible maintenance engineer evaluates the suppliers' recommendations and proposes improvements based on experience. Proposed spare parts are also compared to the current bill of spare parts. Parts that are regarded as repairable will not be automatically reordered. Replenishment will instead be done using manual evaluation.

In connection to daily reviews of material plans, the responsible engineer evaluates whether new parts needs to be procured. The evaluation is based upon experience and statistics of the turnover. During weekly meetings critical failures is brought to attention. The engineer reports different types of analyses and countermeasures. A possible countermeasure might be to reevaluate existing spare parts routines. When equipment is phased out the engineer adjusts the bill of spare parts and removes spare parts related to the equipment.

According to the current spare part management principle it is believed that continuous stocktaking will result in an optimum warehouse holding all necessary spare parts. Today most of the stocktaking is performed by "go and see" procedures. No clear objectives have been found.

5.1.6 Performance measuring and reporting

The maintenance department monitors a large number of KPIs on weekly basis. The results are then analyzed during a weekly meeting.

Table 5.3: KPIs used within maintenance department to monitor the performance of the factory. [1)] An IT-system for controlling and monitoring of the production system.

Category	KPI	Unit	Time horizon
General	MTBF factory (excl. frame factory)	Minutes	Lag
	Failure alarms in total	Number	Lag
	Stops exceeding 10 minutes (Assembly lines)	Number	Lag
Assembly Line 21	MTBF	Minutes	Lag
	Failure alarms	Number	Lag
Assembly Line 22	MTBF	Minutes	Lag
	Failure alarms	Number	Lag
Pre-assembly	MTBF	Minutes	Lag
	Failure alarms	Number	Lag
Frame factory	MTBF	Minutes	Lag
	Failure alarms	Number	Lag
Logistics	MTBF	Minutes	Lag
	Failure alarms	Number	Lag
MONT[1]	Failure alarms	Number	Lag
	Stop time L21	Minutes	Lag
	Stop time L22	Minutes	Lag
	Stop time engine assembly	Minutes	Lag
	Stop time axis	Minutes	Lag
QULIS	Customer complains	Number	Lag

For each of the categories above, Pareto charts are used to stratify the output and to find the most frequently failing equipment. Line plots are used to visualize the data. In addition to these KPIs, the measures regarding the maintenance department seen in Table 5.4 is used.

Table 5.4: KPIs for monitoring the internal performance of the maintenance department.

Category	KPI	Unit	Time horizon
Cost	Overtime	SEK	Lag
	Emergency service	SEK	Lag
Kaizen Center	Visits	Number	Lag
	Ideas submitted	Number	Lag
	Completed products	Number	Lag
Preventive maintenance	Lifting devices (planned)	Hours	Lead
	Lifting devices (actual)	Hours	Lag
	AGVs (planned)	Hours	Lead
	AGVs (actual)	Hours	Lag
	Operation (planned)	Hours	Lead
	Operation (actual)	Hours	Lag

5.2 Maintenance and classification strategy

5.2.1 Root cause mentality

Today, issues are immediate solved thanks to a very competent maintenance crew but the organization work in an unsystematic manner. Unfortunately, only the consequences are reduced and issues are seldom analyzed any further. Regarding WCM and TPM, reactive maintenance should still contain more than just eliminating the consequences. WCM concludes that the technical fix should be followed by a root cause analysis and thorough documentation of the event, i.e. even within reactive maintenance a continuous improvement process must be ensured, for example by using PDCA. It is believed that the organization lacks this approach (see Chapter 5.1.4). It is basically the maintenance mechanic that decides to what extent the event should be analyzed. Both mechanics and engineers tend to close the failure analysis as fast as possible since the consequences have been eliminated. Events brought to attention at meetings are analyzed but still, the conclusion is often in terms of consequences rather than causes. The lack of root cause analysis mentality eliminates the possibility of reducing the probability of the same failure reoccurring. This is a miss in organizational learning and it is believed that, in order to be successful, a classification model needs to facilitate this work (Argyris, 1999).

Finding the most critical equipment will be impossible if the root cause of each failure is not found. Both RCM (Chapter 3.6) and WCM (Chapter 3.5) uses the consequences of failures to determine equipment criticality but needs documented knowledge about the corresponding causes to be able to do this. Without this knowledge, the classification model will base its decisions on assumptions and not help the organization to find the appropriate countermeasure. Instead of a double-loop learning mentality the organization practices a strong concept of single-loop learning making at most the individual mechanic rather than the organization learn from the event. The root cause mentality must not be very complex. The important lesson is rather to continuously monitor the process to create better understanding. The only way to fully understand a process is to grasp the small opportunities of learning caused by failures. (See for example 5G in Appendix B.3 and Lean production in Chapter 3.2)

In those cases where root cause analysis is performed these tends to be rather inadequate. The reasons are seen as three major issues.

- **Lack of understanding and know how**
  The mechanics performing the root cause analysis don't see the gain of doing it properly. This is thought to be related to a lack of education but also, to some extent, related to the next point. Without the understanding of why an analysis should be performed and documented, the analysis will be regarded as "yet another tool" (Liker, 2004).
- **Lack of management support**
  Analyses are discussed during meetings. Even though engineers and managers clearly see the deficiency in the analysis no feedback is given to the analyst. A manager should always challenge his workers as a way to help them improve (Nord, Pettersson, & Johansson, 1997), (Rubenowitz, 2004).
- **Overburden**
  Overburden is mentioned by both maintenance mechanics and engineers. This is thought to be related to the big number of unexpected events and the lack of division of responsibility within the factory. The number of unexpected event will not automatically decrease thanks to a classification model. It is however believed that clear routines will help the staff to prioritize and work systematically.

5.2.2 Strategy selection

The maintenance department often refers to their inability to work proactively. The brace is to move resources from reactive to proactive tasks work since proactive maintenance is thought to be optimum way of working. Even though this is true, it is still very important to handle and learn from unexpected events. Therefore, reactive maintenance must still be emphasized since the documentation from reactive maintenance also creates the foundation upon which proactive tasks can be found. The importance of learning from small improvements is therefore important. Unexpected failures must also be treated as soon as possible since these are very costly. Using this approach, proactive countermeasure can be initiated as a reaction to an event.

The mixture of the reactive, preventive and proactive maintenance must regard the consequences of failures and the accessibility of the equipment. This means that equipment causing big consequences on failure or equipment that isn't accessible during runtime may need preventive or proactive maintenance even though it is costly. For example, the nuclear power plant described earlier needs to utilize a high level of proactive maintenance as the consequences of a failure can be devastating. The fire station also utilizes proactive and preventive maintenance for the same reason.

Moving towards preventive and proactive maintenance should not be seen as a way to reduce the maintenance cost (see Figure 5.2). One may even argue that moving in this direction initially will cause a higher maintenance cost. Proactive maintenance, in general, means more extensive and more costly activities. By a correct implementation of proactive maintenance it is believed possible to reduce the cost of production loss but will involve higher initial resource allocation. This means that the costs in total are thought to decrease over time using proactive maintenance. It may also be possible to reduce the resources needed for maintenance, this should however not be taken for granted as the general relationship according to Nord, Pettersson & Johansson (1997) follows the graph in Figure 5.2.

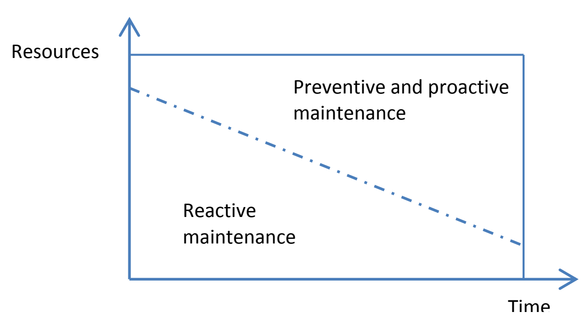

Figure 5.2: The resources needed for maintenance is thought to be constant over time. The mixture of reactive and preventive actions will however change assuming that continuous learning takes place (Nord, Pettersson, & Johansson, 1997).

Moving resources from reactive to preventive maintenance too fast will introduce a risk of improper task selection since learning from reactive maintenance builds the foundation of preventive tasks. Even though reactive maintenance is costly it may become even more costly to spend resources on improper proactive tasks. The correlation between risk and cost is seen in Figure 5.3. The figure also shows the opportunities of reward if correct proactive tasks can be found. The classification model must visualize the connection between failures, root causes and consequences. That is, to make the organization understand the causes of chronic failures (see Chapter 3.10.2). This way, the model will facilitate the organization in its journey from reactive to proactive maintenance.

Preventive maintenance is used when deterioration is known but not yet eliminated to constantly keeping equipment deliver as intended, but should never be seen as the ultimate solution. It should rather constantly be improved to contain only the tasks necessary and to lowest cost possible. Just as for proactive maintenance, the knowledge required to perform appropriate preventive actions comes from the knowledge gained in reactive maintenance.

As mentioned before, proactive maintenance introduces a risk of spending resources by taking unnecessary actions. Considering the Swiss cheese model, proactive maintenance introduces the risk of spending resources removing holes (i.e. potential flaws) not aligned with the holes of any other cheese layer and therefore in a trajectory in which a hazard will never pass. By applying reactive maintenance the trajectory of a failure is used as guidance for flaw prioritization.

Even if the correct actions are taken, proactive work should be considered expensive on another level. When equipment is redesigned, the prerequisites change. This results in that the collected equipment knowledge may become outdated. Before taking proactive actions it is therefore important to (besides ensuring that the correct action is taken) consider how this action affects the organization. It may in some cases be beneficial not to take proactive actions because of these aspects.

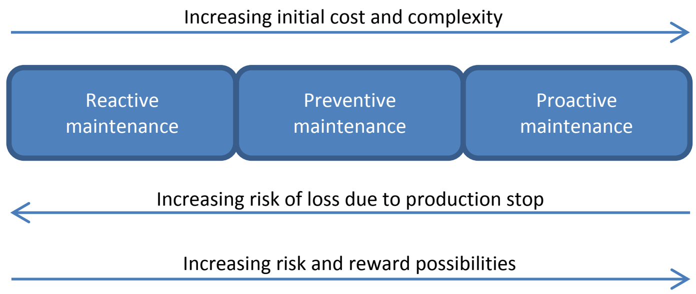

Figure 5.3: The connection between three types of maintenance with regards to cost, risk and reward possibilities. The only way of reducing the complexity is by knowledge (Maylor, 2010). Knowledge is continuously gained through reactive maintenance and will automatically result in a movement towards proactive maintenance (Ljungberg, 2000).

5.2.3 Department cooperation

An underlying, continuously present, “conflict” between maintenance and production department causes problems when implementing new work routines. The project believes that an unwillingness of solving problems together is present which harms the organization. It is of great importance to have a common philosophy and a common goal since the maintenance department is responsible for maintaining another department’s equipment. If the production department neither has the will to improve their equipment nor to demand the maintenance department to improve it, there will be no progress.

A prerequisite for this cooperation is to have clearly defined company objectives regarding equipment reliability, i.e. it is necessary to know the level of reliability that production demands. Well-defined objectives will enable the maintenance department to allocate the appropriate amount of resources to satisfy its customer. It is also important to determine whether to maximize availability or minimize costs. Some equipment may not need full utilization since it is not required.

Not until recently, the production department has not considered autonomous maintenance emphasized in TPM, VPS and WCM. This is by the production department motivated with the low level of automation and that autonomous maintenance only is applicable to process production. The assembly operators also seem to regard maintenance as something not related to their daily work of assembling trucks. In order to succeed, the maintenance department must demand autonomous maintenance. If autonomous maintenance is to be introduced this has to be combined with operator education and training as well as support from the production management and maintenance department.

The maintenance engineers are allocated to a responsibility area covering different types of equipment. This requires broad knowledge. Increased level of automation requires continuously deeper knowledge which may be hard to obtain. It may therefore be beneficial to divide the responsibility upon type of equipment rather than by area.

5.2.4 Inadequate IT structure

Inconsistency in the connections between relevant information within SAP and other IT-systems makes it very hard to browse and search the information. It makes it troublesome to find information about old failures. The lack of structured storing of failures, consequences and countermeasures also limits the organizations ability to see similarities and the effects of its actions. It is also impossible to use statistical data to define the criticality of equipment. As emphasized in both WCM and RCM the current condition of equipment should be used as a basis for decisions of how to improve and maintain it. The reality must be understood before one can predict future failures. Without properly structured information this is impossible. The lack of improper documentation for failures, analyses and conclusions were emphasized by several employees during meetings. According to Liker (2004) knowledge can only be regarded as knowledge as it is documented.

Both VCE and VPT uses SAP for economic management within maintenance but uses separate CMMS-systems better suited for failure documentation and analysis. SAP is believed to satisfy the needs of economic management but not the needs for failure documentation and analysis.

It is believed that VCE, thanks to Avantis, are aware of their failures and the performance of the factory. This constitutes a prerequisite to be able to forecast the future. Volvo Trucks are not, because of the inadequate IT structure, aware of their situation, which makes it hard to prioritize work. Collecting data for weekly KPI meetings requires much work in SAP whilst it only requires a mouse click in Avantis. The possibility to store information in a central system with the possibility to search and stratify the information should introduce great possibilities as a decision basis.

5.2.5 Maintenance performance measuring and reporting

The current KPIs used in the maintenance department do not reflect its core process in a proper way. Instead, the KPIs reflect the production equipment, owned by the production department. It is almost impossible for a maintenance mechanic to improve these KPIs by hard working (characteristic of a KPI). The current KPIs should preferably be monitored by the production department. New performance measurements should instead reflect how the maintenance department has solved its own tasks, or even better, how they should perform their tasks of tomorrow. Since the maintenance department is a support function, performance indicators should be used to visualize the overall performance of the factory. If new, properly determined performance measures are present, it will help all employees in the department to contribute to the vision of the business.

Suggestions on future performance measurements for the maintenance department:

- Performance indicators
    - Percentage of trucks delivered on time
    - Percentage of trucks produced without need for adjustments
    - Net profit Volvo Trucks
- Key performance indicators
    - Number of improvement projects conducted
    - Number of horizontal expansions
    - Number of EWOs without need for correction over number of EWOs
    - Cost reduction thanks to EWO
    - Mean time to repair
    - Mean time to arrival
    - Number of production stops due to lack of spare part

5.2.6 Classification as guidance for maintenance

Today, the maintenance department works mainly with restoration and lacks failure analysis and horizontal expansion. The appropriate way for the maintenance department to improve the situation is by continuously work systematically according to PDCA. This will facilitate root cause elimination using complete reactive maintenance. This builds a rigid foundation of knowledge of the production system which is essential for improving towards a proactive strategy. The approach of first creating a stable process and then improving it can be seen as building a car engine. Before trying to reduce its fuel consumption it must be able to run stable.

Figure 5.4 visualizes maintenance as a treatment of bacteria. Reactive, preventive and proactive are three different approaches requiring different resources and different knowledge. Without the knowledge of several treatments it will be impossible to develop a vaccine or a method to extinguish the bacteria. It is, using this analogy, impossible and considered a high risk to develop preventive and proactive countermeasures before having the knowledge required. The risk and reward correlation of the maintenance approaches is visualized in Figure 5.3.

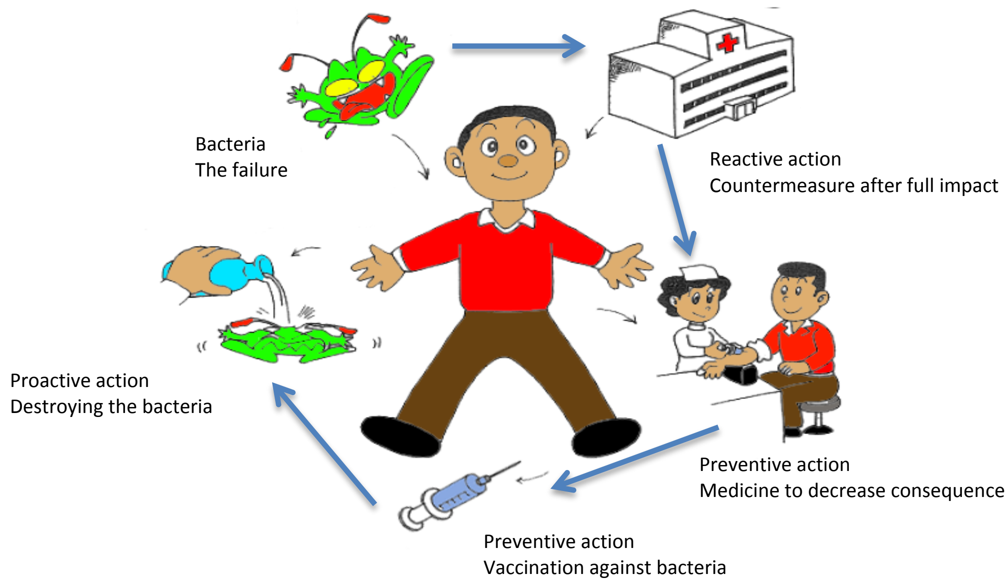

Figure 5.4: Maintenance can be seen as bacteria treatment. Proactive task is the optimum solution but may be impossible without the correct knowledge.

The selection of maintenance strategy also relates to the chosen classification method type. Since supervised and unsupervised classification models introduces big knowledge requirements these can be seen as classification models corresponding to proactive maintenance. Just as in the selection of maintenance strategy, classification must start at the lowest level of complexity. An imposed classification model is therefore most appropriate. An imposed classification model, classifying equipment based on actual events, will also give guidance in how to reduce similar failures – the prerequisite for being able to move towards proactive maintenance. In other words, an imposed classification model will help the organization to develop its reactive maintenance, build its knowledge foundation and in turn move towards proactive maintenance (see Figure 5.5). When thorough knowledge has been gained and the organization has the ability to develop proactive countermeasures potential failures can be found using advanced maintenance strategies such as RCM described in Chapter 3.6. If a proactive classification model is introduced prior to this, it will require side stepping the model every time a failure occurs (as in this VCE example). The results from a proactive classification model will only be applicable when time has been released from breakdowns. This means that a proactive model will allocate resources but not improve your performance as long as all available time is used for reactive maintenance.

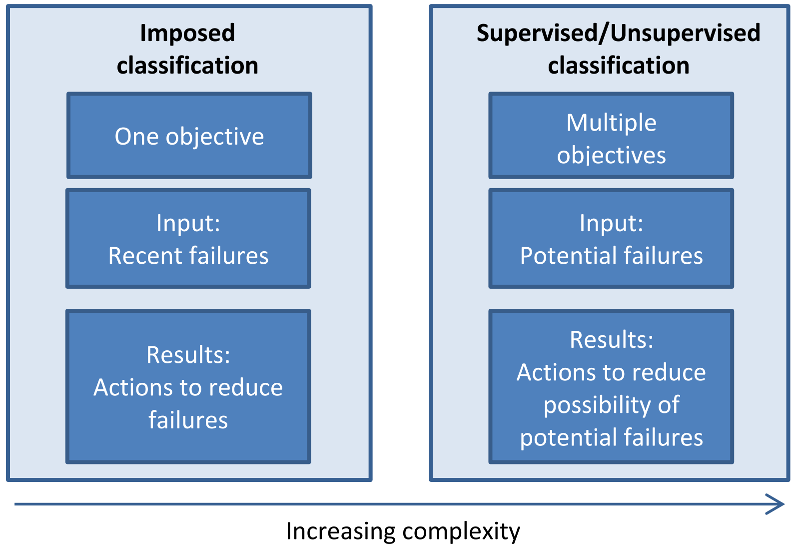

Figure 5.5: Comparison of the different classification approaches in correlation to what it returns in terms of guidance for future activities. An imposed classification model makes classification easier and gives tangible results that contribute to the goal of the maintenance department.

5.2.7 Improvements

Failures with big consequences must be regarded even if they are not conforming to any specific failure pattern (see Chapter 3.10.1). This means that random failures cannot be disregarded even if the elimination requires much resource and possibly redesign.

The WCM approach also emphasizes the need for big thinking and small actions for all unexpected events. This means that small issues should be solved quickly to constantly keep the production running (the left part in Figure 5.6) but also to continuously strive for improvements within maintenance routines, equipment design etc. This is symbolized by the right part of Figure 5.6. The lesson is thus to not disregard reactive actions and wait for standardization. At the same time, do not just restore equipment but also use the knowledge gained to reduce the risk of having the same or similar failure tomorrow. This means that projects will be started from events which root causes has already been eliminated. The reason for doing this is the philosophy of that every failure hides ten other potential failures (Akselsson, 2008), i.e. eliminating one failure only removes the tip of the iceberg and the hidden potential failures (the rest of the iceberg) need to be eliminated using a project (see Figure 5.7). These two processes should run simultaneously and help each other. A well-defined maintenance department is believed to comprise the following aspects.

- Reactive maintenance is the eyes of the department documenting issues.
- Improvement projects are the brain of the department developing it.
- Preventive maintenance is the hands of the department performing its actions.

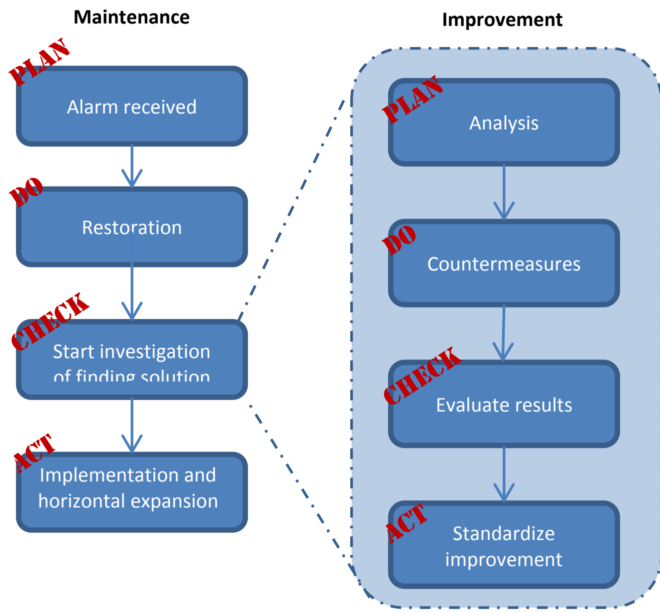

Figure 5.6: Reactive maintenance is more than just restoration. It always covers a root cause analysis and complete elimination of the root cause.

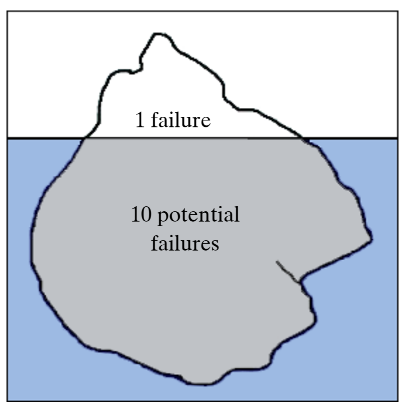

Figure 5.7: Reactive maintenance removes the tip of the iceberg. In addition to this, an improvement project eliminates the rest iceberg (Akselsson, 2008).

5.3 Equipment classification model

The classification model bases its decision on pure facts about previous failures. According to the definition of reactive and preventive maintenance it is reactive maintenance that needs to be developed first. It is therefore believed to be most efficient to classify equipment according to actual failures since these can be treated with reactive maintenance. This way, the classification model will not only highlight the most critical equipment but also facilitate the process of finding the appropriate countermeasures. Once the organization is mature to practice extensive proactive maintenance it will be natural to classify equipment according to proactive aspects such as age, technical level, available documentation etc.

5.3.1 Standardized procedures

The importance of having clear, standardized procedures, regardless of maintenance strategy, cannot be emphasized enough. If no systematic approach is used all failures will be treated differently, and the organization will not learn from the past. Continuous improvements and organizational learning will be inhibited. The use of the PDCA-cycle is believed to help in obtaining a better standard.

The lack of systematic data collection approach is of big concern. If there is no standardized way of treating data it is likely to be forgotten. This leads to the first step of the classification model – data collection.

5.3.1.1 Emergency work order (EWO)

To facilitate the data collection a standardized failure document must be used. The EWO described in WCM (see Chapter 3.5) is suggested. The EWO acts as a central document that connects different kinds of information into one uniform paper. As mentioned earlier, obvious problems has been found within the data collection, handling, analyzing and stratification. Collecting the data using a regular (non-digital) document will make the process more intuitive and visual. This also enables the mechanic to fill in the EWO at the site of failure. Data collection can be facilitated by the use of a CMMS system. If this is done, one can avoid the step of converting the analogue EWO into a digital database. However, the CMMS system will not solve the problems for you, it will facilitate documentation and data analysis but it will not make you understand. Understanding the importance of data collection is a question of maturity.

Each failure will be assigned a root cause category to be able to prioritize and divide issue among several owners and instances. The categories presented in Chapter 3.5.3 are suggested. As mentioned earlier, the EWO will be used within both reactive and preventive maintenance:

- As a tool to investigate and understand the failure (reactive)
- As the rigid knowledge foundation used when prioritizing (preventive)

The EWO template can be a subject for continuous improvement. The number of parameters and the layout is not fixed. It must be developed to fit the needs of the organization and thereby contain the information needed. It is believed to be of great importance to involve the maintenance mechanics, the users, in the development of the EWO to ensure full commitment. The EWO should contain tools appropriate to use when collecting the data. Appendix B shows a big variety of tools that may be suitable in a EWO. A EWO template is available in Appendix D.

5.3.2 Reactive maintenance

Reactive maintenance will always be needed since failures following a random pattern will be impossible to predict. When the organization has collected the right knowledge by performing reactive maintenance more time will be available for preventive and proactive task.

5.3.2.1 Plan

The ability to plan the work within reactive maintenance is of course limited. It is however important that the staff is properly spread out in the factory and that the shifts are planned in such way that ensure competence availability. The project sees no reason to change the current way of manning the different departments with maintenance mechanics. It is however important to consider the trade-off between having expert competence in a (smaller) specific area or more general competence for a bigger area. This step also contains maintaining the equipment used during maintenance. 5S is a simple tool which will help to create and sustain order among the equipment.

5.3.2.2 Do

This step involves eliminating the problem and collecting data by writing the EWO. The importance of doing this, and to do it thoroughly, cannot be emphasized enough.

5.3.2.3 Check

When the problem has been eliminated the maintenance mechanic must ensure that the implemented solution is fully functional and that the EWO is completed with high quality. Check also involves a follow-up analysis regarding the mechanics way of working. The mechanic may evaluate the performance by asking the following questions:

- How can the time to location be improved?
- Can the problem be fixed faster by rearranging my tools?
- Was the error code appropriate?
- Can the collaboration with the assembly operator be improved?

5.3.2.4 Act

If the solution from the prior steps is satisfying, this step will ensure that it is implemented into all similar equipment (horizontal expansion). Not only the solution but also the methodology and knowledge should be horizontally expanded. This means that all operators should be aware of the issue and its solution.

5.3.3 Cost model

The classification model will help the maintenance department to prioritize equipment based upon cost. The cost is determined using a cost model which can be seen as the core of the classification model. A cost model makes it possible to compare failure of different types in a common monetary unit. This makes it possible to find the equipment causing the highest cost. In relation to VDM, the cost model will visualize the cost reduction potential whilst VDM determines the potential cash free up, i.e. both philosophies visualizes the economic aspect of maintenance but uses different tools in doing it. Prioritization upon cost is adequate since all departments will understand why certain equipment is more critical than another. It does not require deep technical knowledge to understand a high cost.

To be able to determine the cost of a failure several aspects needs to be defined. First off, all possible losses connected to a certain process or piece of equipment needs to be defined. This can be done prior to any failure and the method described in Chapter 3.5 is suggested. Any possible subsequent losses also need to be defined. The cost is then determined using the times specified in the EWO and the equations defined in Chapter 3.5.1. Doing this will assign a cost to each EWO. This is later to be used as the weight of the failure. Since it will be time consuming to define all possible losses for equipment, the project suggests that the initial cost model only regards a few losses. It is then possible to increase the level of detail by simply regarding more aspects of losses. The list presented on the next page shows aspects regarded as important within VPS. These can be used as guidance when defining the losses. Since the cost is a way of giving each EWO a weight the equations used does not have to be perfect. The important is to use the same cost model for all EWOs making all costs comparable. To get a more accurate costs associated with a certain event it is however important to develop the cost model continuously.

- Human safety
    - Injury
    - Stress
- Production loss
    - Material- and material handling
    - Employee
    - Overtime to catch up
    - Disturbances
- Quality loss
    - Defects due to abruptness
    - Customer dissatisfaction
- Environmental issues
    - Leakage of liquids or gases

5.3.4 Stratification upon root cause category

Using the cost as a weight, the EWOs will be stratified upon the root cause categories defined in Chapter 3.5.3.2. Since each root cause category has its predefined owner the failures (i.e. the costs) in that particular category can be assigned to the owner. This is of great importance since it makes each instance aware and responsible for its own problem. Without this stratification, all issues will remain in the maintenance department even if they don't regard professional maintenance at all.

For example, production stops caused by human errors by an operator should be assigned to the production department since it is the only instance with the ability to solve its root cause. The maintenance department can only help to remove the consequences. Since all departments has their own financial goal it is not in the interest of the maintenance department to put effort into eliminating the root cause of these issues since it constitutes an income for the department. Therefore, issues must be attacked from the instance where it constitutes a cost.

The root cause categories can be seen as a typical "by-cause" categorization proposed by Gupta (2009). When performing further stratification (described below) multiple objectives can be used.

Once the stratification upon root cause category is done and the EWOs are assigned to its appropriate owner, that particular instance can further stratify and prioritize among the EWOs. This can be done based on the objectives most suitable for the instance.

5.3.5 Prioritization within professional maintenance

The EWOs assigned to the professional maintenance can now be further stratified. Different objectives can be used in order to find the issue responsible for the highest cost. The following objectives can be considered:

- Equipment
- Equipment type
- Competence
- Geographical area
- Shift
- Maintenance type

It may be necessary to stratify the data according to more than one objective in order to find a correlation.

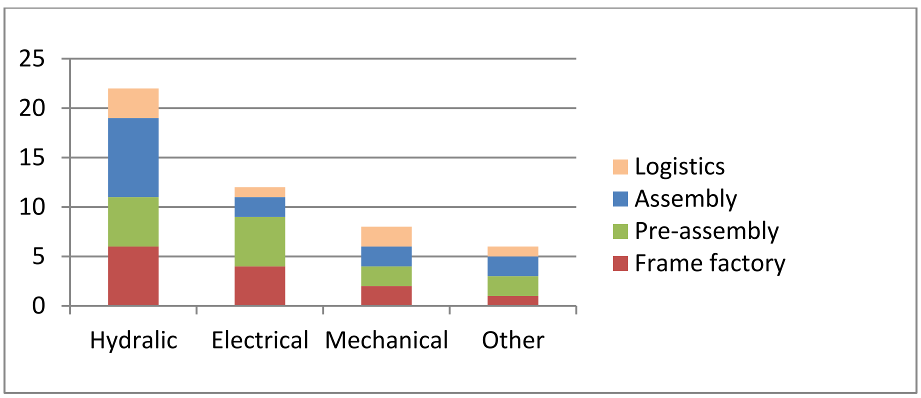

Figure 5.8: Stratification upon technical competence and geographical area reveals that the assembly area constitutes the most costs and that hydraulic failure is the most costly type.

This type of stratification helps the owner of each function to find its own most critical equipment, that is, the one with the highest cost. This means that equipment criticality is a direct result of actual events and that the classification model will constantly reevaluate all equipment and constantly appointing the most critical one. The stratification also helps the owner to find a suitable countermeasure. It will ensure that an equipment failing because of human error does not allocate resources for the development of its preventive maintenance since this will not help (operator education is more likely to reduce the cost).

The issue with the highest cost should, in most cases, be attacked first. However, it may be suitable to calculate a B/C-ratio (benefit over cost) to find the issues with highest profitability. This means that "low hanging fruit" can be attacked prior to larger issues since they have a higher B/C-ratio. Sporadic failures (see Chapter

3.10.2) will typically allocate less resource and therefore have a better B/C-ratio. To find the most suitable countermeasure for a prioritized cost an improvement project needs to be conducted. The methodology is described below.

5.3.6 Improvement project

To lower a prioritized cost, an improvement project needs to be conducted. The most suitable approach for this is, according to TPM, by the use of cross-functional project teams. The advantage of a cross-functional team is that all members are chosen based on their competence and that it promotes collaboration across borders. The team must work according to a project methodology to ensure thoroughness, standardization and horizontal expansion. Once again, the PDCA-cycle is suggested. A project methodology template inspired by WCM is shown in Appendix C. The "A3-methodology" often used in Lean production is another form of compact documentation that can be evaluated. Using this kind of project plans and printing it on a large paper makes the goal, progress and results visible to all project members and other stakeholders. The duration of an improvement project will naturally vary depending on the complexity of the issue. For most issues a couple of hours may be enough but the most complex ones may require much more time. When conducting a project, all EWOs constituting the cost should be analyzed and used as input information in the project.

In contrast to the reactive actions performed when an unexpected event has occurred, which metaphorically was described as removing the tip of an iceberg, an improvement project aims at removing the other ten potential hidden failures, i.e. the rest of the iceberg. Conducting improvement projects can therefore be seen as proactive maintenance initiated as a reaction to an actual event.

5.4 Spare parts management

There exists no standardized classification methodology for spare parts management. Today, prioritization is made upon personal experience and suppliers' recommendations are often not challenged. Optimization is not done using any common objective more than that a shortage is never accepted. The lack of standardization makes it impossible to measure any progress. Annual costs for store keeping are not considered since the total cost is deprecated as the spare part is bought. This is believed to be a bit misleading since, regardless of when the cost is deprecated, the spare will always carry a small, annual carrying cost.

Interviews with maintenance mechanics reveal that the actual numbers of items do not correspond to the defined quantities within SAP. Mechanics also complain about the lack of visualization within SAP, making it hard to find the correct part. Data for spare parts in inventory analysis, such as purchasing costs, ordering costs, material frequency exists within SAP but just like the failure documentation it is hard to interpret it. The validity of the data is also uncertain because of inaccurate input by the users.

It is believed that a systematic approach is needed for spare parts management. The most important functionality of the model is to classify spare parts based upon the potential cost of not having the part in stock versus the cost of store keeping. This is done using the spare part model described below.

5.4.1 Spare parts model

In order to determine if it is beneficial to keep a certain spare part in inventory, the shortage cost must be greater than the cost of purchasing, ordering and carrying the part. The shortage cost is based upon the total cost of the time that the spare part is preventing the function to perform as it is intended to do (i.e. production loss cost). The time of a shortage will therefore be based upon the lead-time of receiving the part. To increase the accuracy of the shortage cost, more parameters can be added. The shortage cost is calculated using Equation 5.1.

Equation 5.1: Shortage cost equation.

$$Shortage\ cost = Lead\ time \times Cost\ per\ time \times \frac{Number\ of\ failures}{Number\ of\ units}$$

The carrying cost C_C is defined by Equation 5.2 and concerns the cost for investment, insurance and risk of obsolescence.

Equation 5.2: Spare part carrying cost.

$$C_C = (C_P + C_O) * (R_O + R_{Inv}) + (C_P * R_{Ins}) + C_W$$

where

C_P = Purchasing cost
C_O = Ordering cost
C_W = Warehouse cost per time
R_O = Obsolescence rate
R_{inv} = Investment interest rate
R_{ins} = Insurance rate

To get a comparable relative measure a criticality index is defined using Equation 5.3.

Equation 5.3:The criticality index of a spare part.

$$Criticality\ index = \frac{Shortage\ cost}{Carrying\ cost}$$

If the criticality index is greater than 1 it is worth keeping the spare part in stock. Spare parts with index lower than 1 may not be kept in inventory, but may need further evaluation to strengthen the decision. It is also important to remember that this approach, apart from the model proposed by Pham (2003), does not consider the age of the component and thus having a constant probability of failure (pure historical average). The optimum solution is to regard the continuously varying probability by the use of distribution fitting for the failure pattern. This will require a more advanced mathematical calculation as shown in Chapter 3.9.3.3. Since extensive data records are missing, it is appropriate to use a simplified version with constant probability visualized in Figure 5.9.

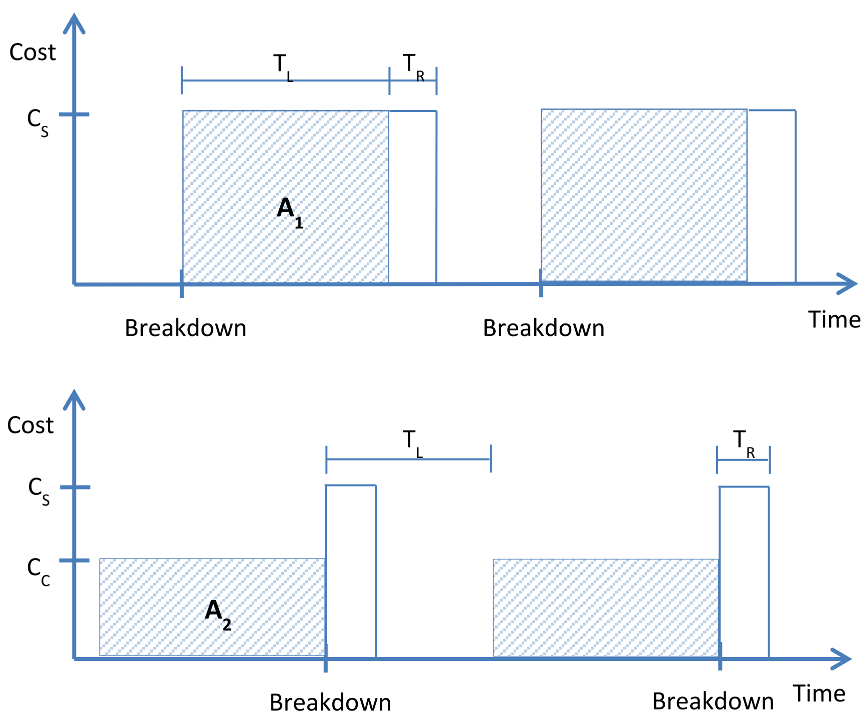

Figure 5.9: The special case of the Pham (2003) theory where the probability of failure has been simplified to a constant value. The upper graph shows the costs of not having the part in stock whereas the lower shows the costs of storekeeping. T_L = Lead time. T_R = Repair time.

Using the notation from Figure 5.9 gives the following definition of the criticality index.

$$Criticality\ index = \frac{A_1}{A_2} = \frac{C_S \times T_L}{C_C \times (MTBF - T_L)}$$

Important to notice is that this criticality index to full extent is based on the MTBF and T_L of last period. If the forecasting period is short, this method will then become sensitive to fluctuations (Jonsson & Mattsson, 2009). To reduce the sensitivity the average of several periods can be used. The number of periods to include must be decided from case to case. It is however important to consider any natural fluctuations.

5.4.2 Classification

All spare parts assigned a criticality index can be further categorized into one of the following criticality classes. The classes in Table 5.5 are defined using ABC classification and Pareto's 80-20 rule. Principle can be then be assigned to each group.

Table 5.5: Suggested spare part classes.

Category class	Percentage of the spare parts	Percentage of the accumulated criticality index
A	10-20	70-85
B	20-30	10-25
C	60-70	5-15

The classes defined in Table 5.5 can then be further categorized using the VED classification approach. The VED approach is used to add qualitative analysis of parts that are needed to meet customer demand (i.e. equipment availability) or lacks historical demand data. This will make it possible to reevaluate spare part routines for any class of spares. However, making too much of a qualitative analysis will increase the risk of introducing deviations from the economic objective. With this said, qualitative assumptions are needed to achieve a practically feasible model at the same time as it creates deviations.

Table 5.6: Appropriate spare part routines can be assigned to each class using a table similar to the one below. To assign these routines will require extensive analysis and the usage of both qualitative and quantitative data. When revising of routines for specific parts is needed, these routines should be updated. The project suggests that the routines for each cell are determined using workshops.

Category Class	**Vital**	**Essential**	**Desirable**
A			
B			
C			

Since the EWO contains information about spare part usage it will be possible to use the EWOs to find spare part demands and to visualize the connection between stop time and spare parts. This means that all production stops can be stratified based upon whether a lack of spare part was present or not. If a strong correlation is found between stop times and shortages of spares, reevaluation of the routines in the table above is needed. Reevaluation and continuous improvements will therefore most certainly be needed.

6 Discussion

6.1 Classification strategy

This thesis has been carried out as a result of a need of a classification methodology for critical equipment. When implementing a methodology it is important to consider the reason for the need and how a classification method would help the organization. Potential pitfalls must also be evaluated to ensure that a model does not become counterproductive. The project believes that a classification model must be designed and accepted as a part of the daily work in order to be effective and efficient. Therefore, managers play an important role for a successful classification model implementation.

The importance of data collection has been emphasized earlier but it is also important to understand why you are collecting the data. If you understand why you are collecting it, data collection will come natural and thus, be a part of your daily work. If you don't understand, data collection will only be performed to satisfy a sporadic demand, for example prior to a VPS revision or when the manager demands it.

VPS also plays an important role in supporting the organization to increase the understanding. Currently, Volvo Trucks is believed to focus too much on the actual statements in the VPS assessments guidelines rather than understanding how and why these are important. A classification model should not be implemented only because of the VPS guidelines but to help the organization towards excellence.

In correlation to a classification strategy appropriate performance measurements needs to be present. Company objectives needs to be considered in the performance measurements. Since the production equipment is owned by the production department, they are believed to be the ones to monitor it. Maintenance should on the other hand monitor their performance and their equipment as a way of ensuring prosperity. This is why examples of new performance measurements are presented in this report. Since this report focuses on criticality from a cost perspective, the brace for continuous improvements and cost reduction must be present in the performance measurements to guide the department. It is also very important to have distinct borders between maintenance and production since mutual understanding will introduce increased risk of communication problems. By having correctly selected performance measurements on both of the departments this can be improved.

6.2 Maintenance strategy

Over time, a majority of the breakdowns will be random (consider pattern E and F in Figure 3.10) and very few will be possible to predict (i.e. conform to the other patterns). This means that preventive maintenance will affect them and that the only way to eliminate them is by proactive maintenance. However, since the organization does not yet hold the knowledge required, reactive maintenance must be used to defend oneself against them. In real life, it is of course impossible to eliminate all random failures using proactive countermeasures whereas reactive maintenance will always, to some extent, be needed.

The vision of VPS is to have 90% preventive maintenance and to initialize all maintenance activities based upon OEE measurements. Why the maintenance vision is formulated like this is hard to understand. As shown in this report, preventive maintenance is only a tool for controlling the flaws of a system. Preventive maintenance should never be seen as a solution but as a tool to avoid production loss while developing better proactive countermeasures. In some cases preventive maintenance should not be used at all since the cost of preventive maintenance exceeds the cost of reactive maintenance and production loss combined. Since preventive maintenance activities do not increase customer value to the same extent as proactive maintenance it should be regarded as more waste than proactive maintenance. Having the VDM philosophy in mind, maintenance can be seen as value adding if it has a positive impact on any of the value drivers. Comparing preventive and proactive maintenance, it is obvious that proactive maintenance increases the quality of the system and therefore adds more value to the business than preventive maintenance. Using this reasoning, preventive maintenance should only be seen as a stop along the road towards something better and hence, not be stated as vision in VPS.

In a company working towards reducing costs in a Lean manner it is also believed to be more interesting to initialize maintenance activities based upon the cost of failures consequence rather than pure OEE. Since the OEE measure only considers availability, performance and quality (not consequence) it may result in bad prioritizations. OEE may still be included in production loss cost calculations.

6.3 Spare parts management

The current spare part management routines are not based upon the economic aspects of store keeping. The current principle is that a shortage of a spare part is never excused, no matter of the cost of keeping the part in stock, nor the cost of production loss. The suppliers' recommendations are taken for granted not regarding the equipment availability to ensure. The cost of a spare part is deprecated immediately when it is bought, and it is therefore considered to carry no further cost. Using this philosophy, all spare parts that will be required sometime in the future should be procured today. If this was done, the warehouse would be filled to the maximum. Since this is not the case, the project strongly believes that the objective is sidestepped. This is probably the reason for continuous manual stock takings. No matter if the carrying cost is allocated to the maintenance department or not, it must be carried somewhere in the organization. Therefore it is believed that the spare part management routines must, in order to be usable, consider all costs together with qualitative decisions.

6.4 Lack of maintenance in Lean production

Maintenance is a supporting function and is therefore often regarded as non-value adding. It is, not only because of this, interesting to mention the lack of maintenance guidelines and strategies within one of the most extensively used production philosophies, Lean Production. For example, the word “maintenance” not even mentioned in the index of the popular lean book, The Toyota Way (Liker, 2004). VPS is thought to go hand in hand with Lean Production philosophies and one cannot disregard the fact that maintenance probably have gained to less attention, or at least have been prioritized in an insufficient manner. In contrast, the WCM approach has no more than three pillars concerning maintenance; professional maintenance, autonomous maintenance and early equipment management. In WCM these pillars have their own owners, which individually strive at improving them and thus reducing their costs.

6.5 Organizational structure

Comparing the organizational structure of Volvo Trucks and VPT reveals more differences. At VPT, maintenance is an individual function whilst it is not at Volvo Trucks. This is believed to play an important role and to reduce the status of the maintenance department.

At VPT, equipment failure is the number one biggest loss. The maintenance department therefore works within the field with the biggest improvement potential. One might argue whether the maintenance manager should participate in the steering committee since it enables easy progress tracking. It would also facilitate communication between the maintenance department and other stakeholders.

These aspects are important and should be regarded when analyzing the potential of the maintenance department. Emphasizing maintenance will enable becoming world class, manufacturing or assembly regardless.

6.6 Validity

6.6.1 Strategy

Strong similarities can be seen between TPM and WCM that heavily is influencing this report. WCM uses TPM philosophies but has been empowered with practical tools for problem solving, stratification and prioritization. The cost deployment pillar also provides the organization with feedback on cost reduction activities. Both frameworks requires constant attention over time and concludes that the journey towards excellence must be started at a basic level, develop the organization and its people over time and to regard failures as learning opportunities. These similarities are believed to strengthen the validity of the results presented in this report.

VPS maintenance is developed from TPM principles and is therefore also compatible with the results of this project. Autonomous maintenance is currently only performed within the frame factory despite the guidelines from VPS to have this function implemented throughout all instances. This thesis proposes the implementation of autonomous maintenance within assembly and is therefore, in that sense, also compatible with strategies from VPS. A key element within VPS is to reduce the unplanned and reactive maintenance. This thesis proposes methods and tools for organizational learning which by time will reduce the need for unplanned and reactive maintenance. This constitutes a major difference between the VPS guidelines and the result of this project. It is believed to be impossible and improper to strive for this vision without having the prerequisites. Over time, it is however believed to be compatible since the strive for proactive maintenance is emphasized and since this project proposes a classification model that helps moving towards proactive maintenance.

The VPS guidelines also mention the use of EWO for failure reporting. This is not performed within assembly today. Visualization and documentation is also strongly emphasized. This thesis proposes the use of EWOs for data collection and for documentation and visualization as a way to create a solid foundation of facts from which further strategic moves towards excellence can be taken. The project shows the power of the EWO since it makes necessary failure information connected and visualized onto one A4 paper and at the same time, conforms to the VPS guidelines.

The vision of VPS is that operators should work together with maintenance specialist to increase reliability and that the specialists should focus on more complex maintenance tasks, e.g. condition based maintenance and improved preventive planning. The results of this project strongly emphasize the need of cross-functional work to improve reliability, which also is emphasized by TPM, WCM, RCM and Lean Production.

6.6.2 Methodology

Information has been collected from different hierarchical levels in the organization, from mechanics, engineers and managers to ensure conformability. The information has been verified by our tutors and by qualified employees as a way to ensure credibility. Different businesses such as nuclear power plant, fire station, manufacturing and assembly have been investigated to ensure credibility and transferability. The organizations contacted have been chosen since they are believed to be successful in the field of maintenance. They are also believed to have different prerequisites due to the consequences of a failure, i.e. a nuclear power plant and a fire-fighting department will be responsible for human lives whilst assembly is concerned mainly with production loss. The results are believed to be transferable to all businesses where there is a need for maintenance. Organizations within all business must be good at learning from the past in order to continuously evolve towards perfection. After presenting a preliminary result for managers both in the maintenance and production department small adjustments has been made. The overall result has however gained a lot of respect throughout the organization which is believed to strengthen the validity of both the result and the methodology. The authenticity of the result is strengthened thanks to the fairness gained through workshops and interviews conducted with personnel of different functions and hierarchal levels.

7 Conclusions

The correlation between reactive, preventive and proactive maintenance can be visualized as in Figure 5.3. Since moving towards proactive maintenance requires extensive competence and knowledge and introduces risks the project concludes that an organization such as Volvo Trucks should start its journey towards "maintenance excellence" using proper reactive maintenance. This also means that an equipment classification model, in order to make it useful and valid, must regard reactive aspects rather than proactive aspects. This leads to the first research question.

How can the equipment criticality be classified at Volvo Trucks?

Equipment criticality should be determined based upon the cost of past events. If prioritization is based upon this criticality, it guarantees that the maintenance department continuously works with the equipment causing the most harm to the organization. By continuously improving this equipment a more robust production system will be obtained. A classification methodology that forces the organization to react upon failures, as a way of systematically learn from the past has been created. The classification model constitutes of the following three blocks.

- **Knowledge foundation**
  Competence and knowledge is needed in all managerial work. No classification can be done without data.
- **Cost model for failures**
  A cost is a uniform measure the enables broad understanding and makes issue of different nature comparable.
- **Stratification and prioritization**
  To make the model useful in daily work it should help in prioritization. By stratifying costs the most critical equipment can be found.

What work methods should be used to support the classification method?

In order to perform the equipment classification, extensive knowledge about the current situation is needed. It must contain information about the systems specification (i.e. what it is supposed to perform and to what extent), failures, errors and improvements from the past. This foundation of knowledge must be documented and continuously improved in order to facilitate the classification model. The main concepts of work methods are described below.

- **Data collection using EWO**
  The project concludes, well in line with the current production system (VPS), that EWOs should be used to collect all necessary data regarding a specific failure. The EWO helps in finding the root cause of the failure, divide responsibility per factory function as well as it constantly improves the knowledge foundation. The EWO is a clear sign for the need of manual data collection, manual analysis, competence and hard work in building an extensive knowledge foundation and in turn improve.
- **Autonomous maintenance**
  All maintenance frameworks discussed in this report emphasizes the importance of autonomous maintenance in order to continuously sustain the basic conditions of the equipment. Professional maintenance will never have the knowledge about the sound and behavior of the equipment as good as the operator. This enables the maintenance department to delegate basic tasks to the operators and thus put more effort into more complex issues.
- **Proper performance measurements**
  All departments needs properly selected performance measurements that facilitates them in their daily work and that ensures working in line with the vision. The measurement used today within the maintenance department does not reflect the departments work.
- **Improvement projects**
  Working reactively does not mean that failures should not be investigated. All failures should be traced back to its root cause in order to eliminate it. More specifically this means that all EWOs should be followed by a small improvement project following a methodology chosen by the organization, for example the PCDA. In addition to this initial improvement all EWOs should be used as decision basis for equipment classification which in turn is used to prioritize and motivate bigger improvement projects. This is done since this report concludes that for each failure occurring (i.e. the one described in the corresponding EWO) ten more potential failures are present. The bigger improvement project aims at eliminating the risk of these ten failures. Conducting improvement projects can therefore be seen as proactive maintenance initiated as a reaction to an actual event.

How should spare parts be managed with regards to equipment criticality?

Spare parts management routines were initially thought to be directly connected to the criticality of equipment. It is however believed that the routines should to the highest possible extent not be based only upon personal assumptions or be based upon whether equipment belongs to a certain criticality class or not. Instead, the consequences of a shortage of a certain component should be regarded. It is also important to consider the cost of keeping the component in stock in contrast to the cost of a shortage in terms of production loss. The cost of a shortage must include the probability of a shortage. The estimated future demand must be used to determine whether or not is profitable to keep the component in stock due to the carrying cost. The future demand may be derived from qualitative or quantitative data. This project suggests the use of a spare parts model in a matrix form combining qualitative VED classification and quantitative ABC categorization. Improvements to the spare part routines should be done either by reclassifying certain parts or by changing the routines for that specific class in the matrix model.

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A Appendix: Equipment criticality table

	Very critical	Critical	Less critical	Low priority
Degree	AA	A	B	C
% of total equipment (guideline)	5%	20%	35%	40%
Classification group	PM Special class	PM 1st class	PM 2nd class	RM class
Consist of	Sophisticated CBM and TBM	Normal CBM and TBM	TBM and RM	Mainly RM
Inspection	Very detailed	Detailed	Simple	None
Spare parts management	Yes	Yes	Yes	No
Lubrication Basic conditions	Yes	Yes	Yes	Yes

- PM: Preventive Maintenance
- CBM: Condition Based Maintenance
- TBM: Time Based Maintenance
- RM: Reactive maintenance

B Appendix: Tools

B.1 Failure mode and effect analysis

Failure modes and effect analysis (FMEA) is a methodology for reliability analysis. It is used to review a product or a products function, failure modes, failure causes and failure consequences. FMEA can be used in different ways and within different levels of the analysis. The method analyzes dependencies between failure modes and failure consequences. The FMEA can also be used to calculate a risk priority number (RPN) of each row in the form. Multiplying the probability to failure (P), the severity (A), and the probability for detection (U), gives RPN (Bergman & Klefsjö, 2010).

B.2 Ishikawa diagram

An Ishikawa diagram is used to visualize different aspects of a quality problem and to determine its root cause. For this reason the diagram is also called cause-and-effect-diagram. Because of its characteristic shape it is sometimes also referred to as fishbone diagram, see **Error! Reference source not found.** (Bergman & Klefsjö, 2010).

When conducting the analysis the following steps are suggested:

- Specify the quality problem at the far right in the fishbone
- List possible causes in the end of each bone
- Divide each bone into multiple smaller bones to refine the level of detail until the root cause is found

Finding the causes of the quality problem can be cumbersome. Therefore, Bergman & Klevsjö (2010) suggests that the following seven pre-defined causes are used. This is thought to help the analyst to get a broad overview of the problem and is referred to as the 7M's-diagram (see Figure B.1).

- **Management**
  Does the management provide resources sufficient enough?
- **Man**
  Is the operator trained and educated to perform the required activities?
- **Method**
  Are the equipment sufficient and in good condition? Is the process properly defined and is it possible for the operator to control the process?
- **Measurement**

Is there any testing equipment in place and is it calibrated? Are there any external factors that might interfere with the measurement?

- **Machine**
  Is preventive maintenance performed in a structured way? Is the machine capable of delivering the quality desired?
- **Material**
  Is the raw material of good quality?
- **Milieu**
  Does the environment affect the process and the quality?

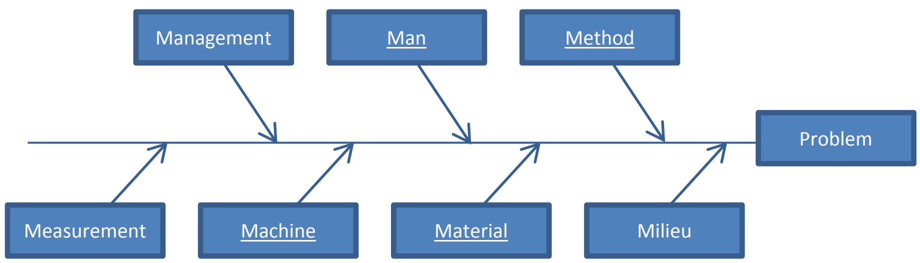


Figure B.1: 7M fishbone. The underlined causes constitutes the simplified version called 4M.

B.3 5G

The 5G tool is used as a starting point in the problem solving hierarchy. It ensures that the initial decisions are based on the actual facts. It is therefore important that the situation is understood by all persons involved.

The 5G tool consists of the following Japanese terms:

- **Gemba** – go to the actual site of the failure
- **Genbutsu** – find the actual material involved in the failure
- **Genjitsu** – analyze the actual situation/occurrence
- **Genri** – analyze the theory before conclusions are made
- **Gensoku** – create standards to avoid the same situation from occurring again

The 5Gs are closely connected to the "Genchi Genbutsu"-concept and the Taiichi Ohno circle within TPS since all three methods emphasizes the importance of facts before making any decision (Liker, 2004).

B.4 5W+1H

5W+1H is a simple method used to grasp contextual information connected to the failure. It should be performed immediately when the failure occurs. The 5W+1H symbolize the initial letter in the following questions:

- What happened?
- Where did it happen?
- When did it happen?
- Who is responsible?
- Which trend?
- How did it happen?

The questions are straight forwards and misinterpretations are not likely. The answers together define the problem and start an investigation by collecting facts and data at the actual location. The goal is not to find the root cause of the problem, rather to collect contextual information needed further on in the process (Sasaya, 2009).

B.5 5 Why

The 5 Whys should be used later in the problem solving process to further increase the understanding of the failure and to find its root cause. Asking "why?" 5 times might seem easy, but it is not. A 5 Why are often answered in a way that results in either of the following two unwanted situations:

- The analyst starts asking "why?" at a level were the answers are very obvious. This makes the first four answers trivial and leaves only one iteration for the actual analysis.

- The final why often ends on a too broad organizational level since the analysis tends to decrease in detail as the level of analysis increases. In order to conduct 5 Whys that contributes with actions, the level of detail must be kept on an appropriate level. It is therefore not appropriate to blame everything on for example top management.

B.6 The 7 WCM tools

The seven improvement tools are used in WCM to ensure working in a systematic way.

1. **Prioritization**
   Prioritization must be made to find the real problems. The following methods may be used.
   - ABC Classification
   - Pareto Diagrams
   - Stratification chart
   - Value stream mapping

2. **Identify the problem**
   The objectives must be divided into the right means and the right solutions. The results must also be measured against the objectives and targets.

3. **Understand the problem**
   With sketches and drawings a higher knowledge about the problem is gathered. There are many tools in WCM to increase the understanding.

4. **Grasp the current situation**
   5W+1H and 5Gs are two commonly used methods that together create a good base for decisions and further analysis.

5. **Identify the real root cause**
   Use methods to create a way of handling root causes in the daily work.
   - Ishikawa diagram
   - 5 Whys
   - 4M (simplified version of 7M's-diagram, see Figure B.1)

6. **Phenomena description with sketches**
   Sketches require deeper understanding of the phenomenon in general.

7. **The Way To Teach People (TWTTP)**
   - How do you do this work?
   - How do you do you are doing this correctly?
   - How do you know that the outcome is free of defects?
   - What do you do if you have a problem

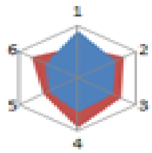
C Appendix: Improvement project template

VOLVO	**IMPROVEMENT PROJECT PLAN**	**PROJECT ID: ID49862**	**Start date: 2011-01-01**	**End date: 2011-05-15**	**Cost: SEK 200 000**	**Saving: SEK 1 500 000**

1. Team members:

- Karl Nilsson
- Martina Håkansson
- Bengt Bergman
- Roberta Sjöstedt

Group competence declaration:



2. Timeline and plan:

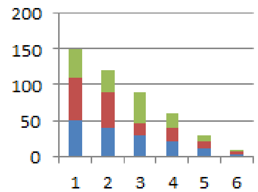
Define tasks and activities within the project. Appoint activity owner. Tools: STM or Gantt

3. Background information:

Description of the problem (5W+1H), context and consequences. The reason for starting the project. EWOs affected by the project can be listed. Images are useful for visualizing the problem.

4. Stratification:

Stratification of events helps to find common causes and aspects that need to be considered.



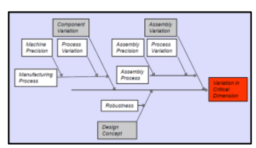
5. Goal:

The goals of the project in measurable units but not monetary.

- MTBF>100h
- MTTR<1h
- Define preventive maintenance actions

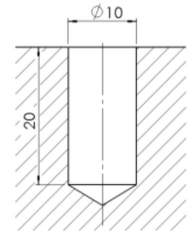
6. Root cause analysis:

Find the root cause of the failure.
Useful tools: 5 Why, 4m (fishbone) etc.
Separate sheets may be used. All documents are given a unique ID number and all documents should contain the project ID.



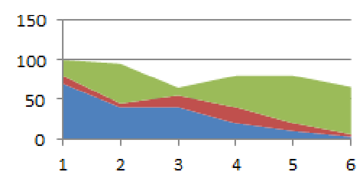
7. Activities and countermeasures:

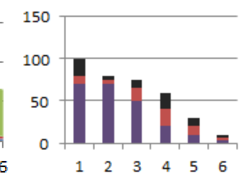
Present activities and countermeasures that solve the root cause, not just limits the consequences.



8. Results

Present the results of the countermeasures from a pilot area. Use graphical aids to visualize the improvement.





9. Standardize and horizontal expansion:

Update documentation and routines to cover the findings and improvements. Use horizontal expansion to implement the improvements on similar systems.

D Appendix: EWO template

English

Professional Maintenance Emergency Work Order (EWO)

Workshop & Process Step:	Issued By:	Breakdown No:
Equipment Name & No:	Issued Date:	

Problem Description

Drawing / Photograph of the Problem:

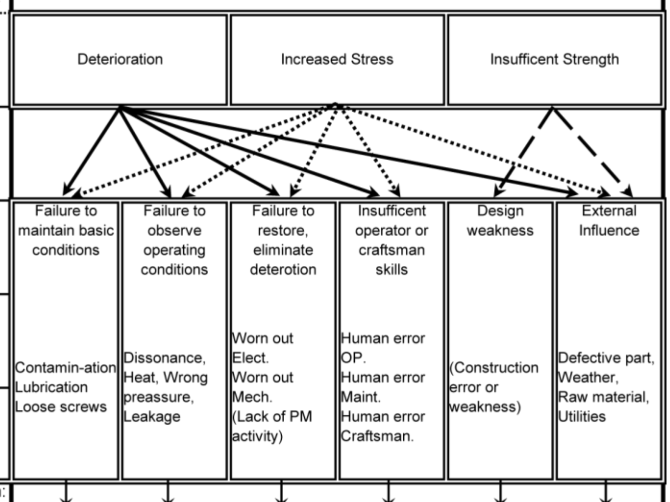
Parts(s) Used:

Define the Problem

5W1H Data: (Gathering the Facts at the Line/machine!)		List Possible Causes:	
What:		1	
When:		2	
Where:		3	
Who:		4	
Which trend:		5	
How:		Notes:	

Root Case Analysis

	Verification of Possible Causes (Quick Kaizen at the machine)	OK or NOK
1		
2		
3		
4		
5		



Countermeasures

Countermeasures:	Who:	When:

Drawing / Detail of Countermeasure:

Sustaining Actions

Roll-out:	Who:	When:	
Review AM standards			AM Standard
Create and communicate OPL			OPL for operating conditions; OPL for operators / craftsman
Review PM calender / Skill Matrix			PM calender; Skills Matrix
Feedback Improvement to Manufacturer			Review Design Standard; Report to relavent Dept

Time:

Start Date:	Finish Date:	Wait Time:	Total DT:
Start Time:	Finish Time:	Total Repair Time:	

Com.