Development and Implementation of Reliability-Centred Maintenance for Job Shop Production Systems in Cooperation with BOSCH Crailsheim

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Abstract of thesis

The paper is creating a reliability-centred maintenance approach to deal with the existence of multiple goals in a job shop production. The discussed job shop production is part of an engineering to order business model and located at BOSCH Crailsheim. Central problems are the lack of transparency and prioritisation of the maintenance tasks. This was determined in two analyses; one assesses the current maintenance activities, especially their benefit to effort ratio. The other analysis evaluates the impact of individual machine tools on the system reliability, facilitating the parameters substitutability and utilisation in an ABC analysis.

With the results of these analyses improvements in the organisational structure, corrective and preventive maintenance were developed. The improvements were implemented, introducing advanced transparency, reliability-centred and condition-based maintenance. The vision is to make condition-based maintenance the future standard at Bosch Crailsheim. Hereby, the goal is to maximise the system reliability, because this parameter was identified to facilitate the production goals best.

Three areas of future research were identified: condition-based maintenance, improved failure analysis processes and higher digitalisation of the system.

Central challenge in job shop production maintenance is to counter the complex nature of the production system, provide transparent processes and work according to the most production-supportive prioritisation of activities.

Key words:

Maintenance, reliability-centred, machine tools, job shop production, engineering to order business model, machine fingerprints, condition-based
Abbreviations

CBM  condition-based maintenance
CM  corrective maintenance
CMMS  computerized maintenance management system
JSP  job shop production
MTW  mean time waiting
MTTR  mean time to repair
OEM  original equipment manufacturer
PDCA  plan-do-check-act
PM  preventive maintenance
RCM  reliability centred maintenance
RBM  risk based maintenance
TBM  time-based maintenance
TPM  total productive maintenance
WIP  work in progress
Table of content

Abstract of thesis .......................................................... v
Abbreviations .................................................................. vi

1. Introduction .................................................................. 1
   1.1 Problems and root causes at the BOSCH Crailsheim maintenance department .............................................. 3
   1.2 Improvement strategies .................................................. 4
   1.3 Transfer of local results into scientific discussion ............... 5

2. Literature review ........................................................... 6
   2.1 Production methods in manufacturing .................................. 7
   2.2 Support function role of maintenance .................................. 9
   2.3 Applicable maintenance techniques .................................... 10
      2.3.1 Time-based maintenance ............................................ 10
      2.3.2 Condition-based maintenance ...................................... 11
      2.3.3 Outsourcing as a strategic element ................................. 13
      2.3.4 Risk-based maintenance (RBM) ...................................... 14
      2.3.5 Reliability-centred maintenance .................................... 15

3. Methodology ................................................................. 17
   3.1 Analysis of current maintenance activities ......................... 17
      3.1.1 Perspective of the maintenance department .................... 17
      3.1.2 Current performance indicators ................................. 20
      3.1.3 Interview process in production .................................. 23
   3.2 Risk analysis machine tools ............................................. 25
      3.2.1 Parameter 1: Substitutability in-house .......................... 25
      3.2.2 Parameter 2: Substitutability with suppliers or contractors .... 27
      3.2.3 Parameter 3: Machine’s bottleneck factor ....................... 29
      3.2.4 Conclusion: Combining the parameters, creating a risk levels for machines ........................................... 31
   3.3 Corrective maintenance .................................................. 33
      3.3.1 Ticket system for deferrable corrective cases .................. 33
      3.3.2 Escalation scheme for immediate cases ......................... 34
      3.3.3 Ordering process improvement ..................................... 35
      3.3.4 Introduction of machine logbooks ................................ 36
   3.4 Preventive maintenance ................................................ 37
      3.4.1 Prioritization by scheduling of tasks ............................... 37
3.4.2 Service contractors (Outsourcing) ............................................. 39
3.4.3 Individual machine fingerprints .................................................... 39

4. Results ......................................................................................... 41
  4.1 Analysis of current maintenance activities ........................................ 42
     4.1.1 Activity based time distribution and difficulty .......................... 42
     4.1.2 Work group based activity distribution .................................. 50
     4.1.3 Interviews with production leaders ......................................... 53
  4.2 Outcome of machine tools risk analysis for the operational performance ... 58
  4.3 Structural changes in the maintenance department .............................. 62
     4.3.1 Scheduling with time slots .................................................... 62
     4.3.2 Outsourcing of fluid management ........................................... 65
     4.3.3 Ordering process ................................................................. 68
  4.4 Improving corrective maintenance .................................................... 71
     4.4.1 Ticket system ................................................................. 71
     4.4.2 Escalation scheme ............................................................ 75
     4.4.3 Service technicians access via internet .................................. 77
  4.5 Periodic preventive maintenance to individual machine fingerprints ....... 78
     4.5.1 Individual machine tool standards ......................................... 79
     4.5.2 Logbook, data collection and analysis ..................................... 82
     4.5.3 Improvement of qualifications to compliment production’s diversity 87
  4.6 Summary of results ...................................................................... 89
     4.6.1 Analysis section of results ..................................................... 89
     4.6.2 Implemented changes to maintenance system ......................... 91

5. Discussion ..................................................................................... 93
  5.1 Analysis as a basis for maintenance improvements ............................ 94
  5.2 Required structural changes ......................................................... 96
  5.3 Corrective maintenance – transferable methods ............................... 99
  5.4 Investment protection, for capital bound in machines ....................... 102
  5.5 PM to fingerprints ....................................................................... 104

6. Conclusion ..................................................................................... 105
List of Figures .................................................................................. 109
List of Tables ................................................................................... 111
Literature references ......................................................................... 113
Appendix of thesis ........................................................................... i
1. Introduction

The following report highlights the cumulative corrective strategies executed as part of an industrial thesis carried out at BOSCH Crailsheim, Germany. It addresses the following three research questions:

a) **Understand** - Why is the maintenance department at BOSCH Crailsheim showing various, negative performance indicators?
b) **Solve** - Measures to improve the maintenance level at BOSCH Crailsheim?
c) **Transfer** - How can the results determined at BOSCH Crailsheim, be translated into the general plant and machinery engineering industry?

The BOSCH Group is a German industrial company with around 73 billion Euros revenue and 390 000 employees worldwide. The firm develops and manufactures a wide range of products from automotive components to home appliance, power tools, sensors and industrial machinery or plants. The company is owned with 92% by the charitable Robert Bosch Stiftung. Currently BOSCH is focusing a lot of effort into developing Industry 4.0 solutions and tries to create a competitive advantage by pushing this technological trend (Bosch Archives, bosch.com, 2017). According to BOSCH (Bosch Packaging Technology - Packaging Machines – Homepage, 2017) more than 100 projects pushing Industry 4.0 were started by 2016 and as seen in the links above the trend accelerates in 2017. As seen in the quoted article from March 2016 the implementation of predictive maintenance of machine tools is one of the key features of this development.

BOSCH Crailsheim is the pharma packaging divisions headquarter and its specialisation is engineering to order of plants and machinery for the handling and packing of liquid pharmaceuticals. Currently around 1300 employees work at BOSCH Crailsheim (BOSCH Crailsheim Homepage, 2017). The firm’s business model is to provide engineering to order and most machines or plants are individually tailored to the customer requirements. All sold products are entirely assembled, tested and costumer-audited in Crailsheim before being shipped to the customer. One special
feature of the factories situation is that it is surrounded by direct competitors. The area received the nickname “Packaging Valley”, because more than 40 companies working in the packaging machine industry have plants there. (Verpackungstechnik Aus Schwäbisch Hall: Packaging Valley – Eine Branche Im Aufwind - Wirtschaft - Stuttgarter Zeitung, 2013). Therefore within 45 kilometres reach the three direct competitors BAUSCH & STROBEL, GRÖNINGER and OPTIMA are located, this creates a supremely high level of competence in the area but also competition.

The thesis is carried out the internal production of BOSCH Crailsheim, which focuses on express manufacturing and the production of the most complex parts and know-how relevant parts. This leads to an extremely wide range of parts and batch sizes between one and eight. External suppliers deliver most of the less complex or urgent parts at a more affordable price, often from Eastern Europe. The in-house manufacturing has around 65 machine tools available, a layout of the factory is found in the appendix. From a maintenance point, almost none of these are similar and quite a few of them are over dimensioned in order to provide a higher range of flexibility. The main focus of BOSCH Crailsheim is engineering, assembly and after sales service. The internal production serves a connecting link between engineering and assembly section and manufactures service parts often in express processes. Hereby the 150 employees produce 25-30% of the parts in sold machines.
1.1 Problems and root causes at the BOSCH Crailsheim maintenance department

Starting the project, the maintenance department was in urgent need of improvement, because of a wide variety of problems. The details are found in chapter 4.1 “Analysis of current maintenance activities”, following is a short overview of the main problems.

a) Regular cases of running to failure with known preventive and deferred corrective maintenance issues occurred. For example:
   - Constantly deferred minor errors causing full-scale breakdowns or
   - Machine tools running out of oil in pre-initiated night production.

b) Extremely high MTW (mean time waiting) caused by an extremely inconsistent waiting times. From 10 minutes up to weeks of respond time, even when contacting maintenance multiple times.

c) Overly complex ordering process boosted MTTR (mean time to repair) and was adding up one or two unnecessary additional days to cases where external service technicians from the machine tool manufacturer were required.

d) Around 80% of the preventive maintenance activities neglected.

e) Maintenance personnel spent roughly 33% of working time with ordering or administrative tasks. Work in which they proved to be 60% slower than administrative staff, as can be seen in result chapter 4.1.1.

These shortcomings lead to the first question this paper will address:

**Why is the maintenance department at BOSCH Crailsheim showing various, very negative performance indicators?**

Hereby the idea is to determine all substantial problems and then identify their root causes to improve the overall situation of the maintenance in the long term. The answer to this research question is found in the chapter 3.1 and 4.1. In chapter 3.1 the methodology is explained and in section 4.1 the results are presented. First identifying all current problems and then analysing the root causes that lead to their occurrence.
1.2 Improvement strategies

After an in-depth analysis of the current problems and activities the next step initiated improvements for the critical issues found. Leading to the second question answered in this paper:

**Measures to improve the maintenance level at BOSCH Crailsheim?**

To achieve improvements four measures were adopted to change the long-term orientation of the maintenance department according to a reliability-centred approach, as opposed to short-term “patchwork” strategies. The exact technique is discussed in detail in section 3 and section 4. To grant readers an overview a summary is included at this stage.

a) **Identify the risk-level for machine tools** - The risk-level for machine tools was defined as a combination of substitutability and bottleneck effects in its utilization.

b) **Prioritizing every maintenance activity according to its ability to lower the risk-level of the production** - Internal job shop production in an engineer to order business model is not solely focused on the pure cost performance indicators. It also has to take into account the quickness to react and the robustness of the production process while offering a large-scale product range. Therefore, a purely production cost or OEE based approach to prioritize maintenance activities falls short of addressing the entire range of requirements this business model has. The risk-based approach formulated in this thesis proved to be a far better indicator for task prioritizing in this particular production system.

c) **Orienting the tasks of the maintenance department relative to the risk-lowering capabilities** - A system was implemented which makes it easy for maintenance personnel to understand how their different activities lower the risk of negative consequences for the production process and how BOSCH prioritizes their tasks.
d) **The definition and implementation of a future vision for the maintenance department’s development regarding new ways to optimize processes** - Use of technological developments according to Industry 4.0 principles and reach a point where individual machine tool fingerprints and machine maintenance standards are introduced.

1.3 Transfer of local results into scientific discussion

The third and final research question addressed in this paper is trying to apply the results in the context of the scientific discussion.

**How can the results determined at BOSCH Crailsheim, be translated into other companies in the plant and machinery engineering industry?**

The answer to this question is found in section 7 and section 8. The results of the thesis project at BOSCH Crailsheim can provide a guideline for the improvement of maintenance activities in the plant and machinery manufacturing industry, particularly for business models based on engineering to order. Job shop production is a very different approach compared to contemporary manufacturing industries with a higher degree of serial production. Highly automated industries commonly draw more interest from the scientific community, because of higher volumes and scaling effects. Furthermore it is was studied to which degree the shortcomings of a maintenance department are due to internal failure as opposed to being caused by the surrounding job shop production system. This aims to answer how negative production system features transfer into the maintenance practises and how to avoid that.
2. Literature review

In this section the ideal strategy for maintenance within a job shop production as part of an engineering to order business model is determined. Hereby various sources from the scientific discussion are taken into account and evaluated regarding their potential for this project. To grant readers an overview a summary is included at this stage.

- **Chapter 2.1** – Comparing the different types of production methods.
- **Chapter 2.2** – Establishes maintenance as support function of the production processes. This will allow determining the position of job shop maintenance within the scientific discussion and its ambiguity compared to other systems.
- **Chapter 2.3** – Illustration of different methods in maintenance applicable to this project.
  - Condition-based maintenance
  - Outsourcing
  - Preventive maintenance
  - Risk-based maintenance
  - Reliability-centred maintenance

The focus will be to identify in which scenarios these methods are feasible. And it will be concluded which elements can be used as strategic components for the improvement of job shop maintenance in an engineering to order business model.
2.1 Production methods in manufacturing

According to Stevenson and Sum (2002) and Scallan (2003) there are five generic types of production methods for discrete part manufacturing; project, job shop, cellular, batch or serial and mass or flow production. The advantages and disadvantages of the different production methods are tabulated and contrasted.

Table 2.1: Job shop production in comparison with other common production methods highlighting accompanying conditions, advantages and disadvantages

<table>
<thead>
<tr>
<th>Method</th>
<th>Conditions</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow/Mass</td>
<td>Lower skilled workforce</td>
<td>High productivity</td>
<td>Completely specializes equipment</td>
</tr>
<tr>
<td></td>
<td>Linked production, strictly balanced tact times</td>
<td>Low labour costs, high automatisation</td>
<td>High investment</td>
</tr>
<tr>
<td></td>
<td>One product or regular mix of few products</td>
<td>Low failure rate</td>
<td>No adjustment or express delivery possible</td>
</tr>
<tr>
<td></td>
<td>Feasible with high output</td>
<td></td>
<td>Only standardized products</td>
</tr>
<tr>
<td>Batch</td>
<td>Skilled workforce</td>
<td>Increased productivity</td>
<td>Flexible only within its possible variants</td>
</tr>
<tr>
<td></td>
<td>Mean constant demand for the offered</td>
<td>Very flexible in terms of lot size</td>
<td>Higher Investments in specialized tools</td>
</tr>
<tr>
<td></td>
<td>Balanced tact times</td>
<td>Lower WIP</td>
<td>No express delivery</td>
</tr>
<tr>
<td></td>
<td>Organized by product families, cells</td>
<td>Optimal for lean manufacturing</td>
<td>Set up times lowered</td>
</tr>
<tr>
<td></td>
<td>produce product families</td>
<td>Lower labour costs, higher</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multifunctional workforce</td>
<td>Shorter lead times, shorter setup times</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Constrain demand for product families, but</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>lot size one</td>
<td>Higher productivity</td>
<td></td>
</tr>
<tr>
<td>Job shop</td>
<td>Small lot sizes</td>
<td>Wide range of products</td>
<td>Overdimensioning of machine tools</td>
</tr>
<tr>
<td></td>
<td>Experts in the work groups</td>
<td>Customer specific changes are possible</td>
<td>High WIP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Express manufacturing</td>
<td>Higher risk of failure, non-repetitive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High quality of work</td>
<td>High number of manufacturing technologies are needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flexible planning</td>
<td>Long personnel training periods</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motivation good</td>
<td>Lower productivity, set up times + less optimisation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Manual movement of products and WIP</td>
</tr>
<tr>
<td>Project</td>
<td>Expert workforce</td>
<td>reduced material and product movement</td>
<td>High WIP</td>
</tr>
<tr>
<td></td>
<td>Space requirement</td>
<td>Team work allows continuous production</td>
<td>Personal and tools have to be moved</td>
</tr>
<tr>
<td></td>
<td>Lot size of one</td>
<td>Flexible towards changes in design or scheduling</td>
<td>High number of equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>High space requirement</td>
</tr>
</tbody>
</table>

The table displays the different positive and negative aspects of the classic production methods (Scallan, 2003). Each production method comes with unique conditions that are linked to its use and make it beneficial under different circumstances. From bottom to top methods are facilitated to produce higher numbers requiring a more constant/predictable demand. On the other hand, the customisation and required workforce expertise to get higher from top to bottom. The
job shop production at high customisation allows for small lot sizes. Since the focus of this paper is on the job shop production it will not discuss the other methods in detail. The job shop approach is applicable under two conditions; the batch sizes are very small and there are experts available to operate the machine tools. Its advantages are a wide range of producible products, high customisation, express manufacturing, high quality, flexible scheduling and high motivation with employees, because of the challenging work environment and importance of their work. On the negative side, there is the required over dimensioning of the equipment to achieve flexibility, high capital binding in work in progress (WIP), higher risk of failure since the tasks are non-repetitive, different technologies needed in one job shop system which makes investments and constant training necessary, lower productivity because of high set up times and less standardisation potential and the manual movement of product and WIP, since the material flow is varying and cannot be automated.

Overall it becomes clear that these methods cannot substitute each other, since the conditions they are applicable to are extremely different. This is a critical point emphasized for the context of this thesis project. The big differences in the production system displayed in the table above will automatically translate into the various support functions and how they can be applied. For example, a flow production system is able to use a just-in-time supply concept, but that is only possible because the times and tasks can be standardized and exactly clocked, so there is no room for variances (Stevenson and Sum, 2002). In job shop manufacturing just-in-time supply concept is not beneficial, because the planning horizon needed to make this concept feasible would eliminate advantages shown in the table such as express manufacturing or flexible scheduling.
2.2 Support function role of maintenance

It is necessary to adjust all the support functions needed in a system to the production method used. As Dhillon (2006) and Ben-Daya et al. (2009) explain, maintenance is one of the key support functions in a production environment. Therefore, just like other supporting fields including logistics or facility management, maintenance has to be adjusted to benefit the entire production system. In literature it is displayed, that this is done in multiple ways with concepts like TPM (Total Productive Maintenance) or RCM (Reliability Centred Maintenance). These are discussed widely in the literature (Ahuja and Khamba, 2008), (Ben-Daya et al., 2009) (McKone, Schroeder, and Cua, 2001). These common approaches are focused on popular, big-scale production methods as project, serial and flow production and serve these specific types of manufacturing best. For example, TPM was designed to be implemented in an automotive production context and therefore, it is connected to the principle of flow production and its standardized environment. In a job shop production context some of these techniques might still be efficient, but they won’t have the desired impact as they are not perfectly adaptable to the job shop principle. A fitting example is the early equipment management, which is highly effective in a flow production because there are few specialized tools. In a job shop, early equipment management is also useful, but it will not have the same impact. This as individual parts are produced and the setup process is too complex to be standardized. Moreover, a job shop system has multiple goal benefits, as seen in the table in the beginning of the chapter. Therefore, it is more likely intended to serve multiple goals. A relevant example is express manufacturing and wide variety of products. This is very contradictory to the flow principle where the focus on maximum productivity allows for the distribution of the fixed costs on many products. This lowers cost for the individual products. These examples indicate why the job shop production is not considered very much in scientific discussion. The scale a job shop environment provides is not large enough to attract much scientific attention. The purpose of this thesis is to show approaches that can help aligning the multiple goals in a job shops production with a maintenance strategy that provides full support for the production system. Hereby it is important to acknowledge that inherent flaws of
the production system which cannot be solved by the maintenance strategy but have to be addressed by the business model. This is one of the limitations that this review highlights whereby maintenance system as a support function has to align with the overall strategy and has no managing influence to correct the production strategy.

2.3 Applicable maintenance techniques

The following part of the literature review will discuss the maintenance methods that are beneficial for a job shop production in an engineering to order business model, within the industry of plant and machinery manufacturing. The goal of this thesis is to combine the most useful methods into a customized maintenance strategy. As such, only the used maintenance elements will be discussed.

2.3.1 Time-based maintenance

The first technique discussed is time-based maintenance (TBM). It is also called preventive maintenance (PM) in the literature regularly. This is however, incorrect as Tsang (1995) argues rightly; preventive maintenance is the hypernym for multiple approaches, including TBM. According to the current perception on maintenance in the scientific literature (Ben-Daya et al., 2009) the subject can be split in preventive and corrective maintenance. Preventive are all measures to prevent error to occur in the system, while corrective maintenance (CM) describes all activity done to correct an occurring error. In this paper TBM is treated as a subcategory of PM, so periodic measures will also be referred to as preventive.

The central objective of all preventive maintenance is to lower the failure frequency of the used machine tools, to reduce downtime and failure costs on product and machine (Usher, Kamal and Syed, 1998). According to Ahmad and Kamaruddin (2012) time-based, periodic maintenance can be implemented based on the machine tool manufacturer’s maintenance guidelines or through the analysis of historical data and experience, which means essentially to identify failure modes. This means that high quality historical data is an important condition for this approach to work. A critique Labib (2004) and Tam et al. (2006) raise with preventive maintenance is that the optimal schedule is hard to define since each machine has to be treated as an
individual. Because of environment, workload and hidden supplier interest regarding spare parts and the tolerances in manufacturing the equipment each machine differs from each other. This indicates that time-based maintenance can be substituted by a condition-based focus, in order to correct the shortcoming of machine individuality and inability to get perfect historical data and failure modes. From the literature it can be derived that TBM is best done as individual as possible for each machine or even better is transferred into a condition-based approach (CBM). Time-based PM is to be preferred if CBM is too complex or to the effort is not in relation to the benefits gained. A simple example would be the fastening of screws, even though it is possible to install vibration sensors, the effort would not be feasible, it is cost effective to install time-based preventive measures, as fastening the screws once a month. This example shows that there needs to be a balance within these two approaches for them to be practically feasible, as is also concluded by Ahmad and Kamaruddin (2012) in their article on time- and condition-based maintenance.

2.3.2 Condition-based maintenance

This approach is also called predictive maintenance, because it tries to predict the occurrence of errors by monitoring the equipment. It is a popular technique in the current scientific discussion, as can be seen from the numerous publications on this topic in the recent years (Veldmann et al, 2011). In CBM the condition of a machine is monitored and with the data collected from multiple parameters as for example vibration, temperature or oil condition (Ahmad and Kamaruddin, 2012). The collection and analysis of data is complex and requires specialists (Jardine et al., 2006) (Tsang, 1995), but with the rise of Industry 4.0 principles and the radical collaboration and connectivity of the emerging cyber-physical systems CBM implementation becomes significantly more cost-effective and technologically feasible (Lee, Kao, and Yang, 2014).

Condition-based maintenance is beneficial, because in modern scenarios the cost of time-based maintenance is increasing with technology becoming more complex, has shorter lifecycles and is used more versatile (Jardine et al., 2006). This leads to CBM being an attractive option, since with the monitoring technology available the
maintenance efforts can be directed more effectively and therefore costs can be reduced.

Veldmann et al. (2011) state three options for introduction of CBM, either done internally by machine tool manufacturer or by specialised companies. Original equipment manufacturers (OEM) start to place a heavy focus on implementing sensors for data acquisition and technology for accessing it conveniently. (“CELOS® from DMG MORI - From the Idea to the Finished Product. “, April 2, 2017). As the field of CBM is becoming an exponentially larger market, with condition monitoring a one-time investment can reduce maintenance costs for the whole lifecycle of a machine tool.

The important question in this paper is if CBM is applicable in a job shop environment with the multiple goals this type of production serves. Obviously the more effective distribution of maintenance activities is beneficial, so CBM is a good approach from that point of view. On the downside, condition-based maintenance requires expert knowledge, as reviewed earlier, which is most likely not available in a small- or medium-sized company with job shop production. Another issue to consider is the lack of sensors within older machine tools, so there are purchasing and placement costs. A job shop production contains multiple different machine tools anyway and has to target them individually (Labib, 2004) (Tam et al., 2006). Therefore, the individual approach CBM is committed to a specialised environment as a job shop, because it will allow the production to get even more in-depth knowledge regarding the machine. This can be utilized in better maintenance and in handling of the machine for a more sophisticated manufacturing process. Therefore, it can be concluded that in the long run CBM is feasible in a job shop production, but it is difficult to implement. As mentioned in the paragraph on time-based maintenance it has to be cost effective compared to TBM. Thus, it should be the goal to introduce CBM whenever feasible, to take advantage of the latest technological developments.

Another issue is that CBM alone does not give a prioritisation to the maintenance activities. If more than one task is due at the same point in time. So in addition to CBM a general prioritisation scheme has to be implemented in order to provide a maintenance strategy for a job shop production, since a condition-based approach lacks the strategic element.
2.3.3 Outsourcing as a strategic element

According to Ben-Daya et al. (2009) two viable options for the execution of maintenance activities is either executing in-house or outsourcing. Two types of tasks are especially attractive for outsourcing, specialist work or tasks that can be done cheaper by third parties and do not lead to a loss of expertise.

Quinn and Hilmer (1994) point out that outsourcing is done to allow a company or department to focus on the functions it is most competent in, while utilizing other firm’s expertise in areas these are more qualified in. Advantages illustrated by Campbell (1995) are extension of capabilities in the company network, better service quality, reduced price, flexibility and updating internal knowledge by collaborating with external expert. The disadvantages are loss of skill, risk to reduce communication within the company, contract bound and dependency on supplier (Grossman and Helpman, 2005).

The question is, if outsourcing of maintenance tasks is a feasible solution in a job shop production (JSP). The advantage of outsourcing suit the concept well, especially since it allows a focus on the core competences and is adding knowledge, if external experts are introduced to the company. What is not suitable in case of a JSP maintenance strategy is to completely substitute internal maintenance with outsourcing. Here a clear loss of knowledge regarding the individual machines will occur. Therefore, the most advantageous option is to partially contract the maintenance tasks to service providers. As mentioned, there is two suitable options; either engage outside experts or hand over trivial responsibilities, that do not generate a lack of knowledge, to set apart capacities or to improve internal areas of competence and high impact.
2.3.4 Risk-based maintenance (RBM)

The risk-based approach’s goal is to reduce the overall risk in the operations (Khan and Haddara, 2003). It considers four different type of losses in its risk analysis; environmental, health, investment and performance. The method is mainly used in the process industry within high risk environments (oil rig) or working with hazardous products (Krishnasamy et al., 2005) (Dey et al., 2004) (Khan and Haddara, 2004). It provides the unique advantage of combining all the relevant factors when choosing a maintenance strategy. This allows the organisation of the activities and achieves acceptable risk of failure at the lowest cost possible (Arunraj and Maiti, 2007) (Bevilacqua and Braglia, 2000). The biggest disadvantage is that it is a very complex approach, which leaves room to failure. Underestimations in the risk assessment have a direct impact on the accident rate, while overestimations increase the costs drastically.

According to (Khan and Haddara, 2004) a RBM strategy is implemented in three steps, risk identification, risk evaluation and adjusting/creation of maintenance activities. It is important to understand that risk is not a static concept and therefore the RMB strategy has to be updated on regular basis. This method is suitable for a job shop production, but too extensive to be practical. As illustrated before, RBM covers four types of risk potentials environmental, health, investment and performance losses. But in a regular job shop production the risk of environmental and health-related accidents is taken care of in the design of the machine tools and the materials used. Therefore, the two objects at risk are the capital bound in the machine and the expected performance. Because of that RBM is only suitable in an adapted version by excluding of health and environmental losses.
2.3.5 Reliability-centred maintenance

Reliability-centred maintenance (RCM) is a method that offers a defined operational reliability at the lowest costs possible (Nowlan and Heap, 1978) (Ben-Daya et al., 2009) (Zhou et al., 2007). This approach is similar with the concept of risk-based ratio maintenance with the focus narrowed to the performance risk parameter. In this article RCM is treated as a subcategory of RBM, because it is essentially a risk-based method adjusted to one specific type of risk. In reviews this idea was not found, a shortcoming of the current scientific discussion. According to Ben-Daya et al. (2009) the components of RCM are:

- Determining a defined reliability of the system function
- Tracking of failure modes
- Identification of the primary failure modes
- Implementation of counter maintenance activities

Benefits of the RCM are the very focused performance that can be established in terms of operational efficiency in the maintenance activities (Nowlan and Heap, 1978) and in terms of cost efficiency to reach a defined level of reliability (Moubray, 1997) (Rausand, 1998). Another benefit is the improvement of knowledge from the intensive work with failure modes and measures to correct them. This has an impact on all types of preventive maintenance. This knowledge can even be translated into the basis of a data analysis in condition monitoring. A disadvantage of RCM is that it will only focus on reliability. Therefore equipment not critical to the performance of the system will be neglected in the prioritisation (Moubray, 1997) (Smith, 1993). Thus, the method ignores the important aspect of investment protection in maintenance entirely for this type of equipment and in a JSP measures to sustain the capital invested have to be implemented in addition to the maintenance strategy.

In a job shop production RCM can be feasible, if the reliability includes the entire system. This enhances the strengths of a job shop system, which are flexible planning, a wide range of possible products and express manufacturing. Depending on the company’s focus these benefits may be exactly in line with what a firm is trying to achieve with establishing the JPS concept.
One example is the manufacturing of urgent after-sales service parts. If the variety of parts is too large for simple stocking, then a small-scale, highly versatile job shop is a beneficial solution. RCM is as such a suitable maintenance approach, because it guarantees a solid reliability of the system. This in turn provides the delivering times that are the justification for a service margin and essential for customer satisfaction.
3. Methodology

The methodology chapter discusses the approaches taken in this thesis. It is split in 4 subchapters, covering the two analyses, corrective and preventive maintenance. The methodology is picked up in the various result chapters where it is applied, therefore in this chapter the methods are discussed only in theoretical detail. For further explanation on the implementation refer to the respective result chapters. To grant readers an overview a summary is included at this stage.

- **Chapter 3.1** - Analysis of current maintenance activities
- **Chapter 3.2** - Risk analysis for machine tools
- **Chapter 3.3** - Corrective maintenance improvements
- **Chapter 3.4** - Preventive maintenance updates

3.1 Analysis of current maintenance activities

Observing the current maintenance activities was the first step taken in the project. It allowed getting a better understanding of the processes and a well-established connection with the maintenance department. This was necessary to promote changes and create an understanding of the strengths and weaknesses in the section first hand.

3.1.1 Perspective of the maintenance department

The first analysed subject was to get an insight into the work processes in the maintenance department. The thesis projected aimed to improve these processes. The idea was to understand the maintenance procedures first and then get to know the related activities in other departments. This allowed a complete picture on the internal production, while guaranteeing focus on the issues in maintenance.
Figure 3-1: Start of information gathering process, for time based task analysis of current maintenance activities

As seen in the graphic above, the first step taken was to accompany the maintenance personnel, to get real life impressions of the maintenance activities. Aside from that, the lack of a system being used made any other approach difficult. When joining the technicians, the goal was to identify the time-intense tasks, determine the current prioritisation scheme and observe the communication channels with production, the internal customer. The time oriented perspective was more important at that stage than grouping tasks according to their respective maintenance type (i.e. preventive tasks). The reason for this is that researching the time spend, will give a clear picture of the effort that is spend on the different tasks. This way, an immediate ranking, emphasising on time-intense measures, is created. In the next step it can be determined if the effort distribution makes sense compared to the risk-
lowering capabilities of the tasks. This is an important basic feature of the approach. Because it is essential to reason that effort must be invested into important tasks.

The information needed was gathered by accompanying the personnel and a four phase interview process with the maintenance staffs. The interview was structured as follows.

a) Commenting on the regular tasks at the maintenance department and the respective observations in the three week monitoring.
b) Time required for the regular tasks was recorded. Herby the normally expected time and the expected time in a worst case scenario was acquired.
c) The real time spend on the tasks was determined, in order to see where plan and reality are not in sync.
d) The stress factor of the different tasks was inquired. The parameter is called “grey hair scale” ranking from 1-4, as can be seen in the sub segment of the results chapter 4.1. The goal is to identify the areas of lacking competence, which cause stress and frustration. Therefore the catchy and humorous name made it easier to answer for the technicians, because naturally it is not popular or easy to reveal one’s own shortcomings.

The last arrow in the figure 3-1 indicates that the information was collected to be used as a basis for the analysis of the tasks. The task analysis based on the effort, measured in time planned and time currently spent, currently invested into the individual activities. The basic structure of this analysis is found in the table beneath.
In the table 3-1 it can be seen how the time-based analysis of the effort per task is working. The tasks are determined while observing and interviewing the maintenance department as described earlier in the chapter. In the second phase of the interview the times per month and the time needed per case are inquired. These parameters are multiplied, extreme cases, defined as worst cases scenarios, are assumed to make around 15% of the total number, based on the previous observations. The real time used is derived from the third segment of the interview process and shows how much time is currently used on the task. Here we see the easy comparison between needed time and spent time that can be done by using the table. Missing in this graphic is the grey-hair-scale, because it covers another parameter, by displaying stress caused by a task.

### 3.1.2 Current performance indicators

Regarding current performance indicators, there was a severe lack of performance control in the maintenance department. The only figure available was the breakdown times per work group, but the figure was calculated by the system and because of the insufficient clarity in the processes not reliable. Another problem for the production and maintenance departments is that they do not have access to the enterprise resource planning system (SAP). This is done to avoid a monitoring of individual
employees, which would be possible with the SAP-system and is not possible with the production planning tools. The downside of that policy is that some figures are only available in SAP and therefore an effective performance measuring for the maintenance department is not possible with the current software tools and their poor data quality and range.

Therefore it became necessary to create a new performance analysis with reliable values. It was decided to approach the work group maintenance from the cost perspective to enhance the information that was created in the time-based-effort analysis. In the following this analysis is displayed.
Table 3-2: Scheme for the analysis of the maintenance costs for every individual work group in BOSCH Crailsheim’s job shop production

<table>
<thead>
<tr>
<th>Work group</th>
<th>Maintenance costs in T€</th>
<th>Mean weekly cases</th>
<th>Distribution in %</th>
<th>Grey hair scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General maintenance costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumps manufacturing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lathing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sheet metal works</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Welding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Express cell</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In table 3-2 the analysis of the cost distribution is displayed as a scheme, in the result chapter this list is displayed including values.

The very left column lists the different work groups within the internal production. Next to it the maintenance costs per year are documented, the analysis was done for 2015 and 2016. The idea is to understand the maintenance’s areas of focus by checking the cost distribution. The columns following the maintenance’s cost columns provide support information, drawing a bigger picture than the purely cost based view. Mean weekly cases provides a time between repair frequency, based on the experience of maintenance and production staff. The distribution segment of the analysis is the ratio planned to unplanned, on one hand indicating the quality and
frequency of preventive maintenance. And on the other hand displaying the quality of communication between production and maintenance, this is crucial to plan preventive measures. In the final row to the right the grey-hair-scale found in chapter 5.1.1 appears again to check the level of stress that the work group causes. As before the highest stress is indicated by the value four and the lowest by value 1. Stress is an important parameter, because it indicates either communication difficulties in the work place interaction or the lack of technical knowledge. Phrasing more sharply, the grey-hair-scale allows identifying areas where either the communication/social or the technical competence are lacking, because this will trigger the most stress. This is a sensitive topic for the affected people, therefore how many grey hair (from 1-4) one gets from working in a specific work group is a humorous and easy way to identify these sensitive areas. The uncovering of these weaknesses is not meant to expose the employees, but is highly necessary information. These particular areas need the most improvement and the most careful approach.

3.1.3 Interview process in production

Within the production, the term always refers to the internal production at BOSCH Crailsheim, the head of production and the team leaders of the work groups/job shops were interviewed regarding two aspects of maintenance.

First a customer questioning to determine their opinion on the maintenance department and second an identification of the key machine tools within their work groups. Key machine tools were hereby defined as bottleneck machines, technological differences, high utilisation and a machines ratio of express order processing. The interview was done with the six production work group team leaders, the head of production and its deputy. The question were deliberately not asked in a neutral way, this was done to provoke more open reactions, since the author of the thesis was working directly with the middle management of the plant. Therefore it was decided to pose the questions in a way to overcome eventual hesitations, which would not have been voiced towards the middle management in a perfectly neutral setting. Furthermore it is easier to connect with the operators if one is using a impactful and informal language.
Graphic 1: Translated customer interview for internal production work groups aiming to identify strength and weaknesses of the maintenance department

Above the interview sheet is translated into English, the use of easy language is intentional since the interview is used in a production context. As displayed in the graphic the interview has two segments the customer satisfaction part and the part regarding the key machine tools. This is very important, because the combination of these two makes the maintenance department perform well. The production leaders will only be happy if the important machines perform well and at the same time current issues are smoothened out.

The interview was used as a review regarding the problems and priority topics identified with the methods in the previous two subchapters. Also the information gained regarding the key machine tools was used in “5.2.1 Parameter 1: Substitutability in-house” as a basis for the discussion with the production planning department regarding the risk factor of the different machine tools. This can also be seen in the result chapter, where the analysis of the high risk machine tools is initiated based on the values and experiences shared in these interviews.
3.2 Risk analysis machine tools

The risk analysis in this thesis is focusing solely on the risk for the operative performance, which is the system reliability; in order to shorten the term risk is used. The analysis takes into account the three parameters:

- Substitutability in-house
- substitutability with suppliers or contractors (company’s external network)
- Bottleneck factor of individual machine tools

These three parameters are explained in detail in the following and the chapter is concluded by an illustration on combining the parameters into a meaningful elaboration of system reliability. In the literature review chapters 2.3.4 and 2.3.5 the theoretical elements of a risk analyses are discussed in detail.

3.2.1 Parameter 1: Substitutability in-house

The first out of the three parameters in the risk analysis of the machine tools is the substitutability of a machine tool in-house at BOSCH Crailsheim. The factor is important, because it indicates the production’s reliability and robustness. As seen in the literature review the substitutability is one of the factors that grant supply chain or production process reliability. Reliability is important because of the engineering to order business model of BOSCH Crailsheim. In this model make to storage is often not a feasible option, because there is individual machinery for every single customer (described in chapter one “Introduction”). The the internal production focuses on express manufacturing, complicated parts, know-how relevant products, an extremely wide range of parts and batch sizes between one and eight. External suppliers deliver most of the less complex or urgent parts at a low price, often from Eastern Europe. This is why low costs are not the major factor of success for the internal production, but its technical capabilities, flexibility and delivery times. The parameter of how many parts are not substitutable onto another machine tool in-house provides a very good measure. It defines the technological capabilities of a certain machine, possible flexibility and the internal productions continued ability to
deliver in-time. This is the best available measure to display the risk level of a machine tool to the production process. Therefore risk management according to machine tool reliability will be the main focus in the new system. In the future the multiple goals in the job-shop production, as described above (express manufacturing, complexity, flexibility, wide product range, small batch sizes), must cause the maintenance department to adjust its strategy and guarantee the smooth function of BOSCH Crailsheim’s job shop manufacturing. That means it is to prioritize keeping up the range of technical capabilities, flexibility and fast response time. This is a crucial difference to what is found in other industries, where the one and only focal point is the up keeping of the equipment efficiency to maximize cost advantages. While at BOSCH Crailsheim, in order to cater the engineering to order supply chain, the focus is split between different goals.

Therefore a clear prioritization becomes necessary, otherwise the production as well as the maintenance department will get caught in-between goals. This is why it is essential to use the risk-level as a measure that makes prioritization possible. Hereby the ratio of substitutable parts per machine provides the best insight into the internal risk-level for the system reliability. Because a lack of other options makes a machine tool more important. For example, express manufacturing is much easier on a machine that has two possible substitutes, since the regular workload that remains unattended can be split up between them. If there is only one machine capable of producing a part the risk for the system performance increases. Added robustness by multiple available machine tools to produce a part makes the production more stable. Therefore it is easier to schedule and react spontaneously to express orders, as mentioned in the literature review. The internal substitutability of machine tools provides a measure for the system reliability it is facilitated as a parameter for the risk analysis.
3.2.2 Parameter 2: Substitutability with suppliers or contractors

The second parameter “Substitutability with suppliers or contractors” addresses the one shortcoming of the first parameter “Substitutability in-house”. If a part can be produced at a supplier, it is not necessary to have a substitute machine tool in-house. Out-house production is possible, but not always feasible. The three limiting factors are higher delivery time, very high extra costs and drain of internal know-how. Thinking back to the introduction chapter; BOSCH Crailsheim is surrounded by three direct competitors within 45 km reach. Consequently the loss of knowledge to competitors is a very real risk when substituting internal parts at supplier facilities. Nevertheless it still can be a feasible option for some parts and the higher costs will often be justified in critical situations. A good example for that is a special grinding machine that has no alternative at BOSCH, but its OEM offers to do contract manufacturing. Here it makes no sense to try and substitute in-house, but using the OEM as the emergency option is perfectly feasible. Since the contracted manufacturing in emergencies is much more cost-effective than buying a replacement that’s capacities are not used at all in regular workload.
For this reasoning, it was decided to include “substitutability with suppliers or contractors” as a parameter in the risk analysis. Hereby the percentage of non-substitutable parts in-house and out-house are multiplied with each other to create the overall parameter of non-substitutability. Below you find an example for the calculation process.

Table 3-3: Examples for calculation of substitutability parameter

<table>
<thead>
<tr>
<th>Machine name</th>
<th>Ratio of parts that can not be processed on a different machine internally [%]</th>
<th>Ratio of parts that can not be processed on a contract manufacturer [%]</th>
<th>Ratio of parts with no alternative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine tool 1</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Machine tool 2</td>
<td>20 %</td>
<td>0%</td>
<td>0 %</td>
</tr>
<tr>
<td>Machine tool 3</td>
<td>0 %</td>
<td>100 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Machine tool 4</td>
<td>50 %</td>
<td>50 %</td>
<td>25%</td>
</tr>
<tr>
<td>Machine tool 5</td>
<td>50 %</td>
<td>100 %</td>
<td>50 %</td>
</tr>
</tbody>
</table>

Table 3-3 shows the five different cases that are thinkable in the calculation of the substitutability for the risk analysis. The overall substitutability parameter is displayed at the right end of the table and named “ratio of parts with no alternative”. It is calculated by multiplying the two factors to its left, “Ratio of part that cannot be processed at a different machine internally [%]” and “Ratio of these parts that cannot be produced at contract manufacturers [%]”. The basis for the ratio for internally substation ratio is the total of products on the machine. The basis of the ratio for external substitution is the number of products not substitutable internally. This is different, because there is no need to externally produce parts that can be substituted in-house.
The first three examples going from the top of table 3-3 describe situations in which either internally or externally machine tool are completely replaceable. For machine 4 only 50% of the parts produced are transferable in-house and of this number another 50% of these non-substitutable parts can be manufactured at a supplier, therefore in total 25% (=50% x 50%) of the parts produced at machine tool 4 are not producible anywhere else in the company’s current network. Reasons for that could be the part size, know-how level or the type of technology used in the machine tool. In the last case displayed in the table above we see an even higher final ratio (50% x 100% = 50%), because for machine tool 5 the suppliers are not able to create any parts produced on it within their facilities. This could be a product with low volume and high specialisation, as for example the high-precision filling needles used for exact distribution of liquid cancer medicine used in chemo therapies.

3.2.3 Parameter 3: Machine’s bottleneck factor

The third and final parameter in the risk analysis is bottleneck factor of the individual machine tools. The measure taken into account here is the possible utilization of a machine, if there would be no capacity limits. A bottleneck factor of three means that the machine has three times as many orders as it is able to finish. For example if the machine is able to produce 5 parts/day then a bottleneck factor of three indicates that 15 parts should be produced on this very day in order to avoid delay in the production flow. The production planning system is partly automated and calculates this specific value every day for every machine tool. The extraction of the values was very difficult because every of the 65 machines listed in the system had to be reviewed individually. But the benefit of reviewing their data manually is high quality of the information gathered. The time period that was analysed is the year of 2016, considering each day individual for every machine tool. The generated data gives out how many days of production would have to be done on the specific day in order to meet all deadlines without touching any buffers. Any bottleneck factor above four is high as far as the system is concerned, so the relevant threshold introduced for its average in the risk analysis is any rate higher than 4,4.
Table 3-4: Example parameters in the risk analysis

<table>
<thead>
<tr>
<th>Machine name [text]</th>
<th>Ratio of parts that can not be processed on a different machine internally [%]</th>
<th>Ratio of parts that can not be processed on a contract manufacturer [%]</th>
<th>Ratio of parts with no alternative</th>
<th>Average bottleneck factor for 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine tool 1</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>1,2</td>
</tr>
<tr>
<td>Machine tool 2</td>
<td>20 %</td>
<td>0%</td>
<td>0 %</td>
<td>2,5</td>
</tr>
<tr>
<td>Machine tool 3</td>
<td>0 %</td>
<td>100 %</td>
<td>0 %</td>
<td>3,3</td>
</tr>
<tr>
<td>Machine tool 4</td>
<td>50 %</td>
<td>50 %</td>
<td>25%</td>
<td>4,3</td>
</tr>
<tr>
<td>Machine tool 5</td>
<td>50 %</td>
<td>100 %</td>
<td>50 %</td>
<td>5,6</td>
</tr>
</tbody>
</table>

Table 3-4 shows the same stats as the table 3-3 in chapter 3.2.2, with the addition of the “average bottleneck factor for 2016” (yellow column). This is the mean utilization that would have been possible on the each day in 2016 for a machine tool. The way it is calculated is described right before the graphic. The factors displayed in the table are all the factors used in the risk analysis of the machine tools at BOSCH Crailsheim.

The bottleneck factor contributed into the risk analysis by being a threshold that raised the risk level for any machine tool that had a bottleneck factor of 4.5 or higher. This way the utilization of the machine is taken into account, in case a machine reaches a critical level of capacity shortness over the period of one year. That is significant, because the breakdown of machines with an overly high workload adds an additional risk to the production’s reliability and robustness. Furthermore it was taken into account that standard deviation could be relevant, since machines with a high standard deviation could also be overloaded with work even though they had what seemed to be an acceptable average for the bottleneck factor itself. But the result of checking this via a pivot analysis of the data, did not back up the hypothesis.
and therefore the bottleneck factor’s standard deviation was not considered as a parameter in the final analysis.

3.2.4 Conclusion: Combining the parameters, creating a risk levels for machines

The combination of the parameters was discussed shortly before. The central question while merging is how to balance the bottleneck factor vs. the substitutability of a machine tool. Hereby it is important to maintain goal focus and the aim is to provide a risk comparison between the different machine tools in the internal production. The first thing to derive from this goal is to understand the relative nature of this analysis. It is not necessary to provide hard universal numbers as for example the costs are, but to provide a ranking that of the internal machine tools. This is only a relative comparison which determines which elements of the internal production have a higher risk for the system reliability. In quintessence maintenance systems can never be self-sufficient, but facilitate the production to achieve its goals. Therefore relative parameters are more beneficial than hard parameters in this analysis. Because the multiple goals the internal production maintenance must focus to improve the overall system reliability. Therefore the comparing element of the risk analysis allows the maintenance department to focus exactly on the needs of the production. This provides the right prioritization of maintenance activities, despite the multiple goals production at BOSCH Crailsheim.

As a side note, the multiple goals of the production system are an indicator for the non-transparent and poorly planned production scheduling and structure. It would be much more beneficial to have a clear goal prioritisation. But as already mentioned earlier in this chapter and in the literature review, the maintenance activities are to support the production regardless its structure being optimal. The flaws in the production system will be pointed out in result, discussion and conclusion chapter and be related to the unsatisfying state of the maintenance department by the start of this thesis project.

As explained in chapter 3.2.2 the substitutability is a combination of in-house and out-house substitutability, this allows a perspective on the entire production network of the company, which can be employed in case of emergencies. The substitutability
parameter provides the central element of the risk analysis, because it best addresses the multiple goals in the production. The second element of the risk-level rating is the bottleneck factor, because it takes into account that not all machine tools are equally utilized in production. This is important because the workload a machine has to face is the leverage onto its substitutability. Therefore the bottleneck factor is introduced as a threshold that increases the risk-level by one (i.e. from B to A), once the critical value in the workload is passed, for the detailed description see chapter 3.2.3.

The just mentioned risk-levels are the result of the analysis being done in an ABC concept. There are three categories, A being the highest risk for the system reliability, C being the lowest. As worked out in the literature review, a typical ABC-analysis has around 15% A-level elements, 25-30% B-Level and roughly 50-60% in category C. Level A includes all the critical components that are most important in the firm’s manufacturing processes. The B-level is parts of medium importance for the system reliability. Category C is the least crucial machine tools for the production flow. The ABC categorization was chosen to simplify the complex risk analysis making it more applicable and communicable with operator and maintenance personnel. Nevertheless it provides a clear cut between the risk-levels. This strict separation is a short-coming of the ranking, since for machines with parameters adjacent to a neighbouring category (i.e. bottleneck factor = 4,3 is very close to 4,6) are treated equally than the ones in its category that do not come close to the neighbouring parameters. But the benefit of increased clarity outweighs this shortcoming in the project. Most essential are easy communication within the factory and clear prioritisations; therefore the ABC analysis was implemented.
3.3 Corrective maintenance

Corrective maintenance refers to all activities that focus on repairing failures. There is immediate and deferrable corrective maintenance. Immediate corrective maintenance is an expensive and disruptive type of failure, because it always occurs unplanned and interrupts the scheduled maintenance and production processes. Therefore it will be seen that improving corrective maintenance is primarily about avoid situation where machine breakdowns occur by attending deferrable failures in time and providing a structured approach to solve breakdowns minimizing their disruptive potential.

3.3.1 Ticket system for deferrable corrective cases

The development of the ticket system is closely linked to chapter 3.1 regarding the analysis of the current maintenance activities. The analysis described in there led to the identification of the problems, chapter 4.1, which made the ticket system for deferrable corrective tasks necessary.

After the identification of the problems the next step was to define the goals for the ticket system, these aims will be explained in detail in the result section. Once that was done, three solutions were developed and in close conversation with maintenance and production one of the solutions was chosen.

Since the whole introduction was a new concept and previous tries to implement any type of system for deferrable cases were all unsuccessful, a PDCA cycle (Plan-Do-Check-Action cycle) for the new ticket system was started. In the first cycle the concept was tried on four machines (two in the milling work group, two in the lathing work group) for two weeks. Then the updated version was implemented in the entire milling and lathing working groups for two weeks and checked again. This version was updated and improved one more time and then introduced in the entire internal production. The last cycle (=fourth cycle) was finished after another four weeks of use in the internal production.
The next step is to facilitate the number of opened and closed tickets as a performance indicator, to link it firmly into the production landscape. The inclusion on the performance dash board is already initiated, but was transferred to the production department. Because the production is naturally interested in monitoring the tickets it hands to the maintenance department, therefore they will be covering the task much faster than the maintenance personnel would do out of sheer self-interest. Since short-term it is not beneficial to the maintenance department to be measured.

3.3.2 Escalation scheme for immediate cases

For the escalation scheme three steps have to be done to prepare finding a solution.

Identification of:

- Possible escalation scenarios
- Current problems when failures occur
- Responsibilities in case of escalation

These three steps make it possible to answer two questions that narrow down the possible solutions.

- What responsibilities are not taken care of in case of escalation scenarios?
- Where are responsibilities placed with the wrong person or in the wrong department?

After these two questions are addressed the follow-up actions are compelling and can be communicated easily. The follow-up actions have to answer the following two statements:

- How to enforce currently neglected activities/responsibilities in the future?
- How to change responsibilities that are currently placed in the wrong hands?

The actions derived from these questions will allow the improvement of the system by giving responsibility to the departments or persons interested in it. Hereby the goal is to identify the stakeholders that benefit most from the outcome of an
activity/responsibility. These stakeholders either get the responsibility itself or they get a direct control function, a good example of this is found in chapter 5.3.1. It describes the implementation of performance indicators for the ticket system as a task for the production department, because this department is interested in the results. The maintenance department itself will be less interested in being measured for its processing of deferrable tickets in corrective maintenance. Therefore the responsibility is within the maintenance department, but the control functions of the ticket system have to be implemented in the production area.

Following the guideline presented above allows coming up with an escalation scheme that addresses all current issues and provides a significant improvement of this critical issue. The implementation in this thesis project is described in the result chapter.

3.3.3 Ordering process improvement

The analysis of the ordering process is based on the results in the analysis of the current maintenance activities. Therefore the methodology for identifying the ordering process as critical is described in chapter 3.1.

The improvement process started with taking times in two settings. First scenario monitored was the ordering process done by the maintenance personnel. The second setting was the ordering done by an administrative staff member in the production overhead. The comparison of the times and method provided an insight in the issues that occur with the ordering process of spare parts or service technicians. This allowed determining possible improvements, listing them and then prioritized in cooperation with the maintenance personnel and the head of internal production. After the implementation of the agreed improvements times were taken again to check on the factual improvement for the administrative staff and the maintenance personnel.

To conclude the improvement process it was decided on a new standard of splitting the work in between the maintenance department and the administrative production
overhead. This was done according to the risk-lowering potential of the tasks, as already mentioned in the introduction and described in the result chapter. As well as according to the extra time consumption the ordering causes in the maintenance department compared to in the administrative functions.

3.3.4 Introduction of machine logbooks

The need was defined with the analysis of current problems, the methodology for that process is found chapter 3.1, because there were no logbooks for the machine tools, neither with the maintenance nor the production department.

Facing the need to document errors occurring on the machine, the first step was to define goals for what values are to be captured in the logbook. Next it was necessary to identify ways of how to implement a logbook and discuss these ideas with the stakeholders. To do this the stakeholders were confronted with the problem and were asked what solutions they would like to see. After gathering the different solutions and understanding the different perspectives, two ideas were introduced into the discussion. In these feedback loops the head of production, workgroup leaders, process engineering and the maintenance department were the major contributors. After agreeing on the most beneficial approach a PDCA (Plan-Do-Check-Act) cycle was started. This PDCA looping was done in combination with the ticket system, because the two concepts are combined, as logbook entries are the information source of the ticket system. Details regarding the PDCA implementation are found in 5.3.1 Ticket system for deferrable cases and the result chapter. Furthermore in the preventive maintenance methodology chapter 5.4.3 “Individual machine tool fingerprints” the use of the logbook data is described.
3.4 Preventive maintenance

All work described in subchapter 3.4 is based on the analysis described in section 3.1 and section 3.2. In these chapters the disarray in the maintenance organization is described and the new prioritization by a risk-based approach is introduced. In this chapter the methodology of the resulting key improvement measures for preventive maintenance will be introduced, in the following order:

- Prioritisation by the scheduling of the daily tasks in time slots
- Outsourcing tasks by enhancing cooperation with a service contractor
- Transformation of periodic maintenance to individual fingerprints for the machine tools

These three sections illustrate the changes the preventive maintenance had to undergo in order overcome the past problems displayed in the introduction and result chapter 4.1.

3.4.1 Prioritization by scheduling of tasks

All work described in subchapter 3.4 is based on the previous chapters 3.1 and 3.2 where current problems and the new risk-based prioritisation are introduced. Acting according to what was found in these chapters motivates the scheduling of the maintenance tasks. But before any scheme could be developed, it was necessary to define the goals that need to be reached. As mentioned before, these goals are based on the risk-analysis and the problems found in the current system. Therefore the goals established are creating risk-oriented prioritization and transparency in the processes done by the maintenance department. Transparency in this project means that the activities done by the maintenance department are easily “visible” and it is transparent why measures are taken. After establishing these goals, the next step was to evaluate different options available as a scheduling system and the degree of details needed. It was aimed to achieve a well-balanced prioritization, while maintaining transparency of its function. Therefore a time-based scheduling approach
was chosen, which consists of four standardized time corridors a day, covering all responsibilities with their respective time needed.

The task-distribution into the four standardized time corridors was done with three parameters.

- Outsourcing feasibility (= Verifying if the BOSCH maintenance is required to conduct the task)
- Risk-lowering ability according to risk analysis
- Time consumption according to documentation and interviews

The first parameter triggered the outsourcing process, if it was answered with “Yes” and had no consequences if it was answered with “No”. The outsourcing methodology for activities designated for outsourcing is described in the next subchapter 5.4.2 and will not be discussed further in here.

The last two parameters where combined in a ratio to determine the risk-lowering relative to the time consumed.

\[
\text{risk lowering ability} \div \text{time consumption} = \text{ratio of impact}
\]

The formula above shows the principle that was applied in ranking the maintenance activities, the formula is not meant to be the subject to complex mathematical calculations. The idea is to prioritize tasks that have a more significant impact on the risk in the basic scheduling, so that the schedule itself gives a concrete idea of how the tasks are ranked relative to each other by the time distributed to them. For details regarding the structure of the different task blocks see chapters 3.3.1, 3.3.3 and 3.4.3 where the features of the new maintenance system are introduced.
### 3.4.2 Service contractors (Outsourcing)

This section is based on the findings in chapter “3.4.1 Prioritization by scheduling of tasks”. There it was established, that the analyses of current activities and risk-level per machine tool lead to a new orientation in maintenance at BOSCH Crailsheim. This required a reassessment of the maintenance department’s tasks. Hereby some of these were identified as outsourceable, due to three factors.

- Suitable for external service contractors in terms of qualification and risk of loss of internal knowledge
- Disturbs the balance of the newly developed scheduling if done in-house
- Financially beneficial to outsource

These parameters are formulated according to the new strategy for preventive maintenance (see chapter 3.4.3 & chapter 4.5) and the installed ticket and escalation system for corrective maintenance (see chapter 3.3 & chapter 4.4.1). Once the areas suitable to immediate outsourcing were known, it was sought to enlarge our current service contractors’ responsibilities. The two reasons for this approach are, that it rewards well-working contractors with additional business, strengthening their ties to BOSCH Crailsheim. And that it increases the chances of a successful implementation greatly to simply extend the contracted tasks compared to setting up an entirely new contract. The result section 4.3.2 will give further insight into the two areas outsourced during the thesis and the outsourcing process itself.

### 3.4.3 Individual machine fingerprints

The need for change in the preventive maintenance systems was identified early in the project as described in chapter 4.1 “Analysis of current maintenance activities” and chapter 4.2 “Outcome of machine tools risk analysis for the operational performance”. All the measures previously defined in section 3 the focus was to how to deal with the dire need for change in the medium and short range. Not discussed was how to develop long-term measures which improve maintenance at BOSCH continuously, even after the thesis project is completed. The individual machine fingerprints are this solution and the foundation for the future vision introduced in the end of this subchapter.
In order to broaden the perspective different sources were accessed; scientific literature, BOSCH maintenance policies and consulting by the production engineering department’s at KTH. The goal was to fit the future approach to the elements implemented in the thesis already in order to enhance them continuously in the future. And to create a tight fit of maintenance production system, because of the multiple requirements towards the production system by the business model as explained in introduction chapter.

The long-term strategy implemented to address the factors described before is to introduce individual machine fingerprints for the machine tools. It’s a maintenance concept that addresses four different areas.

- Machine standards for preventive maintenance activities for each individual machine tool
- Regular scheduled communication between operators and maintenance personnel according to the risk category of the machine tools
- Qualification improvement (i.e. increasing knowledge in machine tool software)
- Identifying and correcting of failure modes with historical data

The detailed work with these four aspects of the fingerprint is found in the result chapter 4.5. From a methodology perspective it is important, that after the definition of the fingerprint it is clearly stated in which conditions this plan is mean to be implemented. So that BOSCH Crailsheim or any other firm is able to understand the requirements needed for its proper execution. The discussion of the necessary conditions is found in the chapter 5.
4. Results

This chapter displays all results relevant to the first two research questions posted in the introduction and discussion. The different sections are analysis of current activities, risk analysis, structural changes, corrective and preventive maintenance. The methodology chapter explains the theoretical approaches that were applied to determine the displayed results. Because of the required limits regarding the extent of this paper some results and activities are not mentioned in detail in this paper. For example 5S optimisations that were performed are not displayed, because the method is an industrial standard and explanation will not benefit the reader.

It is important to keep in mind, that section 4.1 addresses the research question:

**Why is the maintenance department at BOSCH Crailsheim showing various, very negative performance indicators?**

Section 4.3 to section 4.5 picks up the results of the previous two chapters (4.1 and 4.2) and utilises them to address the second research question of this thesis:

**Measures to improve the maintenance level at BOSCH Crailsheim?**

Both of these questions are answered in detail, separating the improvements in three different sections:

a) **Chapter 4.3** - Organisational structure  
b) **Chapter 4.4** - Corrective maintenance  
c) **Chapter 4.5** - Preventive maintenance

In the discussion in section 5 the results of this chapter are debated regarding their transferability and possible impact on other job shop productions.
4.1 Analysis of current maintenance activities

Observing the current maintenance activities was the first step in the project. It facilitates a better understanding of the processes and established the working relationship with the maintenance department. This is crucial to promote changes and create an understanding of the strengths and weaknesses.

4.1.1 Activity based time distribution and difficulty

The basic idea behind activity based analysis was to identify the activities with high time consumption and their difficulty level from the perspective of the maintenance personnel. To provide a more detailed picture the time parameter in the analysis was a time corridor. This way extreme scenarios as well as regular cases were documented and it was possible to put them into relation. Furthermore a problem was, as mentioned in the introduction chapter 1.1, that maintenance activities were neglected in the past. Therefore the analysis was also aiming to clarify which tasks were neglected to what extent.
Table 4-1: Electrical maintenance - Distribution of effort and complexity (grey hair scale) according to central tasks in the old maintenance system

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Frequency [per month]</th>
<th>Time corridor [min]</th>
<th>Planned time incl. 15%</th>
<th>Real time spend [h/mon.]</th>
<th>Ratio of executed tasks [%]</th>
<th>Grey hair scale [1-4]</th>
<th>Time with grey hair activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing orders</td>
<td>12</td>
<td>90</td>
<td>240</td>
<td>23</td>
<td>23</td>
<td>100%</td>
<td>4</td>
</tr>
<tr>
<td>Self management (E-Mails, Documentation, Scheduling…)</td>
<td>20</td>
<td>45</td>
<td>45</td>
<td>15</td>
<td>15</td>
<td>100%</td>
<td>4</td>
</tr>
<tr>
<td>Preventive maintenance, periodic</td>
<td>6</td>
<td>350</td>
<td>350</td>
<td>35</td>
<td>5</td>
<td>15%</td>
<td>1</td>
</tr>
<tr>
<td>Maintaining operating supplies</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Oil storage</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Optimisation + knowledge management</td>
<td>5</td>
<td>120</td>
<td>350</td>
<td>13</td>
<td>0</td>
<td>0%</td>
<td>1.5</td>
</tr>
<tr>
<td>Service technicians (unplanned)</td>
<td>3</td>
<td>75</td>
<td>150</td>
<td>4</td>
<td>4</td>
<td>100%</td>
<td>2</td>
</tr>
<tr>
<td>Corrective maintenance, immediate</td>
<td>32</td>
<td>90</td>
<td>270</td>
<td>62</td>
<td>62</td>
<td>100%</td>
<td>1</td>
</tr>
<tr>
<td>Corrective maintenance, deferred</td>
<td>16</td>
<td>50</td>
<td>150</td>
<td>17</td>
<td>3</td>
<td>20%</td>
<td>1</td>
</tr>
<tr>
<td>Waste elimination</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Spare part management</td>
<td>1</td>
<td>25</td>
<td>150</td>
<td>1</td>
<td>0</td>
<td>33%</td>
<td>2</td>
</tr>
<tr>
<td>Hydraulics periodic inspection</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Regular service contractors</td>
<td>8</td>
<td>30</td>
<td>90</td>
<td>5</td>
<td>5</td>
<td>100%</td>
<td>1</td>
</tr>
<tr>
<td>Pneumatic periodic inspection</td>
<td>1</td>
<td>10</td>
<td>14</td>
<td>0</td>
<td>0</td>
<td>100%</td>
<td>1</td>
</tr>
</tbody>
</table>

In table 4-1 it is illustrated the effort and complexity of each task in electrical maintenance. Furthermore it can be seen that the entire table 4-1 is split into four sections, task description, time distributions, ration of executed tasks and grey hair scale.

The tasks descriptions in the first column are the central responsibilities of the old maintenance system. These were identified by observation and through the interview process, as explained in methodology chapter 5.1. Some of the listed tasks are redundant; therefore in the interview these were clearly separated from their super...
category in order not to be accounted for twice. The splitting was necessary, because some elements needed to be analysed separately. For example the hydraulic inspections because of safety relevance or service technicians monitoring that require a different skill set than any other task. In the second column, which starts the second section of the table, the parameter frequency within a month is displayed. The third and fourth columns shows the time corridor, with the average time planned for incidents related to the task in the beginning of the row, in the next column the expected time consumption in a worst case scenario is found. In the methodology chapter 5 the process of acquiring the data and the calculation of the parameters “time planned with 15% extreme cases” and “real time spend” is described in detail. In essence these parameters indicate the planned time for the tasks and the real times spend on them. The filled the star shows the relevance of the time consumption and the blue to red scale gives a relative statement comparing all values in the column. The parameter “real time spend” correlates with the third section of table 4-1 “ration of executed tasks”. The ratio is highlighted in green showing off the percentage graphically. Boxes ticked in dark green are currently done, the yellow exclamation indicates partly fulfilment and the red cross marks neglected tasks.

It becomes clear that immediate corrective maintenance is the time wise most relevant task in electrical maintenance. This is explainable by the ignored preventive maintenance; 35 hours per month should be invested in these measures, but instead only 5 hours in a month are really used to take preventive actions. But not just ignored preventive maintenance is a critical issue. In addition it can be seen that only 20% of the deferred failures are taken care of. This is another strong proof for problems described in the introduction chapter 1.1 already and the reason run to failure occurs frequently. Therefore one central lesson learned from table 4-1 is the need to lower the time spent on immediate corrective maintenance by strengthening the deferred corrective and the preventive activities significantly to lower the likelihood of situations like run to failure or excessive immediate cases.

Two other major time consumptions in table 4-1 are processing orders and self-management. In their case the planned time is not as relevant as the real time spend on these tasks. Since in the real maintenance work a lot of activities are abandoned, but these two are still kept up, which gives them a major share of the total time spent.
Self-management eats up almost twice the time preventive and deferred corrective maintenance receive combined. In electrical maintenance even processing orders for spare parts and service technicians takes three times more effort than preventive and deferred maintenance together, according to table 4-1. The high number is partly explained with this being a special responsibility for the electrical maintenance personnel, but nevertheless it is highly disadvantageous to have administrative and ordering processes consume so much time. The grey hair scale in table 4-1 ranges from one to four. Four indicates the highest levels of difficulty and stress connected to the task and one the lowest levels. It is designed to determine areas of lacking competence, in table 4-1 it clearly shows that in these lay in administrative and self-organisation.

The last result of table 4-1 that has to be highlighted is the lack of optimization and knowledge management. With 13 hours planned it is a bigger time consumption, this is due to the fact that one electrical technician will reach retirement in two year and has already started working part time in the beginning of the year. It is necessary to transfer knowledge and optimize old processes. Therefore the time is ideal for a massive time investment into the improvement and transfer of knowledge, but as is seen in the analysis this is entirely ignored. In particular the transfer of knowledge must be a central interest for BOSCH Crailsheim, since their current preventive maintenance processes are time-based. Due to the lack of historical data these are dependent on experiences, as explained in literature review chapter 2.3.1. It is essential to act or the quality of electrical maintenance will decrease further long term.

Table 4-2: Electrical maintenance - sums of time distribution in 2016 mean per month, weeks and day

<table>
<thead>
<tr>
<th>Sum of time distribution per task</th>
<th>Planned time, incl. 15% extreme cases</th>
<th>Real time spend currently</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum per month [in h]</td>
<td>176</td>
<td>119</td>
</tr>
<tr>
<td>Sum per week [in h]</td>
<td>44</td>
<td>30</td>
</tr>
<tr>
<td>Sum per day [in h]</td>
<td>8,8</td>
<td>5,9</td>
</tr>
</tbody>
</table>

Table 4-2 shows another finding of the effort distribution analysis in table 4-1. The
Table 4-2 displays the sums of planned time and real time spend in table 4-1. At BOSCH Crailsheim has seven working hours per day. First the planned or expected average time of 8.8 hours per day exceeds the working time available by almost two hours per day. While the real time spend per day, in the column to the very right, amounts to six hours a day. This is essentially short of one hour working time. In the next table 4-3 the same calculations and very similar results for the mechanical side of the activities is seen. Therefore the conclusions will be drawn after the display of table 4-3 and table 4-4, showing the perspective of the mechanical maintenance with the same parameters and analyses. Because this presents a structural issue and is better discussed after displaying all information available.

Table 4-3: Mechanical maintenance - sums of time distribution in 2016 mean per month, weeks and day

<table>
<thead>
<tr>
<th>Sum of time distribution per task</th>
<th>Planned time, incl. 15% extreme cases</th>
<th>Real time spend currently</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum per month [in h]</td>
<td>167</td>
<td>114</td>
</tr>
<tr>
<td>Sum per week [in h]</td>
<td>42</td>
<td>29</td>
</tr>
<tr>
<td>Sum per day [in h]</td>
<td>8.3</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Table 4-3 relates directly to table 4-4, the same way table 4-1 and 4-2 are connected. It displays the sums of working hours per month, week and day. It is interesting the sums of the planned time and the real time spend are widely similar for electrical and mechanical maintenance. Again the planned time of 8.3 hours per day exceeds the regular seven hours per day by more than a full hour. Similar to that the real time spend is also roughly an hour below the available seven working hours per day. Because of this highly similar behaviour in two entirely separate fields the existence of a structural problem was deduced. In addition chapter 4.1.3 it is displays the team leaders in production describe the maintenance department “unenthusiastic” or not working. This is in line with missing out on an hour of working time per day and the problem needs to be addressed. Overall two possible explanations seem most consistent, first lack of motivation in the maintenance department leading to slow
work. Second, a bad structure in the work organization that leads to delays. The extra time planned on top of the regular schedule, as 8,3 hours per day and 8,8 hours per day planned working time illustrate clearly, are demotivating to the personnel. Furthermore this workload has been the current state for an extended period of multiple years. Therefore it is concluded, that this situation in combination with no clear prioritization of the tasks will lead to a high frustration of the personnel forced into this system. The second explanation of bad work organisation being responsible for the missing hour of working time per day is feasible too. In tables 4-1 and 4-4 the biggest individual time consumption for electrical and mechanical maintenance is immediate corrective maintenance, taking roughly 50% of the time spend. In essence this is any form of breakdown that requires instant reaction and the urgent response explains a loss of working time. Because whenever a machine stands still, the maintenance personnel need to stop current activities and immediately attend to the broken machine. It consumes a lot of time suddenly moving equipment and concentration to another topic and afterwards resuming the old activity again, eventually by having to start anew. Table 4-1 and 4-4 display an expected frequency of immediate, corrective cases is 32 to 36 cases per month per maintenance technician. This indicates a high number of “stop and start” cases, where the work efficiency is reduced by the sudden nature of failure.

Both illustrated explanations, lack of motivation and bad work organisation, are root causes for the loss of working time. These causes are addressed in the following chapters of the result section, especially task scheduling, ticket system, escalation scheme and individual fingerprint.
Table 4-4: Mechanical maintenance - Distribution of effort and complexity (grey hair scale) according to central tasks in the old maintenance system

**Effort distribution per tasks per person - mechanical maintenance**

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Frequency [per month]</th>
<th>Average [min]</th>
<th>Extreme case</th>
<th>Planned time incl. 15% extreme cases [h/mon.]</th>
<th>Real time spend [h/mon.]</th>
<th>Ratio of executed tasks [%]</th>
<th>Grey hair scale [1-4]</th>
<th>Time with grey hair activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing orders</td>
<td>12 30 150</td>
<td>10 10</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>100%</td>
<td>4 6% 8%</td>
<td></td>
</tr>
<tr>
<td>Self management (E-Mails, Documentation, Scheduling...)</td>
<td>20 72 150</td>
<td>28 28</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>100%</td>
<td>2.5 17% 24%</td>
<td></td>
</tr>
<tr>
<td>Preventive maintenance, periodic</td>
<td>6 350 350</td>
<td>35 5</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>15%</td>
<td>1.5 21% 5%</td>
<td></td>
</tr>
<tr>
<td>Maintaining operating supplies</td>
<td>3 20 35</td>
<td>1 1</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>100%</td>
<td>3.5 1% 1%</td>
<td></td>
</tr>
<tr>
<td>Oil storage</td>
<td>1 240 350</td>
<td>4 0</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>0%</td>
<td>4 3% 0%</td>
<td></td>
</tr>
<tr>
<td>Optimisation + knowledge management</td>
<td>1 120 350</td>
<td>3 0</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>0%</td>
<td>1.5 2% 0%</td>
<td></td>
</tr>
<tr>
<td>Service technicians (unplanned)</td>
<td>3 120 350</td>
<td>8 8</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>100%</td>
<td>2 5% 7%</td>
<td></td>
</tr>
<tr>
<td>Corrective maintenance, immediate</td>
<td>36 80 180</td>
<td>57 57</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>100%</td>
<td>1 34% 50%</td>
<td></td>
</tr>
<tr>
<td>Corrective maintenance, deferred</td>
<td>16 45 120</td>
<td>15 3</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>20%</td>
<td>1 9% 3%</td>
<td></td>
</tr>
<tr>
<td>Waste elimination</td>
<td>8 20 60</td>
<td>3 0</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>0%</td>
<td>2.5 2% 0%</td>
<td></td>
</tr>
<tr>
<td>Spare part management</td>
<td>1 40 60</td>
<td>1 0</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>33%</td>
<td>2 0% 0%</td>
<td></td>
</tr>
<tr>
<td>Hydraulics periodic inspection</td>
<td></td>
<td>0 0</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>0%</td>
<td>4 0% 0%</td>
<td></td>
</tr>
<tr>
<td>Regular service contractors</td>
<td>8 15 30</td>
<td>2 2</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>100%</td>
<td>1 1% 2%</td>
<td></td>
</tr>
<tr>
<td>Pneumatic periodic inspection</td>
<td>0.5 30 60</td>
<td>0 0</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>100%</td>
<td>1.5 0% 0%</td>
<td></td>
</tr>
</tbody>
</table>

In table 4-4 shows the effort distribution per task per person for mechanical maintenance. The parameters in table 4-4 and table 4-1 are similar. Therefore none of the parameters will be explained a second time, refer to the beginning of this chapter and table 4-1 for explanation.

Table 4-4 displays, that the mechanical department has a higher amount of self-management compared to electrical maintenance. The reason is that most of the documentation tasks are with this section, while the order process is done by the
electrical personnel. Nevertheless the amount of time spent there is too extensive and two main reasons can be found. First, the personnel lack the administrative skill set these tasks require. And second, the prioritization of work is unclear making it difficult to organize the activities and do efficient self-management. Therefore the maintenance requires a structure and skillset that allows them to tackle administrative and prioritization issues in a more effective manner.

In table 4-1 and table 4-4 it becomes abundantly clear that the preventive maintenance is lagging behind, in fact hardly any measures are taken. Table 4-4 shows this is directly related to the immediate corrective maintenance, which is boasted to around 50% of all the time spent in mechanical maintenance. While deferred activities are ignored until they escalate into breakdowns or safety issues. Another important issue is that all other tasks are widely abandoned due to the lack of time and structure. The management is not aware of the extent of problems, but significant troubles with the machine tools have to be expected in the long-term.

The grey hair scale in table 4-4 ranges from one to four. Four indicates the highest levels of difficulty and stress connected to the task and one the lowest levels. It is designed to determine areas of lacking competence and or time. In table 4-1 it clearly shows that in these lay in self-organisation, hydraulic inspection, maintaining operating supplies and oil management. These topics are picked up in the course of the project, hydraulic inspection and oil management are addressed in the outsourcing chapter 4.3.2, maintaining operating supplies with the ticket system in section 4.4.1 and self-management by the structural changes described in chapter 4.3.
4.1.2 Work group based activity distribution

Data basis are the maintenance costs in 2015 and 2016. The sum of the expenses for all maintenance activities is 464 T€ and 494€, which means the costs are stable. Furthermore it was established that the milling work group needs the most attention, but that is due to the high complexity of the 5-axis machines. The maintenance cost distribution is varying therefore a simple cost overview did not provide useful information. Therefore this chapter sums up the most relevant findings of the analysis, the full results for 2015 and 2016 can be found in the appendix.

Table 4-5: Development of the general expenses from 2014 – 2016, according to the managerial control department’s calculations

<table>
<thead>
<tr>
<th>Maintenance department</th>
<th>General expenses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>Cost in T€</td>
</tr>
<tr>
<td>2014</td>
<td>21</td>
</tr>
<tr>
<td>2015</td>
<td>28</td>
</tr>
<tr>
<td>2016</td>
<td>103</td>
</tr>
</tbody>
</table>

In table 4-5 further evidence for the lack of motivation is found, it can be seen that suddenly the amount of general expenses triples. As mentioned in the beginning of this subchapter the total sum of expenses is 494 T€, therefore 103T T€ amount up to more than 20% of the total budget. This increase cannot be explained with any changes in the maintenance department or the cost distribution concept, so it can be concluded that this development is a clear indication a drastically reduced motivation.
Table 4-6 was created by monitoring and interviewing the maintenance personnel for three weeks. The results in the table above are shocking; again evidence for the extremely unfavourable distribution of planned vs. unplanned maintenance is found. Their ratio is leaning towards unplanned activities by 85% to 15%. This is an issue in terms of investment protection, because unplanned activities are always a response to occurring errors, these failures can significantly damage the machines. Another issue with this is this situation is the inability to organise the working structure based on mainly unplanned activities.

Table 4-6: Distribution planned vs. unplanned maintenance activities per workgroup and grey hair scale for determination of competence communication level

<table>
<thead>
<tr>
<th>Work group</th>
<th>Expected distribution [%]</th>
<th>Grey hair scale, [1-4]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>planned</td>
<td>unplanned</td>
</tr>
<tr>
<td>Milling</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>General maintenance costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumps manufacturing</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>Cutting/Labelling</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Lathing</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Sheet metal works</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>Welding</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Express cell</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>~15%</td>
<td>~85%</td>
</tr>
</tbody>
</table>
The grey hair scale is created according to the same principle as in table 4-1 and 4-4, on a scale from one to four, four shows the highest level of difficulty and stress connected to the task and one the lowest level. It is found, that the table is consistent with the technological complexity of the machine tools in the different department. For example a mean of 3.25 on the grey hair scale for the milling work group makes sense, since that is the most advanced technology available at BOSCH Crailsheim job shop production. Also ranked highly with a mean of 4 is the pump manufacturing work group. In there the pumps that help conveying the liquid pharmaceutics are grinded and honed to their tolerances. The workshop is very small with only five different machines and the technological level is not comparable to high-end milling processes. The high grey hair ranking occurs due to the lack of competence regarding the maintenance of these machines. Therefore the subjective complexity of this area is ranked higher, than the technological level justifies. Two key points have to be deduced from this situation.

- Increase of maintenance knowledge for equipment in the pump manufacturing work group necessary
- Future maintenance concept has to prevent this kind of knowledge loss

All the facts described in this chapter are the summary of all relevant results of the work group based activity distribution analysis. The detailed results of the analysis can be found in the appendix.
4.1.3 Interviews with production leaders

As mentioned in chapter 3.1.3 “Interview process in production”, there was a questioning of the production team leaders, the head of production and his deputy. A total of eight interviews are assessing the current state of the maintenance department from the perspective of the supported work groups and their respective management. The results of these interviews will be summed up in two sections; first the responses regarding the maintenance activities and the interaction with the team will be displayed. Second, the key machine tools in the individual work groups were identified and these will be listed in the second section of this chapter. Regarding the interview process and methodology, please refer to chapter 3.1.3 “Interview process in production” in here there will purely be an introduction and interpretation of the results.
Table 4-7: Summary of results in production customer interviews with head of production and team leader regarding the maintenance department's current performance

<table>
<thead>
<tr>
<th>Results interviews in production</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Question: Negative aspects of maintenance department?</strong></td>
</tr>
<tr>
<td><strong>Frequency of answer</strong></td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

| **Question: Positive aspects of maintenance department?** |
| **Frequency of answer** | **Answer** |
| 2 | Newest employee is very active and motivated |
| 2 | Newest employee is very fast to respond |
| 2 | Executed measures are done properly |

| **Question: Which machine tools need the most maintenance in your workgroup?** |
| **Frequency of answer** | **Answer** |
| 1 | No extreme outliers (Pumps manufacturing work group) |
| 3 | New machines need external technicians more often |
| 5 | Old machines |
| 2 | Complex technologies are more error-prone |

The table 4-7 illustrates the results of the interviews with the production team leader and the head of production in a condensed form. It is important to note, that in the methodology chapter one more question is introduced, but regarding maintenance problems outside the internal maintenance department no answers came up.
Table 4-7 clearly shows that there is resentment towards the maintenance team. The reasons given are in line with the results seen before in the chapters 4.1.1, 4.1.2 and the introduction. The three most prominent errors in table 4-7 are lack of preventive maintenance, slow respond time and the ignoring of deferrable cases. During the interview process it became very clear that the maintenance department is perceived as a source of trouble for the manufacturing processes. All problems listed address structural issues, with the exception of “lack of competence” (frequency: three times) and “problems have to be solved by operators tentatively” (frequency: two times). The structural problems can be summed up as a lack prioritization, no defined communication channels and no transparency. These three points have to be addressed in the new concept of maintenance according to the interviews with the maintenance customers in production.
Table 4-8: Sum up high risk machines according to interviews in production and after reconfirming them with the production planning department

<table>
<thead>
<tr>
<th>Maschine name [text]</th>
<th>Part without internal backup [ % ]</th>
<th>Ratio of parts with no alternative [%]</th>
<th>Explanation [text]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graviermasch. Baublys</td>
<td>80%</td>
<td>80%</td>
<td>Engraving machine. Very old machine, but neccessary to engrave part identification onto flexible setup elements.</td>
</tr>
<tr>
<td>Böhringer DUS 630</td>
<td>75%</td>
<td>45%</td>
<td>Lathe. Over-sized drills for screw conveyors and spindle is a specialized tool, bottleneck for screw conveyor.</td>
</tr>
<tr>
<td>Matec 30HV</td>
<td>80%</td>
<td>40%</td>
<td>Lathe. Highly specialised manufacturing technology, high utilisation. Can partly be substituted at much higher costs internally.</td>
</tr>
<tr>
<td>MF Twin 65</td>
<td>33%</td>
<td>33%</td>
<td>Lathe. Processing technology not substitutable internally and parts considered know-how relevant.</td>
</tr>
<tr>
<td>DMC 125 FD</td>
<td>40%</td>
<td>32%</td>
<td>Milling machine with rotatable worktable, can be substituted at high cost and with much higher failure rate.</td>
</tr>
<tr>
<td>CTX 800 beta linear DMG</td>
<td>50%</td>
<td>25%</td>
<td>Lathe. Specialized equipment.</td>
</tr>
<tr>
<td>DMF 360</td>
<td>80%</td>
<td>0%</td>
<td>Milling machine. Work table over-sized for big parts. Alternative at supplier is around 300% more expensive if express manufacturing.</td>
</tr>
<tr>
<td>Honmaschine Nagel</td>
<td>80%</td>
<td>0%</td>
<td>Manual honing, low risk of breakdown because technological level is basic.</td>
</tr>
<tr>
<td>Laserbeschriftungsma.</td>
<td>50%</td>
<td>0%</td>
<td>Because of the production for the pharmaceutical industry all parts have to be traceable. This machines labels the produced parts with laser.</td>
</tr>
<tr>
<td>Kellenberger Vista</td>
<td>5%</td>
<td>0%</td>
<td>Grinding process, specialized equipment.</td>
</tr>
<tr>
<td>Kasto Vario Speed C15</td>
<td>0%</td>
<td>0%</td>
<td>Risk is high loss of capacity (70%). Alternative within BOSCH Group is available but reaction times are significantly higher, because of the transport.</td>
</tr>
</tbody>
</table>

Table 4-8 shows the listed high risk machines according to the team leaders and the production management. The results of these interviews were reconfirmed with experts from the production planning department, in order to verify the answers and make sure the gathered information was as accurate. Hereby it has to be mentioned that the statements made by the team leaders were extremely precise, which indicates the good knowledge and process competence within the production department.

Interesting is the fact that two machines in the list have labelling machines functions,
which is due to the specific requirements in the manufacturing machinery and plants for the pharmaceutical industry. Apart from this the areas of expertise with no substitutions are primarily within milling and lathing, in addition of specialized, non-conventional production methods. Here it can be seen that mainly specialized equipment and distinct machine capabilities are the reason for the lack of alternatives. The specialized equipment issue is possible to be solved by investment into specialized tools on alternative machines, if economically feasible. The non-substitutability regarding the machine capabilities is more difficult to address, because here investments in new machine tools would be necessary. A step that would cost between half a million Euro and more than a million Euro in each of the cases above and is therefore not justifiable from the cost perspective. For the non-conventional manufacturing processes it is central to comprehend their importance within the production. In the past these areas have been neglected by the maintenance department, but the analysis of the interviews illustrates their relevance within the production context. Here it will be necessary to adjust the current maintenance system, so these sections get all the required attention regularly. Another important lesson from the interviews is that it will not be possible to focus on one or two specific work groups with the maintenance activities, a broader scheme is needed. Nevertheless it is displayed clearly, that the milling and lathing work groups are the teams that will require the most attention, since they have the highest number of important machine tools. Therefore it is concluded that the new maintenance system requires a well-balanced approach, allowing for flexible activities in the different workgroups, while at the same time having a much better prioritization of the scheduled tasks. Furthermore it indicates the need for investment protection, since specialized manufacturing methods require high investments. Consequently the maintenance activities have to protect the capital bound into this distinct equipment and additionally avoid expensive replacement costs.
4.2 Outcome of machine tools risk analysis for the operational performance

In the risk analysis it is important to emphasise that it focuses specifically on operational performance. This means the risk analysis is essentially evaluating the contribution of a machine tool to the system reliability. Therefore the system developed from this analysis is a reliability-centred approach. The risk ranking in the following table 4-9 is a central element of RCM (reliability-centred maintenance), conclusively it has to be done with great care and be reconfirmed within the organisation. For the risk analyses in this project first the production team leaders and then the production planning department’s experts were questioned in two loops. The final results of this investigation were then confirmed by the head of production and its deputy. Therefore it is expected that the risk assessment of the machine tools impact on operational performance in case of a breakdown is accurate. This is of primary importance, according to the literature review chapter 2.3.4 and the methodology chapter 3.2 where the risk analysis is described more explicitly and identified as a key factor for the success of a RCM system.
Table 4-9: A and B category of ABC risk analysis for performance risk regarding the impact on the overall system reliability

<table>
<thead>
<tr>
<th>Machine name</th>
<th>Manufacturing process performed</th>
<th>Parts with no internal alternative [%]</th>
<th>Parts with no int./ext. alternative [%]</th>
<th>Bottleneck factor 2016 [1-6,4]</th>
<th>Category [A;B;C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hochregallager</td>
<td>Autom. storage</td>
<td>100%</td>
<td>100%</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>Graviemsch. Bauklys</td>
<td>Engraving</td>
<td>80%</td>
<td>80%</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>Matec 30HV</td>
<td>Milling</td>
<td>80%</td>
<td>40%</td>
<td>0.5</td>
<td>A</td>
</tr>
<tr>
<td>Böhringer DUS 630</td>
<td>Lathing</td>
<td>75%</td>
<td>45%</td>
<td>3.2</td>
<td>A</td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Lathing</td>
<td>50%</td>
<td>25%</td>
<td>1.8</td>
<td>A</td>
</tr>
<tr>
<td>DMC 125 FD</td>
<td>Milling</td>
<td>40%</td>
<td>32%</td>
<td>5.8</td>
<td>A-1</td>
</tr>
<tr>
<td>MF Twin 65</td>
<td>Lathing</td>
<td>33%</td>
<td>33%</td>
<td>5.2</td>
<td>A-1</td>
</tr>
<tr>
<td>Galvanik</td>
<td>Galvanising</td>
<td>100%</td>
<td>0%</td>
<td>1.9</td>
<td>B</td>
</tr>
<tr>
<td>Strömungsschleifen</td>
<td>Grinding</td>
<td>100%</td>
<td>0%</td>
<td>1.1</td>
<td>B</td>
</tr>
<tr>
<td>Elektropolieranlage</td>
<td>Polishing</td>
<td>90%</td>
<td>0%</td>
<td>3.5</td>
<td>B</td>
</tr>
<tr>
<td>DMF 360</td>
<td>Milling</td>
<td>80%</td>
<td>0%</td>
<td>3.2</td>
<td>B</td>
</tr>
<tr>
<td>Honmaschine Nagel</td>
<td>Honing</td>
<td>80%</td>
<td>0%</td>
<td>2.5</td>
<td>B</td>
</tr>
<tr>
<td>Laserbeschriftsmas.</td>
<td>Laserlabelling</td>
<td>50%</td>
<td>0%</td>
<td>1</td>
<td>B</td>
</tr>
<tr>
<td>Kellenberger Vista</td>
<td>Grinding</td>
<td>5%</td>
<td>0%</td>
<td>2.2</td>
<td>B</td>
</tr>
<tr>
<td>DMC 60/2</td>
<td>Milling</td>
<td>0%</td>
<td>0%</td>
<td>6.4</td>
<td>C-1</td>
</tr>
<tr>
<td>DMC 60/3</td>
<td>Milling</td>
<td>0%</td>
<td>0%</td>
<td>6.1</td>
<td>C-1</td>
</tr>
<tr>
<td>DMC 60/1</td>
<td>Milling</td>
<td>0%</td>
<td>0%</td>
<td>5.9</td>
<td>C-1</td>
</tr>
<tr>
<td>Kellenberger Vista</td>
<td>Grinding</td>
<td>0%</td>
<td>0%</td>
<td>5.7</td>
<td>C-1</td>
</tr>
<tr>
<td>Kasto Vario Speed C15</td>
<td>Sawing</td>
<td>0%</td>
<td>0%</td>
<td>1</td>
<td>B</td>
</tr>
</tbody>
</table>

In table 4-9 the risk categories A and B of the ABC risk analysis are displayed. The analysis is focused on the risk added to the system performance by a specific machine. In the first column one can find the German machine name and in the second the manufacturing process this machine is performing is listed.

Column three to five are explained in methodology chapter 3.2 explicitly. The third and fourth columns refer to the substitutability of the machine by other machines and the ratio is how many parts in percent do not have an alternative internally or externally. The fifth column, bottleneck factor, is the average of how many days of immediate orders the system wanted to distribute to the machine on each day. For example a bottleneck factor of five means that if a machine can produce 6 orders a day the system in average wanted to place 30 orders per day on the machine. Therefore the bottleneck factor is five because there is five times as many critical
orders as there is capacity. The bottleneck is the parameter for the utilization of the individual machines, the higher the utilization the higher the risk for the system reliability. According to the production planning department at BOSCH Crailsheim the critical threshold hereby is five or higher.

The last column is the risk category allocated to the machine tool regarding its impact on the productions reliability. In short, the determining factor is the substitutability, “A” if the parts cannot be produced anywhere else internally or externally and “B” if there is only no alternative in-house. In case the bottleneck factor is five or above, the risk category is upgraded by one. In the table 4-9 this is indicated by an arrow, for example “C -> B”, showing the previous and the new, upgraded category. In the table risk class “C” is excluded, because the primary focus of the analysis is to identify the high leverage machine tools and use specialised maintenance activities on them in order to improve the reliability of the system. The full table of results, including category “C”, can be found in the appendix.

In the risk assessment the central goal is to provide a highly accurate evaluation of the risk, as explained in chapter 2.3.4. Nevertheless there is additional information required for the interpretation of the analysis in table 4-9.

a) **Technological level** - The high-bay raw material storage, the engraving machine and the manual honing are high risk assets, but their low technological level makes them maintenance friendly and therefore the focus is on paying attention to changes and the lowering the response time in occurrence of failure.

b) **Milling work group** - Milling is the largest work group within the job shop production and it is also most relevant in terms of reliability management.

c) **Low bottleneck factor** - For some machines the bottleneck factors are one or close to one. That means the machine was in average able to fulfil all time critical orders placed on it daily. There is two reasons, first the machine is not separately planned and works on a pull principle or the machine is not subject to many time critical orders compared to its capacities and therefore not a bottleneck in the current production system.
d) **Overall variation of bottleneck factor** - The strong variations in the bottleneck factor in between the different machine tools in the same work group indicate that there is a significant over dimensioning of certain machine tools. A good example is the lathe CTX 800 beta linear, this lathe has a 1.8 bottleneck factor, while other lathes have a three times that value. Another example is the grinding tool called “Strömungsschleifen”, with a bottleneck factor of 1.1. The machine is over dimensioned, but it is in the smallest size available, and the outsourcing of the specialised process was too time intense to be feasible.

In the analysis there are 43 machine tools investigated. In table 4-9 it can be seen that overall there are seven risk “A” machine tools, which is around 15% of all machine tools. In addition twelve category “B” assets exist, roughly 25% of all equipment examined. In total “A” and “B” account for 40% of the equipment, this is considered a well-balanced distribution.
4.3 Structural changes in the maintenance department

This chapter describes the structural changes that took place in the thesis project. Not all improvement introduced can be categorized as either preventive or corrective. In addition to these two categories structural changes have to be implemented to introduce reliability-centred maintenance successful. Three of this improvement will be presented in one of the following subchapters; they enable an in-depth understanding of the structural changes needed.

4.3.1 Scheduling with time slots

The intention behind scheduling with time slots was to address the structural problems that were uncovered in the analysis of the current maintenance activities, in chapter 4.1. The main issues are the lack of preventive maintenance and the ignoring of deferrable corrective cases. The root cause is the bad prioritisation in the maintenance department, which leads to a considerable loss of transparency and to increasing frustration in production and maintenance department. This was proofed in the interviews in production, presented in chapter 4.1.3. And the in evaluation of the activity and work group based effort distribution in subchapters 4.1.1 and 4.1.2. In order to address the unsatisfying prioritisation processes a scheduling system that already empowers a defined distribution of the working time (=prioritisation) was developed. The advantage of that system is that it provides clarity within the maintenance department regarding the ideal distribution of time. At the same time it equips the production department with a clear understanding of how the maintenance system functions. This will facilitate constructive co-operation, because now the system is responsible for the work time distribution in maintenance. This removes personal critique that flourishes when the personnel has to prioritize its tasks spontaneously and by themselves. The other achievement of the new scheduling is that it avoids miscommunications, because the times are repetitive and therefore they will not interrupt the production flow unexpectedly anymore.
In figure 4-1 it is illustrated how the maintenance activities will be scheduled in the future. The advantage of the timetable is the simplistic approach, focusing on the most elemental tasks. The time slots introduced are not there to make hard cuts through the day, but to give a basic structure and a clear time frame for the individual areas, which leads to better transparency and better prioritisation.

The first time slot of the day, in figure 4-1, is an “open time” slot accounting for one hour and 45 minutes. This time is dedicated to address backlog activities that couldn’t be finished on the last day and gives room to the work with documentation and other
minor tasks. Another reason for this very long open starting period is that the maintenance department at BOSCH Crailsheim is working in one shift, while the production is working in a two shift system, with CNC programmes running in the night. This can lead to issues with the availability of maintenance personnel during the late shift, therefore the maintenance personnel needs to have a save time slot in the morning to work with cases like that. Because if there is no reserved period failures during the late shift will immediately make the following day stressful and frustrating for maintenance and production personnel. Since the scenario is likely to happen on regular basis, it is easy to plan a time slot that leaves room for that in the morning.

The second time slot is dedicated to the work with the newly introduced ticket system for deferrable corrective maintenance cases. The ticket system is explained in a specific chapter in this result section. This slot was introduced because it was absolutely necessary to stop the escalation of deferrable problems into breakdowns. The well trained operators are able to recognize problems early on, this ticket system leverages on these skillsets and provides the production with a direct control over two hours of maintenance activities every day. Within this time slot there is also a regular meeting with the head of production that will rank the tickets and ensure that the tickets are processed.

The third time slot is another "open time" period, the reason the system is structured is to allow the maintenance department to be flexible. Maintenance has a high degree of uncertainty therefore it is important to leave room for unexpected cases. This time slot serves that purpose, it gives the maintenance personnel the possibility to use more time for the adjacent activities or address upcoming small tasks immediately without delaying them unnecessarily.

The fourth and final slot addresses all preventive measures, in the past these were neglected and reserving a specific time for these tasks every day will contribute to the re-establishing of these crucial activities. In figure 4-1 it is displayed that each day one department is focused upon, in the past the maintenance department had troubles getting down time at the important machines because of the express manufacturing that is required of the production, as explained in the introduction and literature review. Therefore with the new maintenance system one or two days per
work group are reserved for preventive maintenance in that department. This allows the production to have stable planning conditions and the maintenance department has clear structure to their preventive approach. The day before the actual activities take place the maintenance department will contact the production team leader and offer two to three machines that are due to preventive maintenance. Now the work group team leader can decide which machine will be most suitable and the next day the maintenance personnel will attend to that machine in the 12.30pm to 3.00pm time slot. This allows for easy communication and high transparency. The time required for the preventive measures was calculated by adding all individual machine standard activities and using the average time per day for the time slot. The concept is described in detail in the chapter regarding preventive maintenance and therefore not illustrated further in here.

4.3.2 Outsourcing of fluid management

Aside from the outsourcing of the fluid management, the regular hydraulic inspections were handed over to a service contractor. Due to the limited extent of this thesis this process will not be discussed. The reason this area was outsourced is the high safety risk and the liabilities for BOSCH in case the hydraulic inspections are neglected. And the analysis in chapter 4.1.1 clearly proofs that hydraulic inspection was currently ignored entirely.

As illustrated in the literature review chapter 2.3.2, outsourcing, if done correctly, is a strategic element for improving the cost-efficiency as well as including specialist knowledge. This section will focus on the outsourcing of the fluid management to transfer this mundane, time-consuming task onto a service contractor. This frees the internal maintenance personnel to cover other more complex tasks. As explained in the introduction run to failure was a serious issue within BOSCH Crailsheim’s production. Lubrication issues, especially lack of lubrication, were one of the more frequent causes for breakdowns.

The decision to outsource fluid management was based onto the fact that parts of it were already handled by a service contractor. Therefore a relatively simple extension of the cooperation was possible. In the old system the contractor only monitored and refilled the cooling lubricant. In the new maintenance concept the service contractor
additionally takes care of monitoring and refilling the lubrication of all the conventional machines (saws, lathes and milling machines) in the entire job shop production. The handover and testing period started in the middle of March 2017. In April 2017 the service contractor officially took over the extended tasks and the outsourcing operation is considered successful and went smooth without troubles. Important regarding the outsourcing was to install agreements that both sides were comfortable and familiar with. The relevant areas are tool provision, responsibilities for replenishing of the oil storage, working time measurements and how the clocked service would be billed towards BOSCH. The details regarding the reached agreement are not relevant for the thesis and will therefore not be illustrated in detail. The outlines are a regular time slot of one hour per week for pure checking of lubrication levels in production. And the refilling of the individual machine tools is separately captured via a system for every specific machine and invoiced every other week. This means it will be possible in the future to monitor how much oil the different machine tools consumed.

In order to provide a clear task description for the service contractor and to document the formerly unwritten knowledge within BOSCH, all lubrication activities were captured in a lubrication documentation.

**Figure 4-2:** Lubrication documentation for a lathe at BOSCH Crailsheim displaying all relevant information
In figure 4-2 it can be seen how the lubrication documentation for the lathe “CTX beta 800 linear” looks like. In order to provide a unique identification the “Invnr.”, German abbreviation of inventory number, was added. Furthermore the “ID-Nummer” is the order the service contactor is using when working with machine tools. “Intervall” means how often that machine was lubricated in the past, it provides orientation for the personnel regarding how critical the machine was in the past. But with the individual capture of how much oil uses it will be possible to get the required information via an online portal and will not have to be extracted from experiences. The arrows in different colours show the different type of fluids as hydraulics oil, spindle cooling, lubricating oil or grease. An arrow always points to the specific point where the monitoring can be performed if that spot is located next to the refilling access, no further arrow is introduced. Is the refilling done in a different position an additional arrow will indicate that clearly. As can be seen in the central picture in figure 4-2 extra comments or explanation are included into the applicable pictures. By structuring the documentation this way it is supposed to combine all lubrication relevant information regarding a machine tool in one specific page, so it becomes clear and all information is stored in one central place.

The disadvantages that come with the outsourcing of the fluids management for BOSCH Crailsheim are:

- Loss of direct control
- Regular checking on service contractor necessary
- Increased monitoring and training effort in the beginning
- Additional costs, because no decrease of internal maintenance personnel
- Employees might react negative to outsourcing

The advantages of the solution are:

- Exact refilling data is available online on service contractors web application
- Adding external expert knowledge
- Decreased costs for the lubrication process
- Internal maintenance personnel gets freed for more complex tasks
- Stops run to failure because of lacking lubrication
o Investment protection
o Lower breakdown frequency

- Improved atmosphere because lubrication issues caused many troubles

If one compares the listed advantages and disadvantages, it becomes clear that for multiple reasons it was beneficial to outsource this area of maintenance. The cost difference for one hour of contractor work is 35€ for BOSCH, while internally a maintenance technician is calculated with around 80€. The reason for this is that maintenance personnel is well-paid within the already very generous salary structure within the BOSCH Group, that is known to be one of the top employers in Germany salary wise. Basically only the cost issue would push a decision towards outsourcing of this mundane task, but also the internal maintenance neglected lubrication activities and other preventive measures too much, as seen in the different analyses in chapter 4.1. So this outsourcing will stop part of the run to failure issues and in addition allow Bosch Crailsheim to collect high quality data regarding the machine lubrication from the service contractor’s web application.

4.3.3 Ordering process

In the activity based analysis, chapter 4.1, one of the results was that the ordering process consumed extraordinary amounts of time during a month. Therefore one of the structural changes had to be optimizing this process. In the analysis of the process it became clear that there were five major problems with the process.

- Low competence in maintenance department regarding the administrative processes and workflow
- Slow execution of administrative tasks cause little computer skills
- Lack of transparency, no possibility to see sum of department orders for single requestors.
- Arrival of good not registered due to complicated process
- Ordered spare parts are delivered in different locations, some are getting lost or forgotten
The created solutions were developed in cooperation with the maintenance team, production administrative staff and the purchasing department. This guarantees a well-functioning procedure that is feasible with adjacent process stakeholders. The listed solution that is all in-house. Nevertheless it was tried to convince DMG, the plant’s main machine tool supplier to adjust its invoicing process for express spare parts. Unfortunately that was not possible, mainly because BOSCH Crailsheim is too small as a customer to justify special treatment, therefore the following internal solutions were found and implemented.

- Standardized process for ordering introduced, with clear step by step documentation to follow through.

- Introduction of a BANF, one specialized role within the production’s administrative stuff, responsible for the ordering requests of all non-administrative teams. This is a concept already established in other BOSCH facilities and therefore it was decided to benchmark the BANF solution.

- “Ready to attach” templates for all additional documentation.

- Centralised folder for all ordering documents, plus introduction of standard shortcut links to reach that folder by configuring the laptops of the maintenance department.

- Introduction of a team-based order process that allows team members to view each other’s orders.

- If working with deferrable cases (all deferrable cases are part of the new ticket system as explained in chapter 4.4.1), order date has to be remarked on the ticket in order to identify slowing processes or lost orders right away in the future.

- Central, standardized delivery spot for all spare parts and service technicians ordered by the maintenance department.

The effects in the order process that were triggered by these changes are an massive decrease of time spent with the ordering spare parts or service technicians. Because all the maintenance department has to do in the future, is to contact the technical service of the machine tools OEM. The BANF role in the administrative overhead takes care of ordering the offer the OEM has sent. Since all the additional documentation has been updated to a “ready to attach” state, the maintenance
department no longer has to take care of this task either. To validate the changes time measurements were taken and the BANF person from the administrative staff took 12 minutes to finish one order with one item, while the responsible maintenance personal took between 35 and 40 minutes for a task of the exactly same scale. The work with orders was most unpopular according to the grey hair scale introduced in chapter 4.1.1. In the light of the threefold time consumption these tasks took it is understandable why the ordering of spare parts was so unpopular. The combination of administrative work, lack of workflow understanding and absence of computer skill made this task three times more troublesome to the maintenance technicians than it is to administratively trained employees. Moreover the redistribution of these activities does not only safe the maintenance department frustration and unideal work load, it also saves BOSCH working hours, because in the future these tasks will consume significantly less time. Furthermore the introduction of the BANF role gives the maintenance personnel a person to turn to in case of administrative issues so that troublesome situations and lack of knowledge can be corrected in a familiar environment.

The other major improvement is the increase of transparency. With the updating of the ordering process, it becomes clear if parts are ordered and where they will be delivered. The responsibilities are clearly defined and the centralised structures (through the BANF) help to transfer required information. This will significantly reduce the stress that was identified in the first analysis, described in chapter 3.1 and 4.1, the positive outcome of these optimisations and their immediate impact were “quick win” and helped to win the maintenance personnel’s approval and support for the changes that were introduced.

In the long run the ordering process will further improve under the tutelage of a trained administrative responsible and turn this former area of weakness into a source of strength. Plus it leaves the maintenance personnel well connected with an administrative advisor and with respect to their struggles in this area that is an ideal instalment to equip the department with improved administrative and computer skills over time, by co-working closer with administrative staff.
4.4 Improving corrective maintenance

Corrective maintenance refers to all activities associated with repairing; generally there is immediate and deferrable corrective maintenance, as explained in methodology chapter 3.3. Immediate corrective maintenance is an expensive and disruptive way of solving problems, because it always occurs unplanned and interrupts maintenance and production processes with breakdowns. Therefore this chapter proofs that improving corrective maintenance is primarily about avoiding situation where machine breakdowns occur or alternatively providing a structured approach to solve them minimizing their disruptive potential.

4.4.1 Ticket system

First in this chapter, the objectives of the introduction of a ticket system are introduced, and then the structure of the system is displayed, followed by two figures to illustrate more details. Finally the subchapter is finished by a short description of the concepts implementation.

The ticket system was developed to serve multiple goals:

- Deferrable corrective maintenance tasks have to be addressed again
- Documentation of occurring errors is required
- Costumer orientation of maintenance needs improvement
- Investment protection for machine tools with low impact on system reliability
- Prioritisation has to be clear
- Process needs to be transparent
- Process needs to be simple

To achieve the goals stated above an old maintenance organisation approach was reviewed, updated and reinstated. In 2015 a ticket system was already discussed and introduced, but it did not sustain, due to structural weaknesses and the overload with tasks, as analysed in chapter 4.1.1. It was determined that each maintenance technician would have to work more than one hour of overtime every day to fulfil all the planned tasks. Therefore the ordering process was changed, tasks outsourced
and a schedule for correct time distribution was introduced. Furthermore basic steps towards normalising the workload by clear prioritisation were taken and a better focus on key reliability-relevant activities was achieved.

It was decided to implement the ticket system as a part of the “machine measures list”, that already existed and where issues with CNC programs, setup configuration or working schedules were documented and counter measures introduced. The mentioned list with measures is a concept that already works and on a daily basis the listed issues are checked at a shop floor walkthrough by the head of production, work planning, CNC programming team and the production planning. This system already works successfully and allows a quick communication between the participating teams. The idea was to include the maintenance department in some form and extend the measure list by maintenance issues. This transforms the measure list into a logbook regarding all issues an individual machine tool has, the immediate advantage is that issues can be identified easier if all information is gathered in one place. So in the newly implemented ticket system the operators fill in issues with the measure list / machine logbook and on the daily shop floor walk through the head of production or his deputy are putting all the deferrable corrective measures on tickets. As the last stop of the walk through the head of production is visiting the maintenance department at 11am and the new tickets are added to the ticket ranking and the old tickets are checked. This allows the head of production to prioritise the most relevant tickets and to check on the current state of the older tickets. As mentioned in chapter 4.3.1 “Scheduling with time slots”, the head of production has a 2 hours and 15 minutes time slot every day during which the production can directly control the maintenance department in order to work with deferrable failures. The advantage of this is that customer orientation is guaranteed, clear prioritisation is available, the responsibilities and the state of the tasks is transparent and therefore the measures are automatically easy to schedule with the respective production teams. Furthermore it adds an element of managerial control to the ticket system, because the development of the cases is monitored by the internal customers interested in the activity to be performed.

Another major advantage of the system is adding an investment protection mechanism to the reliability centred maintenance approach, because all machine
tools can write tickets to get repairs. Therefore assets which are subject to preventive maintenance less frequently due to their unimportance for the systems reliability can still write tickets if attention is required for deferrable failures. This is a conscious step to open an opportunity for older or less relevant machine tools to get maintenance whenever it is needed. Because the risk of ignoring those machines due to the extensive maintenance workload is significant and past experiences show that those machines will be ignored unless there is a structural element that adjusts the focus on them.

<table>
<thead>
<tr>
<th>Machine:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problem:</td>
</tr>
<tr>
<td>Date:</td>
</tr>
</tbody>
</table>

*Figure 4-3: Ticket for new deferrable corrective maintenance concept, final version after PDCA review process*

In the figure 4-3 the composition of a ticket for a deferrable maintenance case is displayed, these tickets are filled in during the daily shop floor walkthrough. The field “Machine” identifies the machine the error occurred at. “Problem” is a three to seven word sum up of the problem; any further details are discussed in the conversation between the head of production and the maintenance department at 11am every morning or by contacting the machine tool operators. “Comments maintenance” is the comments section for the maintenance department regarding the progress of the repair. This was introduced to increase the transparency in case anyone wants to review the ranking or progress of a ticket. “Date” refers to the day the ticket was
introduced on the ticket board, while “time required” is the expected time required for analysing, procuring and repairing to eliminate the error described on the ticket. The tickets were developed with multiple PDCA cycles and this is the final version, providing best transparency without “overfilling” the ticket.

Figure 4-4: Picture of the ticket board at BOSCH Crailsheim, show the ranking of the open tickets

Figure 4-4 shows the structure of the ticket board, as stated in the goals earlier in this chapter, the idea was to keep the design simple and intuitive. The tickets are listed according to their prioritisation from top to bottom; the comments added on the yellow background state the basic rules of use in German. These comments are flexible and can be adjusted to whatever information is deemed necessary to smooth the process further.
The implementation of the ticket system, as described in methodology chapter 3.1.1, was done by doing multiple PDCA cycles, the details of the introduction are as described in the methodology section and will not be introduced in here another time. Nevertheless it should be stated that the instalment of a ticket system requires at least three cycles of PDCA and extensive communication with all stakeholders. Thereby, it is necessary to explain the importance of writing precise entries in the logbook. The results presented are the final outcome of the PCAA cycles.

Once the tickets are done, the maintenance department updates the logbook of the machine since they are at the machine in that moment already to do the necessary repairs. This allows the logbook to identify failure, but also document the activities to solve them. In the long run this will proof the efficiency of measures taken and give opportunity to fine-tune the execution of repairs.

4.4.2 Escalation scheme

The escalation scheme was required, because there were issues in the communication between the production and the maintenance department. The problems were established in the analyses in chapter 4.1 and were especially clear in subchapter 4.1.3 in which the production team leader criticized the current communication channels sharply. Similar remarks were found when speaking with the maintenance department. In essence, four problems could be found:

- Operators walk to maintenance personnel and ask them to repair things (problem: many people ask at the same time, constant interruption)
- Agreements are not possible, because maintenance prioritisation might change suddenly and without further notice (i.e. machine breakdown)
- No transparency for tasks priorities or progress (problem: no clear communication channels established and production personnel is unfamiliar with maintenance processes)
- Slow response times (problem: no clear communication rules)

The escalation scheme found below aims to address the issues listed in here by providing clear communication rules, communication channels, defined responsibilities and therefore prioritisation.
In the figure 4-5 it can be seen that corrective, immediate cases are escalated to the team leader, which is responsible for contacting the maintenance department via phone. This guarantees, on the one hand, that the maintenance department is not overloaded with everyone asking to help. On the other hand, contact via phone assures that the maintenance department is available at any given time. If the maintenance department is bound to a task, the head of department is contacted and the tasks are compared and prioritised by the manager. For the yellow cases, indicating corrective deferrable situations, the ticket system is used as a mean of escalation. Hereby, the logbook allows the operators to document their cases, the head of production is responsible for prioritising, for details see chapter 4.4.1.

The green boxes in figure 4-5 display problems with preventive maintenance topics, they are escalated to the team leaders and solved during the weekly preventive maintenance, as described in chapter 4.5.1. If this solution fails the next escalation level is to create a ticket for the problem. Then the ticket is noted in the logbook and prioritised by the head of production in the regular ticket processing.

The introduced scheme is meant to escalate quickly, which is done because the job shop production has the advantage of being comparatively small for industrial
manufacturing and therefore it is easier to involve the management. The easy communication structures are an advantage for any small production and the maintenance gets oriented this way in order to leverage these benefits, while the clear structure avoids creating a loss of transparency by under hand agreements or favouritism.

4.4.3 Service technicians access via internet

The reason to have service technicians access the machines via internet is that it allows for a much cheaper handling of software or electronic related issues. Ordering a service technicians from the OEM costs BOSCH Crailsheim between 1200€ and 2000€ every time. The access from the Internet costs 300 € per year, plus the time spent on working with the machine. This means that the cost saving effect is immediate. Another reason for maintenance activities via internet is the improved response time. Instead of having a minimum delay of 1-2 days, the online access offers a maximum response time of less than three hours. BOSCH Crailsheim in average has two to five service technicians per month coming in. If only 20% of all cases can be solved online in the future, it will provide a significant increase in productive availability and decrease in maintenance costs. For the introduction of remote servicing, three measures had to be taken:

- **Original equipment manufacturer (= service provider)**
  OEM signed disclosure agreements and proof that internal data security standards are up to date and provide sufficient protection for the BOSCH production network.

- **BOSCH IT**
  Purchasing infrastructure for additional service network in production and configuration of this service network

- **Firewall and VPN Channel**
  A specific VPN Channel was created in order to allow the OEM safe access to the highly protected BOSCH production network.

The final equipment will arrive in May 2017, therefore the measures will be finished right after the end of the project period at BOSCH Crailsheim, and the responsibility went to the process engineer in the production department.
4.5 Periodic preventive maintenance to individual machine fingerprints

In the introduction and the analysis in 4.1 it was displayed that preventive maintenance activities are widely abandoned at BOSCH Crailsheim, it has been established that less than 20% of the preventive tasks are currently done. In chapter 4.3 structural changes aiming to improve the overall performance of the maintenance department are illustrated. In this chapter further details regarding the preventive strategy are explained. The general idea is to transform the periodic maintenance into individual machine tool activities that are based on analysis of historical and monitoring of current condition. The overall concept is to move from pure periodic preventive measures to condition-based maintenance in the future, as described in the literature review chapters 2.3.1 and 2.3.2.

Below one can see the different measures as an overview, hereby the different colours indicate in which one of the three chapters the details can be found.

*Table 4-10: Overview of preventive maintenance measures introduced according to risk category, colour marks their respective subchapter*

<table>
<thead>
<tr>
<th>Risk category</th>
<th>Machine standards</th>
<th>Communication for Condition monitoring</th>
<th>Logbook &amp; Data analysis</th>
<th>Qualification improvement operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Extensive</td>
<td>Every other week</td>
<td>Intensive search for failure modes</td>
<td>High priority</td>
</tr>
<tr>
<td>B</td>
<td>Upgraded</td>
<td>Once a month</td>
<td>Strong search for failure modes</td>
<td>Medium priority</td>
</tr>
<tr>
<td>C</td>
<td>Regular</td>
<td>Every other month</td>
<td>Regular search for failure modes</td>
<td>If in line with other goals</td>
</tr>
</tbody>
</table>
Table 4-10 displays the different measures introduced in the preventive maintenance. It can be seen that there is a different approach to each of the risk categories. The reason is that machine tools with a heavy impact on the system reliability have to be monitored more carefully. The table indicates the levels that have been introduced for and the colours mark which chapter explains the measures. Blue indicates section 4.5.1, yellow section 4.5.2 and green is section 4.5.3. The measures will be described in the respective chapters and therefore no further explanation is given here.

4.5.1 Individual machine tool standards

As a job shop production the BOSCH Crailsheim has very diverse machine tools in order to have high flexibility and a wide range of products. Consequently this leads to different measures for the single machine tools and manufacturing technologies. For a maintenance system it is essential to adjust to the diversity of equipment with diverse maintenance activities.

That logic lead to introducing individual machine tool measures in the past, currently the problem is that the approach has not changed in the last seven years, despite new technologies and drastically changing requirements towards the internal production. Therefore it was necessary to develop the not working current system and bring it back to a functional and future-orientated state. The old measures were derived from maintenance personnel experience and the OEM’s maintenance recommendations. In the future this data will be enhanced by the data provided by the logbook and other data that will be analysed, hereby the target is to start introducing life-monitoring of the machine tools. But before implementation of life condition monitoring is possible the organisation of the maintenance department has to be taken to a stage where it is able to handle this type of approach. Therefore the introduction of “fingerprints” for the machine tools is the positioning for the future step towards condition-based maintenance. This policy was also discussed in the literature review regarding CBM in chapter 2.3.2.

Below the maintenance plan for one of the lathes is displayed, because the size is too small for details it is attached in the appendix in full page size.
Table 4-11: Machine standard maintenance activities for lathe “CTX 800 linear”

<table>
<thead>
<tr>
<th>Machine</th>
<th>Task</th>
<th>Duration</th>
<th>Turnuszeiten</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTX 800 beta linear</td>
<td>Späneförderer Vorkammerfilter kontrollieren, ggf wechseln</td>
<td>15 KW1</td>
<td>1. Quartal</td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Hauptspindelfilter reinigen</td>
<td>10 Januar</td>
<td>2. Quartal</td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Schaltschrankfilter reinigen / wechseln</td>
<td>10 Januar</td>
<td>3. Quartal</td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Maschinenabdeckung/Spanneinrichtung reinigen</td>
<td>25 1. Quartal</td>
<td>4. Quartal</td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Führungsbahnen reinigen und prüfen</td>
<td>70 1. Halbjahr</td>
<td>2. Halbjahr</td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Hauptspindel kontrollieren X- / Z-Achse kontrollieren</td>
<td>70 1. Halbjahr</td>
<td>2. Halbjahr</td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Werkzeugrevolver Schmierstoff-Ventil kontrollieren</td>
<td>70 1. Halbjahr</td>
<td>2. Halbjahr</td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Backenfutter reinigen</td>
<td>45 1. Halbjahr</td>
<td>2. Halbjahr</td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Filter prüfen ggf. wechseln</td>
<td>20 1. Halbjahr</td>
<td>2. Halbjahr</td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Maschinenfähigkeitsuntersuchung</td>
<td>15 1. Halbjahr</td>
<td>2. Halbjahr</td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Abstreifer tauschen</td>
<td>160 Jährlich</td>
<td></td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Automatische Arbeitsraumtüre prüfen ggf. Zahnriemenwechsel</td>
<td>160 Jährlich</td>
<td></td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Druck prüfen und evtl. auffüllen</td>
<td>160 Jährlich</td>
<td></td>
</tr>
<tr>
<td>CTX 800 beta linear</td>
<td>Öl- und Filterwechsel Hydraulikanlage</td>
<td>160 Jährlich</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-11 displays the miniature version of the maintenance activities necessary for the lathe “CTX 800 linear”, the first column gives the machine name, the second is describing the machine specific tasks to be done and the third column is stating the time that is needed to complete the activity. What follows is the cycle necessary for the preventive activity to be most impactful, the maintenance personnel marks the boxes once the task is completed for the cycle. There is an entirely individual plan for each of the machine tools listing the necessary actions; the plans were updated in this project to match the current state as good as possible without the availability of historical data on equipment failure.

In addition to these updated activity plans, the new system also introduces regular communication with the operators, because these highly skilled workers provide significant insight into the condition of the machine. Hereby the visiting periods are; risk category A - every other week, category B machines - once a month and risk level C - every other month. This communication serves two purposes:

- **Knowledge** creation, by regularly combining operational and maintenance expertise.
- Introduction to **condition monitoring**, where the “sensor” is the operator that is interacting daily with the machine.

Another important aspect of the work with the new planned preventive maintenance is that the prioritisation of the tasks is done according to their risk level and in
cooperation with the production teams. As already mentioned in the result chapter 4.3 on structural changes within the scheduling concept the production teams have one fixed weekday (i.e. Tuesday) for the preventive maintenance. The reasoning and details are explained in 4.3.1 and therefore it will not be repeated in here, basically it is supposed to implement an automatic prioritization by time slot and to smooth communication and planning issues.

In this system the maintenance representative offers the team leader two to three machines that can be worked with one day before the scheduled preventive maintenance; this allows the team leader to pick the most convenient machine in terms of planning and personnel.

The total of these changes allows better monitoring and service on the machines, while keeping a close focus on the reliability of the system by including risk categories into the scheduling.
4.5.2 Logbook, data collection and analysis

This chapter illustrates how data is collected in the newly introduced system and how these data is processes and analysed.

Logbook

The goals of the logbook are all focused on reliable documentation of errors for each of the machine tool, therefore each machine has a separate logbook. The aim of the logbook is as follows:

- Document all failures
- Document all activities/measures to correct failures
- Deliver basis for the introduction of performance indicators in maintenance

The structure of the logbook, literally called “open measure list production” is displayed and explained below.

![Image](image.png)

Figure 4-6: "Open measures list production", original version, translated explanation below

Figure 4-6 shows the lost for open measures used at each of the machine tools. A full version of the “open measures list production” is found in the appendix. The three relevant columns for the purposes of maintenance are column two, where the operators insert a description of the problem or maintenance activity he has taken.
In the next column he picks what type of measure is/was required for maintenance one can choose between three options:

- Deferrable failure repair
- Machine breakdown
- Operator maintenance

The last relevant column is located forth from left, here the maintenance personnel is documenting the measures taken in order to solve the problem, this is a crucial element of the logbook, because it enables to analyse which measures were effective when looking at historical data.

**Data fluid management**

By outsourcing the fluid management BOSCH Crailsheim now has the option to get an exact documentation on how much oil and cooling lubricants were refilled on the individual machine tools. Obviously it is beneficial to utilise this for the analysis of maintenance patterns and improvements. The guiding aspect of the analysis is the logbook and the data regarding the fluid management is used as an additional information to identify issues or in order to access more information regarding a failure mode recognized in the analysis of the logbook.

Another bonus of the cooperation with the service contractor on the oil and grease refilling is that it is possible to purchase oil analyses in the company’s laboratories. If a failure setting transpires the analytical possibilities of BOSCH Crailsheim, using the contractor’s expertise is an attractive option in order to understand oil-related failure mode better.

**Geometrical data on machine tools**

The geometrical analysis of machine tools is a concept introduced into the production for more than two years already, it is used to monitor the condition in half year cycles, in case of unsatisfying values the machine, possible repairs are discussed. This means there is data available, but currently it is not used in the best possible
way. In the new concept the old comparison process will still be done separately, but the data will also be used in the general analysis of failure modes, to enhance the data provided. Thereby the data is used as a compliment to the logbook data, so that in case failure modes are detected the geometrical state of the machine can be considered as a possible root cause of occurring production problems.

Analysis process of the inquired data

The goals of the analysis are:

- Monitoring the maintenance activities
- Improve the range of maintenance activities and knowledge
- Use operator presence and experience to develop additional measures
- Better transparency and understanding how the individual machine tools are performing

In order to achieve this a process was developed that takes into account all failures documented and then aims to narrow the list down to critical issues and failure modes.

<table>
<thead>
<tr>
<th>First half of the year</th>
<th>Second half of the year</th>
<th>Targeted work group in job shop production</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>July</td>
<td>Galvanizing, pump manufacturing</td>
</tr>
<tr>
<td>February</td>
<td>August</td>
<td>Sawing</td>
</tr>
<tr>
<td>March</td>
<td>September</td>
<td>Milling – machine tools risk category A + C</td>
</tr>
<tr>
<td>April</td>
<td>October</td>
<td>Milling – machine tools risk category B</td>
</tr>
<tr>
<td>May</td>
<td>November</td>
<td>Lathing</td>
</tr>
<tr>
<td>June</td>
<td></td>
<td>Others</td>
</tr>
</tbody>
</table>

Figure 4-7: Schedule for logbook and failure review cycles through the year

In figure 4-7 the schedule for doing the regular failure analysis is displayed, the concept is to spread the numbers evenly, but at the same time it is necessary to keep the different work groups as bundled as possible. Because that allows to find failure
patterns within one type of machines much easier and requires less rethinking within the cycle. The details regarding the schedule are not explained in this thesis because the different dates are not relevant from the scientific perspective. To be mentioned is only that the schedule repeats every half year, this cycle time is the most appropriate one because it balances out amount of information to process and adequate sample size. Furthermore December was left out in the schedule, because it is the month with the heaviest workload and the group of machines that is looked at in this month is not critical and does produce the smallest amount of failure.

Figure 4-8: Process overview of the failure mode analysis introduced to identify potential improvements in preventive maintenance

In the figure 4-8 three different steps are displayed in the explanation these steps will be highlighted in the same order. In figure 4-8 it can be seen that the first step is called “preparation” this process is started by the production’s process engineer. The engineer is responsible to deliver the data of the logbook to the maintenance department. Because the review of the listed machine tools repairs and problems is started there. The goal for the maintenance experts is to find interconnections between failures and develop the first ideas on how to deal with these in the future. In the second step there is an official meeting between the production’s process engineering here the possible interconnections of failures are discussed and documented within the system. After this the measures of correction are debated and
there implementation outlines are defined. In order to prepare this meeting it is the process engineer’s responsibility to review the failure modes found in the last meeting regarding the machine tools and to provide an access to the information regarding oil refilling and geometrical data during the meeting. Hereby it is important that additional attention is paid to the risk category A and B equipment, in order to secure its proper function. The final and third step in figure 4-8 is a meeting between maintenance experts, production teams, which is hosted by the process engineer. Here the planned measures for the failure correction are introduced and fine-tuned with the production. The agreed measures are scheduled and implemented in the machine tool standard maintenance plan.

The displayed process allows the effective identification of occurring failure modes for machine tools as well as on a work group basis. Furthermore it targets the established issues and offers a clear strategy to target them.

Table 4-12: Parameters for analysis of failure root causes and identification of counter measures, coded by colour

<table>
<thead>
<tr>
<th>Analysis parameter</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>Verifying frequency and time frame</td>
</tr>
<tr>
<td>Machine name</td>
<td>Machine tool identification</td>
</tr>
<tr>
<td>Failure description</td>
<td>8-10 Word description of failure</td>
</tr>
<tr>
<td>Measure taken</td>
<td>8-10 Word description of corrective measure</td>
</tr>
<tr>
<td>Sum of failure on the machine tool in the last 6 months</td>
<td>Identifies machine tools with high failure frequency</td>
</tr>
<tr>
<td>Same failure multiple times</td>
<td>Gives ID tag to failure that happened multiple times, for quick identification</td>
</tr>
<tr>
<td>Root cause in one word</td>
<td>Key word for quick categorisation</td>
</tr>
<tr>
<td>Root cause, long description</td>
<td>Quality description of the reason for the multiple occurrence</td>
</tr>
<tr>
<td>Different failure, but possibly same root cause</td>
<td>If interconnection between failures is suspected</td>
</tr>
<tr>
<td>Suspected root cause</td>
<td>Theory on root cause, open field to inspire the use of acquired expertise</td>
</tr>
<tr>
<td>Measure to target root cause</td>
<td>Measure to target root causes identified in the previous analysis</td>
</tr>
</tbody>
</table>

Table 4-12 shows the parameters that are used to analyse the occurred failures on a machine tool and to identify and target their root causes. Hereby it is important to
mention that only errors that occurred multiple times are targeted in this analysis, simply to maximise the effectiveness of the process, instead of spending time on preventing irrelevant failures. This analysis is done in the first two of the three steps introduced earlier in this chapter in the process overview in figure 4-8. In the table above there are 5 different sections marked by different colours, since the parameters are described within the table 4-12 only the categories will be explained further here.

The grey category is the documentation that was written in the logbook and provides the basis for this analysis. The blue category is the sum of failures that occurred on the individual machine tool in the period under observation. The red analysis indicates the errors that occurred multiple times or were written down multiple times, mainly there is two reasons for that, very slow progress by the maintenance department or a high frequency of failure. In either case the root cause has to be identified. The yellow category gives room to connect failures that are suspected to have the same root cause, here guesses by the maintenance experts are encouraged. The green and final category is were measures to address and correct the root causes are documented.

4.5.3 Improvement of qualifications to compliment production’s diversity

A key element of a job shop production is the diversity in the machine tools used, as described in the literature review, chapter 2.1. In terms of maintenance this leads to the problem that a fairly small number of machines use very diverse manufacturing technologies and it is hard to provide expertise support across all equipment. At the same time the technological level of machine tools is rising, leading to increasingly complex software and electronic applications the maintenance department has to deal with on regular basis. Therefore the maintenance department at BOSCH Crailsheim has lack of software knowledge regarding the increasing number and diversity of machine tools in the production. It will not be possible to overcome this lack of expertise by training the maintenance department alone, because this multitude of machines and technologies does not allow for that. Therefore it was decided to involve the operators into the creation of knowledge.
This has two advantages:

- Relief of maintenance department
- Improved qualification of operators with software issues will increase their expertise on their machines

The increase of expertise is very much in line with the job shop production characteristics and improves the possibilities and productivity of the system.

In order to improve the software expertise training is required, hereby two strategic elements were defined.

- **Formal training**
  Formal training targets the operators and is done in cooperation with the machine tool’s OEM. Since every machine can be operated by at least 4 people these people are consequently trained to solve minor software issues by themselves or alternatively identify the failure.
  - **Risk category A**: Training has high priority
  - **Risk category B**: Training is done when production schedule favours it
  - **Risk category C**: Training is only done when in line with other goals

- **Informal training**
  Accompanying of service technicians when they are called to solve cases related to software problems. The degree of attention paid to the work of the service technician depends on the risk category the machine is in.
  - **Risk category A**: 50% of the time is spend at the machine tool to monitor the problem solving closely
  - **Risk category B**: Multiple visits at machine tool during the repair to understand and witness the problem solving
  - **Risk category C**: Asking for detailed explanation of the problem solving strategy when it is finished and before final report is handed in
4.6 Summary of results

This section will give a short overview about the most relevant results, that will be referred to in the discussion chapter.

The results can be split into two different parts:

a) **Analysis** of risk for system performance, maintenance activities and time distributions, section 4.1 and 4.2.

b) **Changes implemented** to the maintenance system, section 4.3 to 4.5.

4.6.1 Analysis section of results

The analysis section can be split into two different parts, chapter 4.1 describes the analysis of the current maintenance activities and chapter 4.2 the risk analysis conducted.

In the analysis of current maintenance activities three major outcomes can be identified:

- The **production goals** are not clearly defined, and therefore do not impact the maintenance work
- High amount of **hidden buffers**, that make it hard to measure maintenance performance
- Lack of **control** executed by the management

These results indicate that it is necessary to create an improved maintenance system. It is needed to have clear maintenance goals given by the production department’s leadership. There have to be performance measures that are not influenced by the hidden buffers and the improved maintenance concept has to establish clear responsibilities and control.
The second part of the analysis section is the risk analysis. The parameters found below allow calculating the expected impact on the system reliability by the individual machine tools.

**Parameters:**
- Internal substitutability
- External substitutability
- Utilisation

Figure 4-9: Summary parameters in the ABC-Analysis

The parameters in figure 4-9 were taken into account when displaying a machine tools impact on the system reliability. The substitutability parameters hereby indicate the ability to express manufacturer and the overall impact on the productivity of the system. These two goals were defined as the central production goals. The utilization of a machine shows the impact a machine has on the overall workload in the production system.
4.6.2 Implemented changes to maintenance system

In the following graphic the three main areas of change and the most important elements of these improvements are highlighted.

<table>
<thead>
<tr>
<th>Corrective maintenance</th>
<th>Preventive maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Ticket system</td>
<td>• Fingerprints for individual machine tools</td>
</tr>
<tr>
<td>• Escalation scheme</td>
<td>• Condition-based maintenance</td>
</tr>
<tr>
<td>• Logbook for failures</td>
<td></td>
</tr>
</tbody>
</table>

**Organisational structure**
- Schedule with fixed time slots
- Simplifying or outsourcing

*Figure 4-10: Summary of changes implemented in maintenance system*

In figure 4-10 it can be seen that the implemented changes can be split into three categories. Furthermore it becomes clear that the improvements in corrective and preventive maintenance had an impact on the organisational structure of the department. The overall idea of the changes is to implement the changes introduced in chapter 4.6.1 in the summary of the analysis results.

The **organisation** is extended by a weekly schedule that has fixed time slots to guarantee a defined distribution of maintenance activities. The simplification and outsourcing serves to renew the focus on core competences.

The **preventive improvements** in figure 4-10 are all based around the vision of introducing condition-based maintenance. The individual fingerprints for each machine tool allow acquiring the necessary data and introducing the principles of condition-based maintenance step by step.

The **corrective maintenance** measures displayed in figure 4-10 are a ticket system for deferrable cases, a clear escalation scheme in case of emergencies and a logbook to document the failures on the machine tools.
5. Discussion

In this chapter the lessons learned from the project at BOSCH Crailsheim are discussed and related to the broader context of maintenance in a job shop production, to answer the third research question from the introduction chapter:

**How can the results determined at BOSCH Crailsheim be translated into other company's job shop production?**

Different approaches can lead to the improvement of a maintenance organisation (Mikler, 2015); therefore it will be possible to extent the results of this thesis with further research. The topics discussed regarding there transferability are:

- **Section 5.1** – Thorough analysing is elementary for this project. This chapter debates how the analysis conducted be adjusted to different job shop productions.
- **Section 5.2** – Identification of activities that have potential for either outsourcing or simplification. Discusses how to asses if simplification or outsourcing is more beneficial.
- **Section 5.3** – Argues how the disruptive character of breakdowns can be contained best and displays transferability of these methods.
- **Section 5.4** – Investment protection of not reliability relevant machines is a limitation of a RCM approach. This section discusses measures to counter this disadvantage.
- **Section 5.5** – Vision and advantages of the fingerprint approach. And the limitations placed on the machine standard as preventive maintenance scheme.
5.1 Analysis as a basis for maintenance improvements

The result of this thesis are proofing that the analysis is the basis for effective improvement measures. For this project analysing two aspects of the maintenance system had most impact regarding what changes were implemented:

- Time distribution
- Risk for operational performance of the system / system reliability

The correlation of time distribution and system reliability worked outstandingly well for the purpose of this thesis and was the reason to choose a reliability centred maintenance approach. The combination of time and reliability analyses was this impactful because system reliability is directly in line with the primary production goals (timely delivery and frequent express manufacturing), while time distribution is the best possible indicator for the effort distribution in the maintenance department. Therefore the following formula was developed in this thesis; it is applicable for the improvement of maintenance systems, which required renewed prioritisation:

\[
\text{Prioritisation of maintenance activities} = \frac{\text{Activity's impact on primary production goal}}{\text{Effort of maintenance activity}}
\]

The equation 5.1 illustrates that in order to identify maintenance activities that have to be prioritized the correct approach is to compare the activity's impact on the primary production goal to the effort the maintenance activity requires. The ratio is utilized to rank the tasks in the analysis. In this thesis the parameters were.

- **Activity's impact on primary production goal** - System reliability as the production's primary goal, risk for system reliability as parameter.
- **Effort of the maintenance activities** - Effort was expressed in relative time distribution.
Nevertheless these parameters are exchangeable depending on the production and maintenance state in the system. For example effort could be expressed in time or as costs, it depends on the available data and the overall situation which parameter is more ideal. Generally it is recommended to use the cost approach, because it states the effort more sophisticated and makes the results comparable easily comparable. This is also a shortcoming of the analyses in this thesis. Since there was no data on costs available, there was no possible to compare a time effort and cost effort to choose the most beneficial parameter.

Regarding the activity’s primary production goal in case of BOSCH Crailsheim it is system reliability, nevertheless this parameter is exchangeable. It could be substituted by safety as primary production goal, if the production deals with hazardous materials. Or be replaced by minimizing the amount of rework, in case the production’s first goal is to have high quality. Each of these orientations requires a very different orientation of the maintenance concept. The equation 5-1 allows modifying the prioritisation process of the maintenance activities to the respective production system and its goals.

The ability of the approach to be highly adjustable is required, because one of the key features of any job shop production is that it can serve very different goals, as was established in the table 2-1 in the literature review. Therefore it can be stated that the principle displayed in equation 5-1 is transferable onto other job shop production if the parameters are adjusted onto the goals in this specific production.
5.2 Required structural changes

From an organisational perspective the project showed that changes in the maintenance management were required to facilitate improvement. Hereby two specific areas have to be highlighted within the maintenance department:

- Time distribution
- Focus on core competences

Time distribution was addressed by the scheduling with time slots, introduced in chapter 4.3.1. Important is not the system used to distribute time, but communicating the distribution ratios. Knowing how the time should be distributed between the different general areas gives the personnel orientation, where the focus lays. This is something that is transferable and important to any job shop production maintenance; because the multiple work groups and types of failure have to be prioritised. Otherwise the maintenance department will work according to their own preference, as seen at BOSCH Crailsheim this will lead to extreme failures for the less popular tasks.

Focus on core competences is the second structural element that has to be reviewed when improving any maintenance department, especially in a job shop production context. Because with the multitude of technologies available it is not possible to have an equal expertise in any given field. Therefore it is important to critically assess the how much effort the maintenance department spends on its core competences and how these impact the primary production goals. This is in line with chapter 5.1, where the ratio of contribution to primary production goal and effort was introduced. In this section a further step is taken. It is determined what amount of time should be spent on the maintenance’s core competences.
For activities that are not part of the core competences three types of tasks can be distinguished:

- **Special**
  Tasks that require specialised knowledge and/or equipment

- **Mundane**
  Activities that are not demanding enough for the well trained and highly paid maintenance personnel

- **Alien**
  Processes that are not subject to regular maintenance, as for example administrative tasks.

For these three types of tasks two solutions are most feasible,

**a) Simplification**
Activities can be simplified, for example by the use of additional/better tools or the improvement of the process flow. This was done with the order process in this project, as described in chapter 4.3.3.

**b) Outsourcing**
Hire a service contractor to do certain activities; this was done for the fluid management, see chapter 4.3.2 for details. The advantages, disadvantages and implementation of the two solutions are discussed in the literature review in section 2.3 and in the methodology chapter 3.3.3 and 3.4.2. Taking into account these details it can be summarized that the simplification of processes is preferable to outsourcing.

\[
\begin{array}{c|c}
\text{Simplification} & > & \text{Outsourcing} \\
\end{array}
\]

*Figure 5-1: Principle for dealing with non-core competence activities when deciding to simplify vs. outsource*

As summed up in figure 5-1 is simplification the preferable option when dealing with non-core competence activities. It is beneficial due to not losing internal knowledge.
and keeping tighter control over the process. In some cases outsourcing can be much cheaper than internal work or the investments in tools are not justifiable in this case outsourcing is a viable option. Another scenario that makes outsourcing viable is if there is the bonus of learning new methods from the external experts that are employed. This is a rather uncommon situation, because external experts will most likely not be willing to share information unless their contract requires them to do so. The two approaches can help a maintenance department to become more cost-efficient while getting an increased focus on its core competences. Therefore they can be applied in other situations, as long as there is a careful evaluation of advantages and disadvantages.
5.3 Corrective maintenance – transferable methods

Immediate corrective maintenance is countering the most disruptive form of failure, sudden breakdown. It disrupts the scheduling process, the machine tool performance and significantly increasing stress for all stakeholders of the problem. Deferrable corrective maintenance issues have to be addressed before escalating and can provide additional information regarding the equipment deterioration. Overall for the improvement of a job shop production maintenance some lesson can be learned from this project.

Deferrable corrective cases

For the deferrable corrective cases it was required to create transparency and clear responsibilities. The details of the solution are described in “4.4.1 Ticket system”. Most important was to prioritise the occurring deferrable cases and to make the process transparent for the production and maintenance personnel. Suggested for other job shop production maintenance setups is to adopt the two primary goals:

- Process transparency
- Clear responsibilities

This allows an effective handling of deferrable problems, hereby the solution can be different from what was implemented in the project. A recommended improvement would be to digitalize the ticket system or use of a CMMS (computerized maintenance management system) for the entire maintenance management. For BOSCH Crailsheim the new system is the most applicable solution, because it is based on enhancing existing procedures. Therefore the new ticket concept was not digitalized, but this can be a beneficial improvement for the future or other companies. The evaluation is whether introducing a completely new system is more advantageous than enhancing the existing approaches.
Additional use of connectivity

As mentioned in chapter 4.4.3 it became clear in the project that it was necessary to make better use of modern technology and connectivity. Most feasible example is the use of online access to the machine tools by the OEM’s service technicians instead of having the service technicians visit the factory in person. This will be an important improvement in the modern industry maintenance. The advantages are:

- Faster service
- Higher availability of expert advise
- Cheaper compared to physical visit of the service technician

Critical issues with this approach are:

- Cyber security is compromised
- Possible loss of critical data to the OEM
- Decrease of expertise with external expert available all the time

If comparing the arguments above it becomes clear that in most situations the advantages outweigh the risks. Because the high costs of service technicians and the losses through breakdowns are a very impactful on the costs of a production. Therefore any improvement on that scale is beneficial for cost and performance of a firm’s maintenance activities.
Escalation scheme

As mentioned in the introduction of this subchapter, immediate corrective maintenance cases are most disruptive. Because they impact scheduling of maintenance and production, lead to losses in performance and increase the stress level. Therefore it is central for any type of maintenance approach to address the disruptive occurrence of breakdown effectively. The best way to address immediate corrective failures is an escalation scheme that provides guidance and a step by step orientation for all thinkable scenarios. This is such an elemental step to a maintenance organisation that the requirement of an escalation scheme is transferable to any maintenance department.

Therefore it should always be implemented when the maintenance processes are improved in any (job shop) production, because it permits fixing breakdowns most effectively, while guaranteeing that all stakeholders are timely involved.

Documentation of failure and counter activities

Another very important aspect of improvement in corrective maintenance is to document failure and counter activities, so that they can be analysed and reviewed at a later point in time. On one hand this enables performance measurement of the maintenance department. On the other hand it allows improving the current maintenance activities, by reviewing them and their consequences over an extended period of time in a long term analysis.
5.4 Investment protection, for capital bound in machines

A significant disadvantage for the reliability-centred maintenance (RCM) system is that the focus of the system is on the machines that are relevant to guarantee the system reliability. Hereby equipment that is not very relevant for the system performance is treated with less attention; this can lead to the faster deterioration of these machine tools, because of the limited maintenance activities. A negative impact on the equipment life time will lead to higher investment costs, due to faster replacement and therefore a higher deterioration rate is to be avoided. In order to avoid these costs it is necessary to introduce investment protection measures in the RCM. This project used three types of measures to include a correction of this disadvantage:

- **Ticket system for the deferrable failures**
  This allows operators on less relevant machines to indicate failures on their equipment. Because deferrable failures bear a significant risk for the overall life time and state of a machine tool, this measure is very important in guaranteeing investment protection.

- **Failure analysis of the machine logbooks**
  Doing this analysis for all machines is crucial for the continued performance of the low relevance tools. Because it allows monitoring their condition without the effort of live monitoring, as discussed in chapter 4.5 analysis of failures provides numerous opportunities for improvement and extended life time. Therefore this measure should not be neglected for low risk machines in a RCM system.

- **Machine standards**
  Machine standard maintenance plans and measurements have to be done on all machines. It is acceptable to lower the effort for low risk machines, but it cannot be ignored that all machines require individual machine standards.

The measures described in here are not the only solutions for this problem, but they provide guidance on where investment protection measures can be installed. It is an
area for further research to develop additional mechanisms that overcome this inherent weakness of any RCM concept. All introduced measures have in common, that they are measures that would have been implemented regardless and got extended to guarantee sufficient maintenance for low risk machine tools. The same approach is recommended if RCM is introduced in a different setting. Enhancing measures in order to provide additional protection is the most effective way of implementation. Furthermore it does not require much added effort in the development of specific investment protection methods.
5.5 PM to fingerprints

The improvement was to transfer the general periodic maintenance into individual machine tool activities, called machine standards. These are based on machine fingerprints, which are created from historical and geometrical data. The vision is to move from pure periodic preventive measures to condition-based maintenance in the future. This will be easier having fingerprints already, because these can be utilized to analyse the life data in a CBM context. It will therefore ease the transfer that would be harsh, if moving directly from periodic preventive to condition-based maintenance. Difficult regarding this transfer will be the integration of sensors into older machines and acquiring the expertise to do successful interpretation of the generated signals. The understanding for condition-monitoring is what the fingerprints and the regular communication between maintenance staff and operators are meant to facilitate. A step to step approach for the introduction of CBM is recommended, because it allows starting immediately and cumulatively increasing the required internal expertise.

Important regarding the machine standards in combination with the scheduling with fixed time slots is the availability of personnel. During the project it became clear that the approach requires one technician that can react immediately. The reason is the occurrence of breakdowns or other emergencies, for these cases enough staff members need to be available. Because it takes a significant amount of time to reset started preventive measures to free the maintenance personnel.

Another problem for any form of preventive maintenance is hidden buffers in the production system. These hidden buffers will weaken the impact of breakdowns from the performance perspective. Therefore forced machine stops do not get the required attention and preventive maintenance is not monitored. BOSCH Crailsheim is an example for this problem and the numbers in the analyses (see chapter 4.1) proof the drastic consequences. The maintenance department cannot solve the hidden buffer issue in its function as a support role. An effective counter is to install an independent logbook that documents all failures on the machine. It is easy to implement and provides the required data to improve the maintenance processes, without depending on system data that includes the hidden buffering.
6. Conclusion

The project showed that a job shop production is the most complex production method, because it often aligns multiple goals. But as can be seen in the case of BOSCH Crailsheim, poorly defined goals lead to a lack of transparency and orientation in the production and its support departments.

Analysis

The analyses indicate how much the lack of prioritisation and transparency impacted the maintenance department. Run to failure and neglecting of central responsibilities were consequences of the lack of organisation efforts and skills within the maintenance department. But the root causes for the high need of improved organisation were the multiple goals in BOSCH Crailsheim’s job shop production. Because if a production is excessively filled with buffers (i.e. 24 hours transportation time after every work group in a 30m x 90m factory hall) and does not have a well-communicated ranking of its goals, it is close to impossible to build a support structure around it. The main improvement introduced in this thesis project was the definition of system reliability as the primary production goal. Therefore it was possible to structure the maintenance activities and prioritise tasks.

Equation 6-1: prioritisation of maintenance activities in improvement process in any type of job shop production

\[
\text{priorisation of maintenance activities} = \frac{\text{activity's impact on primary production goal}}{\text{effort of maintenance activity}}
\]

The need of a primary production goal for the development of a maintenance concept becomes clearer looking at the equation 6-1, which was introduced in discussion chapter 5.1. It is clearly displayed that one of the parameters for prioritisation of maintenance activities is their impact on the primary production goal. If there is no ranked production goals it is not possible to structure the maintenance tasks according to their importance. The other parameter is the effort of the maintenance activity, which can be captured in different ways, i.e. cost or time. Therefore this parameter is more flexible, but requires accurate data.
Methods

The most important improvements introduced were in the organisational structure, corrective and preventive maintenance.

Regarding the organisational problems the two crucial methods were to rearrange the time distribution by implementing a schedule with fixed slots. And to allow the maintenance department to refocus on core competences, by simplifying or outsourcing tasks as order processing or fluid management. Feasible tasks fall into the three categories mundane, special and alien. Hereby it is important to evaluate whether simplification or outsourcing is most beneficial for the individual activity.

For corrective maintenance the most important improvements were the introduction of the ticket system, escalation scheme and logbook for documentation and analysis of occurring machine errors. These measures allow prioritising tasks, improving the process transparency and enabling the identification of failure modes. These failure modes can then be used to substitute corrective with preventive or condition-based maintenance. Because immediate corrective maintenance is the worst case scenario for any production system as explained in chapter 4.4. Therefore it is crucial to implement improvements in this area rapidly and document and analyse the performance of maintenance activities in details.

The preventive maintenance section benefited most from the development of the fingerprints for the individual machine tools. This starts transferring the maintenance approach from purely periodic preventive measures to condition-based maintenance, by introducing the basic of future condition monitoring. Hereby it is crucial that aside from the fingerprints a process of failure mode analysis was developed and installed. It is the first time that information regarding failure modes, geometrical state and input from the operators is combined. Another important measure is the increase of training for the operators in order to provide assistance with software problems. The reason is that the maintenance staffs are not able to achieve expertise in the software of all available technologies, while the operators profit from the additional knowledge.
Future research

Future research could be conducted in three areas, condition-based maintenance, improved failure analysis processes and higher digitalisation of the system. CBM provides the advantages of avoiding breakdowns and targeting individual machines. The fingerprints introduced are the first step to get a holistic picture of the machine and will support the introduction of CBM in the future. Improvement in the failure analysis is required to constantly understand the machine tools better and be more effective in the maintenance activities. Furthermore a detailed failure and pre-failure analysis will be needed for CBM; consequently this is wide field for research. The digitalisation of the maintenance system benefits a further transparency, allows a more effective and convenient interaction. Therefore it is one of the possible areas of further research on how to improve maintenance in job shop productions.

Another area for extensive future research is a general guideline for maintenance within job shop productions. This guideline would have to provide a maintenance strategy that can be adjusted to all the different goals possible. Because of the wide range of possible objectives such a paper would be extensive, but it could provide an extremely valuable handhold for production and maintenance management in job shop productions.

In conclusion the central requirement for job shop production maintenance is to counter the complex nature of the production system, provide transparent processes and work according to the most supportive prioritisation of activities.
List of Figures

Figure 3-1: Start of information gathering process, for time based task analysis of current maintenance activities ........................................................................................................................................................................ 18

Figure 4-1: New weekly schedule with fixed daily time slots for the maintenance department at BOSCH Crailsheim ........................................................................................................................................................................ 63

Figure 4-2: Lubrication documentation for a lathe at BOSCH Crailsheim displaying all relevant information .... 66

Figure 4-3: Ticket for new deferrable corrective maintenance concept, final version after PDCA review process 73

Figure 4-4: Picture of the ticket board at BOSCH Crailsheim, show the ranking of the open tickets ............... 74

Figure 4-5: New escalation scheme for maintenance ........................................................................................................ 76

Figure 4-6: "Open measures list production", original version, translated explanation below ......................... 82

Figure 4-7: Schedule for logbook and failure review cycles through the year ...................................................... 84

Figure 4-8: Process overview of the failure mode analysis introduced to identify potential improvements in preventive maintenance ........................................................................................................ 85

Figure 5-1: Principle for dealing with non-core competence activities when deciding to simplify vs. outsource.. 97
List of Tables

Table 2-1: Job shop production in comparison with other common production methods highlighting accompanying conditions, advantages and disadvantages.................................................................................. 7

Table 3-1: Example for the time-based analysis of the effort distribution in the analysis of current maintenance activities (time per month = frequency * (15% extreme cases + 85% regular cases)) ........................................... 20

Table 3-2: Scheme for the analysis of the maintenance costs for every individual work group in BOSCH Crailsheim’s job shop production .................................................................................................................................................. 22

Table 3-3: Examples for calculation of substitutability parameter .......................................................................................................................................................................................... 28

Table 3-4: Example parameters in the risk analysis .................................................................................................................................................................................................................. 30

Table 4-1: Electrical maintenance - Distribution of effort and complexity (grey hair scale) according to central tasks in the old maintenance system .............................................................................................................................................................................. 43

Table 4-2: Electrical maintenance - sums of time distribution in 2016 mean per month, weeks and day .......... 45

Table 4-3: Mechanical maintenance - sums of time distribution in 2016 mean per month, weeks and day ....... 46

Table 4-4: Mechanical maintenance - Distribution of effort and complexity (grey hair scale) according to central tasks in the old maintenance system .............................................................................................................................................................................. 48

Table 4-5: Development of the general expenses from 2014 – 2016, according to the managerial control department’s calculations ........................................................................................................................................................................ 50

Table 4-6: Distribution planned vs. unplanned maintenance activities per workgroup and grey hair scale for determination of competence communication level ........................................................................................................................................................................... 51

Table 4-7: Summary of results in production customer interviews with head of production and team leader regarding the maintenance department’s current performance ........................................................................................................................................................................ 54

Table 4-8: Sum up high risk machines according to interviews in production and after reconfirming them with the production planning department .............................................................................................................................................................................................................. 56

Table 4-9: A and B category of ABC risk analysis for performance risk regarding the impact on the overall system reliability .............................................................................................................................................................................................................................................. 59

Table 4-10: Overview of preventive maintenance measures introduced according to risk category, colour marks their respective subchapter .............................................................................................................................................................................................................................................. 78

Table 4-11: Machine standard maintenance activities for lathe "CTX 800 linear" ............................................. 80

Table 4-12: Parameters for analysis of failure root causes and identification of counter measures, coded by colour .............................................................................................................................................................................................................................................. 86
Literature references


WEBPAGES


Appendix of thesis

Appendix 1: Layout of internal production at BOSCH Crailsheim
## Appendix 2: Chapter 4.2.2 - Analysis of the work group cost distribution in 2016

### Maintenance cost distributions per work group 2016

<table>
<thead>
<tr>
<th>Work group</th>
<th>Maintenance costs in T€</th>
<th>Mean weekly cases</th>
<th>Repair distribution in %</th>
<th>Grey hair scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>total</td>
<td>%</td>
<td>cum.%</td>
<td>planned</td>
</tr>
<tr>
<td>Milling</td>
<td>154</td>
<td>31%</td>
<td>31%</td>
<td>14</td>
</tr>
<tr>
<td>General maintenance costs</td>
<td>103</td>
<td>21%</td>
<td>52%</td>
<td></td>
</tr>
<tr>
<td>Pumps manufacturing</td>
<td>94</td>
<td>19%</td>
<td>71%</td>
<td>1,75</td>
</tr>
<tr>
<td>Cutting</td>
<td>47</td>
<td>10%</td>
<td>81%</td>
<td>4,5</td>
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<tr>
<td>Lathing</td>
<td>46</td>
<td>9%</td>
<td>90%</td>
<td>7</td>
</tr>
<tr>
<td>Sheet metal works</td>
<td>36</td>
<td>7%</td>
<td>97%</td>
<td>1,6</td>
</tr>
<tr>
<td>Welding</td>
<td>10</td>
<td>2%</td>
<td>99%</td>
<td>1</td>
</tr>
<tr>
<td>Express cell</td>
<td>4</td>
<td>1%</td>
<td>100%</td>
<td>0,5</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td>494</td>
<td></td>
<td></td>
<td>30</td>
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</table>
## Appendix 3: Chapter 4.2.2 - Analysis of the work group cost distribution 2015

### Maintenance cost distributions per work group 2015

<table>
<thead>
<tr>
<th>Work group</th>
<th>Maintenance costs in T€</th>
<th>Mean weekly cases</th>
<th>Repair distribution in %</th>
<th>Grey hair scale</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>total</td>
<td>%</td>
<td>cum.%</td>
<td>planned</td>
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<tr>
<td>Milling</td>
<td>240</td>
<td>52%</td>
<td>52%</td>
<td>14</td>
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<tr>
<td>Lathing</td>
<td>83</td>
<td>18%</td>
<td>70%</td>
<td>7</td>
</tr>
<tr>
<td>Cutting</td>
<td>44</td>
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<td>79%</td>
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<tr>
<td>General maintenance costs</td>
<td>28</td>
<td>6%</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td>Pumps manufacturing</td>
<td>25</td>
<td>5%</td>
<td>91%</td>
<td>1,75</td>
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<tr>
<td>Sheet metal works</td>
<td>20</td>
<td>4%</td>
<td>95%</td>
<td>1,6</td>
</tr>
<tr>
<td>Express cell</td>
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<td>4%</td>
<td>99%</td>
<td>0,5</td>
</tr>
<tr>
<td>Welding</td>
<td>6</td>
<td>1%</td>
<td>100%</td>
<td>1</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>464</strong></td>
<td></td>
<td></td>
<td><strong>30</strong></td>
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</table>
## Risk analysis for individual machine tools

<table>
<thead>
<tr>
<th>Machine name</th>
<th>Manufacturing process performed</th>
<th>Parts with no internal alternative [%]</th>
<th>Parts with no int./ext. alternative [%]</th>
<th>Bottleneck factor 2016 [number]</th>
<th>Category [A;B;C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hochregallager</td>
<td>Autom. storage</td>
<td>100%</td>
<td>100%</td>
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<td>A</td>
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<tr>
<td>Graviermasch. Baublys</td>
<td>Engraving</td>
<td>80%</td>
<td>80%</td>
<td>1</td>
<td>A</td>
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<tr>
<td>Böhringer DUS 630</td>
<td>Lathing</td>
<td>75%</td>
<td>45%</td>
<td>3,2</td>
<td>A</td>
</tr>
<tr>
<td>Matec 30HV</td>
<td>Milling</td>
<td>80%</td>
<td>40%</td>
<td>4,5</td>
<td>A</td>
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<tr>
<td>MF Twin 65</td>
<td>Lathing</td>
<td>33%</td>
<td>33%</td>
<td>5,2</td>
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<tr>
<td>DMC 125 FD</td>
<td>Milling</td>
<td>40%</td>
<td>32%</td>
<td>5,8</td>
<td>A --&gt; A</td>
</tr>
<tr>
<td>CTX 800 beta linear DMG</td>
<td>Lathing</td>
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<td>25%</td>
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<tr>
<td>Galvanik</td>
<td>Galvanising</td>
<td>100%</td>
<td>0%</td>
<td>1,9</td>
<td>B</td>
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<tr>
<td>Strömungsschleifen</td>
<td>Grinding</td>
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<td>0%</td>
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<td>Elektropoliieranlage</td>
<td>Polishing</td>
<td>90%</td>
<td>0%</td>
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<td>DMF 360</td>
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<tr>
<td>Honmaschine Nagel</td>
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<tr>
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<td>0%</td>
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<tr>
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<td>0%</td>
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<tr>
<td>Heckert</td>
<td>Milling</td>
<td>0%</td>
<td>0%</td>
<td>4,6</td>
<td>C</td>
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<tr>
<td>Hurco Vakuum</td>
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<tr>
<td>Hurco Edelstahl</td>
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<tr>
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<td>0%</td>
<td>3,5</td>
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<tr>
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<td>0%</td>
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<tr>
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<td>0%</td>
<td>2,6</td>
<td>C</td>
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<tr>
<td>Honmaschine Degen</td>
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<td>2,5</td>
<td>C</td>
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<td>1,8</td>
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<td>0%</td>
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<td>C</td>
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</tbody>
</table>
Appendix 5: Chapter 4.5.2 - Full example of the "open measures list production" filed in by the machine tool operators.
### Appendix 6: Chapter 4.5 - Example of machine standards for individual machine tool, in this case one of the lathes

#### Maschine CTX 800 beta linear

<table>
<thead>
<tr>
<th>Tätigkeit</th>
<th>Dauer</th>
<th>Turnuszeiten</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zugang gewünscht durch TEF</td>
<td>15 KW</td>
<td>1. Halbjahr</td>
</tr>
<tr>
<td>Zugang möglich</td>
<td>10 KW</td>
<td>2. Halbjahr</td>
</tr>
<tr>
<td>Zugang gewünscht durch TEF</td>
<td>5 KW</td>
<td>3. Quartal</td>
</tr>
<tr>
<td>Zugang möglich</td>
<td>10 KW</td>
<td>4. Quartal</td>
</tr>
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</table>

#### Maschine CTX 800 beta linear

<table>
<thead>
<tr>
<th>Tätigkeit</th>
<th>Dauer</th>
<th>Turnuszeiten</th>
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</thead>
<tbody>
<tr>
<td>Zugang gewünscht durch TEF</td>
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</tr>
<tr>
<td>Zugang möglich</td>
<td>10 KW</td>
<td>2. Quartal</td>
</tr>
<tr>
<td>Zugang gewünscht durch TEF</td>
<td>5 KW</td>
<td>3. Quartal</td>
</tr>
<tr>
<td>Zugang möglich</td>
<td>10 KW</td>
<td>4. Quartal</td>
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#### Maschine CTX 800 beta linear

<table>
<thead>
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<th>Dauer</th>
<th>Turnuszeiten</th>
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<tbody>
<tr>
<td>Zugang gewünscht durch TEF</td>
<td>5 KW</td>
<td>1. Halbjahr</td>
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<tr>
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<td>10 KW</td>
<td>2. Halbjahr</td>
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<tr>
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<td>3. Quartal</td>
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#### Maschine CTX 800 beta linear

<table>
<thead>
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<th>Dauer</th>
<th>Turnuszeiten</th>
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<tbody>
<tr>
<td>Zugang gewünscht durch TEF</td>
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<td>1. Quartal</td>
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<tr>
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<td>10 KW</td>
<td>2. Quartal</td>
</tr>
<tr>
<td>Zugang gewünscht durch TEF</td>
<td>5 KW</td>
<td>3. Quartal</td>
</tr>
<tr>
<td>Zugang möglich</td>
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<td>4. Quartal</td>
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#### Maschine CTX 800 beta linear

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<td>Zugang möglich</td>
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<td>2. Quartal</td>
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<tr>
<td>Zugang gewünscht durch TEF</td>
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<td>3. Quartal</td>
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<td>4. Quartal</td>
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#### Maschine CTX 800 beta linear

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<th>Turnuszeiten</th>
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<td>2. Quartal</td>
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<tr>
<td>Zugang gewünscht durch TEF</td>
<td>5 KW</td>
<td>3. Quartal</td>
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<td>4. Quartal</td>
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