Thomas Wildbolz, BSc.

Condition Monitoring

Implementation and Evaluation of Condition Monitoring in Series Production

Master Thesis

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Supervisor: Dipl.-Ing. Clemens Gutschi

Assessor: Dr. Dipl.-Ing. Nikolaus Furian

Institute of Engineering and Business Informatics

Head of Institute: Univ.-Prof. Dipl.-Ing. Dr.techn. Siegfried Vössner

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In cooperation with:

AUDI HUNGARIA Zrt.

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Abstract

The economic impact of the maintenance strategy and operation on a company is often underestimated. The costs caused by non-optimal maintenance systems and processes can influence the profitability of a business significantly. The developments of Industry 4.0 allow for multi-site data collection, inter-connection of hardware systems and thereby guide maintenance operation and planning into digital age. The goal is to avoid breakdowns and to reduce machine downtimes to a minimum. However, the raising complexity of machines lead to new requirements in the field of maintenance, including the need for easier maintainability or longer live times. Due to these new requirements, the economic potential of including Industry 4.0 concepts into a company's maintenance strategy is indispensable. An example for such new strategy is given by the equipment of machines with sensor-based condition monitoring systems.

This thesis was done in cooperation with an engine manufacturer (AUDI HUNGARIA Zrt.). Especially downtimes and breakdowns have a high effect to the key performance indicators such as machine availability and process stability. The target of this thesis is to find an optimal system for monitoring the condition of main spindles in mechanical machining centers. Recent studies showed that vibration and temperature data are well-suited for monitoring health conditions of bearings. Within a detailed market analysis, several commercial diagnostic systems have been analyzed and evaluated. Based on the results three systems were used for experiments under laboratory condition. The results collected under laboratory condition lead to the selection of the two final systems for shop-floor integration and further experiments. The experiments show, that it is possible to implement sensor-based condition monitoring systems in machining centers with little effort for monitoring the spindle and bearing condition. Depending on the available space, not all spindle types offer the ability to additionally implement a vibration sensor.

Finally, a model was created to estimate the average cost of a downtime per hour. This economic analysis shows that the investment to equip a complete production line (roughly 80 machines) amortizes within a mid-term period.

Therefore, it can be concluded that the use of sensor-based condition monitoring systems enables a nearly optimal use of the spindles' wear reserves. Hence, it also supports programmable maintenance strategies and reduces the share of reactive operations.

Kurzfassung

Der wirtschaftliche Einfluss der Instandhaltung auf ein Unternehmen wird weitestgehend stark unterschätzt. Die verursachten Kosten einer nicht optimal laufenden Instandhaltung können signifikante Auswirkungen auf das Ergebnis eines Unternehmens haben. Gerade in Zeiten von Industrie 4.0, Vernetzung der Maschinen und standortübergreifender Datenerhebung bieten sich immer mehr Möglichkeiten, um auch den Bereich der Instandhaltung zukunftssicher zu gestalten. Maschinenausfälle und Stillstände müssen vermieden werden. Gleichzeitig entstehen durch immer komplexere Maschinen neue Anforderungen, wie leichtere Wartungsmöglichkeiten oder höhere Lebensdauern. Aufgrund dieser Anforderungen hat auch in der Instandhaltung das Konzept von Industrie 4.0 Einzug gehalten und eine steigende Zahl an Maschinen wird mit sensorgestützten Zustandsüberwachungssystemen ausgestattet.

Diese Arbeit wurde in Zusammenarbeit mit einem Motorenhersteller (AUDI HUNGARIA Zrt.) erstellt, bei welchem sich Ausfälle und Stillstände von Maschinen stark auf wichtige Leistungszahlen wie Maschinenverfügbarkeit und Prozessstabilität auswirken. Inhalt dieser Arbeit ist die Findung eines optimalen Systems zur Überwachung des Zustandes der Hauptspindel in einem mechanischen Bearbeitungszentrum. Bereits durchgeführte Untersuchungen haben gezeigt, dass mit Hilfe von Schwingungs- und Temperaturdaten der Zustand eines Lagers überwacht werden kann. Mit Hilfe einer Marktanalyse wurden Systeme für erste Experimente unter Laborbedingungen evaluiert. Basierend auf den Ergebnissen der Experimente unter Laborbedingung, konnten Systeme für die Integration in die Fertigungsline selektiert und weitere Experimente durchgeführt werden. Die durchgeführten Experimente haben gezeigt, dass eine Nachrüstung sensorbasierter Zustandsüberwachungssysteme in Bearbeitungszentren mit geringem Aufwand möglich ist. Abhängig vom verfügbaren Bauraum, ist eine Nachrüstung nicht bei allen Spindeltypen gleichermaßen möglich.

Abschließend wurde ein Modell erstellt, mit welchem die durchschnittlichen Kosten für einen Stillstand per Stunde abgeschätzt werden können. Die wirtschaftliche Betrachtung hat aufgezeigt, dass die Ausstattung einer kompletten Produktionslinie (ca. 80 Maschinen) sich mittelfristig amortisiert.

Durch die Verwendung von sensorbasierter Zustandsüberwachung ist es möglich, die Verschleißreserven von Spindeln bestmöglich auszunutzen und die notwendigen Instandhaltungsarbeiten planbar zu machen.

Foreword

This thesis was written at the institute of Mechanical Engineering and Business Informatics under the supervision of Univ.-Prof. Dipl.-Ing. Dr.techn. Siegfried Vössner in cooperation with AUDI HUNGARIA Zrt. in Györ after a six-month lasting internship from May 2017 to October 2017.

My special thanks to Univ.-Prof. Dipl.-Ing. Dr.techn. Siegfried Vössner for his support. Prof. Vössner gave me the opportunity to write my master thesis at the Institute of Mechanical Engineering and Business Informatics.

Further, I would like to thank my supervisor Dipl.-Ing. Clemens Gutschi and assessor Dr. Dipl.-Ing. Nikolaus Furian. Both actively supported me at all times and answered all my questions in the best possible way.

I would also like to thank AUDI HUNGARIA Zrt. for their personally and financial support. Especially I would like to thank Mr. Albert Fazekas for supervision from the side of Audi. I always felt free to talk with him about professional or personal questions.

Also, I want to thank the entire technical service team, specially Mr. Dipl.-Ing. Christian Müller for their technical support. Particularly, I want to name and thank Bende Zoltán and Tamás Schwarcz for their help. They supported me during the technical integration and configuration of the systems.

Finally, I would like to thank especially my family, my girlfriend and my friends. They supported me during my studies and have always been there for me even in difficult times. (Still the last month have been very intense – “THANK YOU!”)

Table of Content

List of Abbreviations

AH	AUDI HUNGARIA Zrt.
CIP	Continuous Improvement Process
CM	Condition Monitoring
CMS	Condition Monitoring Systems
DIN	German Institute for Standardization
ERP	Enterprise Resource Planning System
EU	European Union
FFT	Fast Fourier Transformation
KPI	Key Performance Indicator
MES	Manufacturing Execution System
NC	Numerical Control
OEE	Overall Equipment Effectiveness
PC	Personal Computer
PLC	Programmable Logic Controller
R&D	Research and Development
RAMS	Reliability, Availability, Maintainability, Safety
RCM	Reliability-Centered Maintenance
RFID	Radio Frequency Identification
RMS	Reliability, Maintainability, Safety
TPM	Total Productive Maintenance
USA	United States of America

List of Symbols

x	[m]	Displacement
f	[Hz]	Frequency
ω	[rad*s^{-1}]	Angular frequency
α	[°]	Angle of contact
D_T	[mm]	Pitch diameter
D_W	[mm]	Rolling element diameter
z	[-]	Number of rolling elements
n	[s^{-1}]	Shaft speed

1. Introduction

Over the years the market of automotive industry changed a lot. The industrial competition swapped from a region to a global fragmented competition. The customers expect to get the best product with the best price without waiting time. To stay successful in production is becoming more and more difficult and requires new methods of thinking and acting. Regarding to Bengtsson (2004), it needs a high degree of flexibility, low-cost/cost optimized manufacturing processes, and short delivery times to satisfy the costumer expectations.

New ways of acting and thinking are contained in the Industry 4.0 concept. Machines become connected and forms new interconnected communities. So-called “Smart Factories” are the main element of the Industry 4.0 concept. The concept of smart factories goes beyond to every department of a company and introduces new terms like “Smart Production” or “Smart Maintenance”. Nowadays Smart Production is becoming a standard. Machines are intelligent systems and connected to a network which gives the capability to exchange and respond information between the machines. This leads to the opportunity to manage and optimize operating processes.

A very essential tool to secure the productivity is the use of a good maintenance strategy. The maintenance organization in a company is perhaps one of the most important departments to ensure a secure production process. A suffering maintenance organization will cause high costs. These costs can be a result of bad spare parts keeping, unplanned breakdowns or a lost in production output.

Related to Smart Maintenance condition monitoring of machine components is becoming increasingly important. There are already a few number of techniques available on the market like lubrication analysis, thermography or vibration analysis. These methods have the aim to monitor the condition of main elements of a machining centers like bearings, main spindles, or the tool conditions. Regarding to Caoa (2016) the concept of “Smart Machine Tools” and “Intelligent Machine Tools” was first introduced about ten years ago.

The approach that this thesis will take is the new way of maintenance at AUDI HUNGARIA Zrt. (AH). AH located in Hungary (Györ) belongs to the AUDI AG which is apart from the VOLKSWAGEN Group. In the premium segment of car manufacturer, Audi is one of the most successful manufacturer in the world. The slogan of AUDI is “Vorsprung durch Technik” which means "Advancement through Technology". The plant in Hungary is the largest engine production plant worldwide. Only this plant is capable to produce more than two million engines per year. To achieve such enormous quantities, a lean process in the production is particularly important. Furthermore, a high level of availability and short downtimes of the machines are important factors to manage such high quantities. It is necessary to avoid downtimes of production machines as well as possible and furthermore, it is also necessary to extend the time of component or tool usage as much as possible. For this reason, the use of an efficient maintenance strategy is essential.

The primarily applied maintenance strategy at AH can be described as a periodic preventive maintenance strategy. This means that machine components are replaced after a certain production time or produced quantity. This often leads to a too early replacement of components. Furthermore, the wear reserve of these components is not used optimally. This have an impact to the costs and can be avoided with using other strategy concepts. To decrease the high maintenance costs nowadays condition-based maintenance is used. Today condition-based maintenance is enabled by using different sensors to monitor different machine parameters. Such systems are called condition monitoring systems.

1.1. Goals of this Thesis

The main goals of this thesis are the

- Improvement of technical availability of machining center
- Optimizing the overall downtime costs
- Minimizing unplanned breakdowns → "*make repairs predictable (plannable)*"

Furthermore, this thesis presents a feasibility study for implementing vibration monitoring systems machining centers to determine the main spindle condition of these machining centers. This work is the fundament to make maintenance action plannable.

In scope of this thesis special attention was given to monitor and analyze the condition of main spindles at machining centers. Machining centers are often used in the engine production plant from AH. Therefore, implementing condition monitoring systems (CMS) will have a big impact to the overall downtime costs and the improvement of machining center availability.

Regarding to the aim optimizing the overall downtime costs, a cost model with different scenarios had to be created. Therefore, the objective was to determine the average costs for an hour downtime regarding to different cost drivers like the effect of machine downtimes to the complete production line, catch-up and rework costs. Furthermore an additional aim of this thesis was to identify the breakeven point of such a CMS.

1.2. Structure of this Work

This thesis is divided in two theoretical, three practical parts, conclusion and perspective

1.2.1. Theoretical Parts

Maintenance Systems (Chapter 2)

This chapter deals with the theoretical background of the term maintenance and the different existing maintenance strategies and policies. Furthermore, the chapter describes the evolution of maintenance over the years and explains the different driving forces in maintenance.

Condition Monitoring (Chapter 3)

This chapter deals with the basics and definitions around condition monitoring and the different systems. It illustrates the several types and possibilities of condition monitoring and has a focus on the basics and opportunities of vibration analysis in machining centers.

1.2.2. Practical Parts

Feasibility and Verification (Chapter 4)

At the beginning this chapter contains a short theoretical part about the structure of main spindles. Then it describes the existing potential using vibration monitoring techniques and an effort estimation to integrate such CMS into machining centers. At the end, this chapter deals with the selection of useful CMS and illustrates a completely new system (Prototype)

Experiments (Chapter 5)

This chapter describes the execution of experiments under laboratory and production condition. Furthermore, this chapter deals with finding the optimal sensor position, first conclusions and first experience with the prototype.

Calculation of Overall Downtime Costs (Chapter 6)

This chapter gives a short overview about the different existing types of production at AH. Afterwards it deals with the calculation of the overall downtime costs and how different scenarios have an impact to the overall downtime costs. .

2. Maintenance Systems

This chapter describes the position of maintenance in a company environment as well as their development steps over the time. It shows the evolution and the needs to get from a very simple “run-to-failure” strategy to a very complex Reliability-Centered Maintenance (RCM) and gives an overview about different driving forces in the maintenance. As Michael Schenk considers in his book Schenk (2010 p. 1) the development of maintenance as an independent company sector is closely linked to the introduction of industrial production structures at the beginning of the 19th century.

Regarding to Fedele (2011 p. 33) there is a differentiation in maintenance between policies and strategies. Figure 1 shows the several types of strategies and policies for maintenance systems.

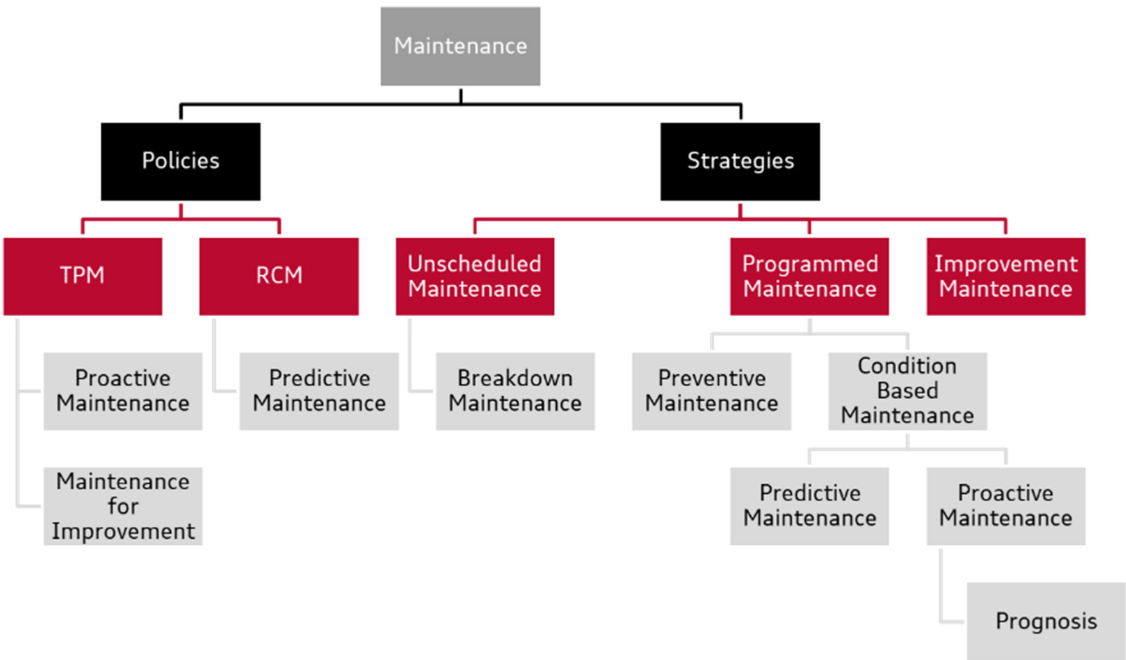


Figure 1: Maintenance policies and strategies modified from Fedele (2011 p. 35)

Maintenance policies could be the approach of Total Productive Maintenance (TPM) (developed in Japan) or the concept of RCM. The classification of maintenance strategies could be done related to three basic strategies. These strategies are unscheduled, programmed and improvement maintenance. In case of the programmed maintenance strategy there is a further differentiation in preventive or condition-based maintenance. Condition-based maintenance is furthermore divided into predictive and proactive maintenance. The basic strategies significantly impact the availability and reliability of the object and have an impact to the maintenance cost. Further explanations and details to these policies and strategies are given later in chapter 2.3. (Fedele (2011 p. 35))

Besides the evaluation and to get a deeper understanding of the terms and meanings around maintenance, this chapter deals at the beginning with the definitions of the different maintenance strategies and their needs. Afterwards, it will give a deeper insight into the different available maintenance strategies and policies and will explain the meaning of these words and it will show the driving forces in maintenance.

2.1. Definition

The definition of the term maintenance is given by the German Institute of Standardization (DIN) and written in the DIN standard. It defines maintenance as a

> *“combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function”.* DIN EN 13306 (2010 p. 6)

Furthermore, a maintenance strategy is defined there as a

> “*management method used in order to achieve the maintenance objectives”.* DIN EN 13306 (2010 p. 6)

The main goal of maintenance is to delay the wear velocity and to avoid and prevent an object breakdown. In case of production and service industry this means to use resources if possible without having errors. The focus is especially on the bottleneck and capital-intensive machines. Besides this, also inspecting and maintaining software or archiving and restoring books or paintings is also a part of maintenance. However, the main task of industrial maintenance is to achieve a failure-free service life and to keep the required effort as low as possible. (Strunz (2012 p. 2ff))

Preventive measures around maintenance are only for reducing the wear velocity. Regarding to the DIN 31051 (2012 p. 4) standard it is possible to divide maintenance into four main divisions. These divisions are inspection, service, repair and improvement.

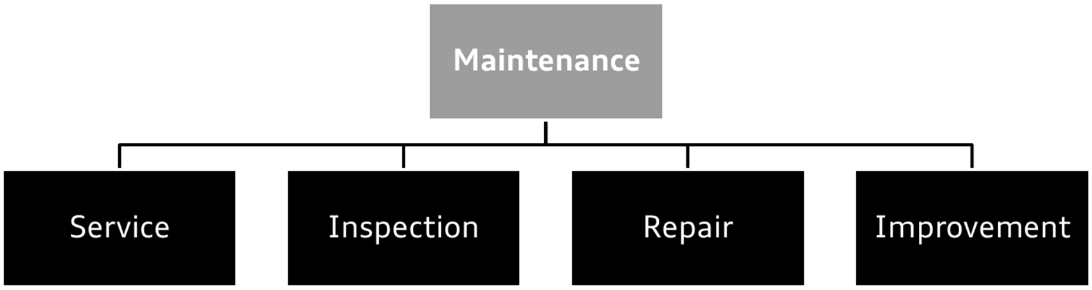


Figure 2: The four main divisions of maintenance modified from DIN 31051 (2012 p. 4)

The classification shown in Figure 2 includes internal and external claims, the accordance of the maintenance goals to the business goals and the consideration of different maintenance strategies. (Pawellek (2013 p. 14))

Regarding to the DIN standard DIN 31051 (2012) and Matyas (2016) these terms have the following definition:

Service

Service includes all tasks to delay the wear of the machine condition as best as possible (DIN 31051 (2012 p. 4)). Furthermore, service is also to maintain the initial condition of technical facilities, to ensure labor safety and to increase the lifetime of machines.

Regarding to Matyas (2016 p. 38) the following examples could be part of service tasks:

- Cleaning: Removing foreign and auxiliary substances
- Conservation: Implementation of safeguards against foreign influences
- Adjusting: Elimination of an error with the help of facilities provided for this purpose
- Greasing: Supply of lubricants to the lubrication or friction point to maintain the lubricity
- Supplement: Refilling and filling of auxiliary substances
- Replacing: Replacement of auxiliary substances and small parts (short-term and easy to implement activities)

This sector mainly consists of administrative and preparatory activities. It is very important to give this phase much attention.

Inspection

Inspection includes all tasks to determine the actual condition of an object. It also includes the determination of the reason of the wear and leads to the necessary consequences for future use. To compare the origin with the actual condition, the condition should be identified under constant operating and environmental conditions. To determine and evaluate the actual condition measuring and checking is necessary. The implementation of the inspections can be supported using diagnostic systems. (DIN 31051 (2012 p. 5) and Matyas (2016 p. 35))

Following the DIN 31051 (2012 p. 5) these examples could be part of inspection tasks:

- Creation of a plan to determine the actual condition
- Preparation and execution
- Proposal and analysis of the actual condition
- Demonstration and validation of alternative solutions, maybe a repair is not necessary
- Decision for one solution
- Feedback

A lot of computer controlled machine tools and machining centers already have built-in fault diagnosis systems. If errors occur, these can be displayed by the diagnostic system and can be repaired very quickly. In addition, errors can be detected by a diagnostic system before they cause an interruption in the production process. This improves the profitability and process reliability as well as the safety and environmental compatibility of the plants. (Matyas (2016 p. 35f))

Repair

Repair is the physical task to restore a function of a broken object. Regarding to Matyas (2016 p. 39f) and DIN 31051 (2012 p. 6) repair can be categorized in the following categories:

- Repairing the component
- Replacing the component

The following example could be part of these tasks regarding to DIN 31051 (2012 p. 6):

- Creation of a repair plan (scheduling, supply with staff and material)
- Execution
- Functional test and object acceptance procedure
- Evaluation, documentation and showing possible improvements

Improvement

Improvement are all activities relating to technical, administrative and management tasks to improve the reliability, the safety and/or the maintainability of an object without changing the original functionality. (DIN 31051 (2012 p. 6))

To identify possible improvements, maintenance is needed in a company. To specify the term improvement, you should distinguish between modification and improvement. A modification is a change of the object function and so the modified object fulfills other functions after the modification. On the other hand, an improvement has the aim to increase the functional safety of an object and maintaining the original function. (Matyas (2016 p. 40f))

Regarding to DIN 31051 (2012 p. 6) the following examples could be part of these activities:

- Creation of a plan to determine the possible improvements
- Execution
- Functional test and object acceptance procedure
- Ready message
- Evaluation, documentation and show possible improvements
- Feedback

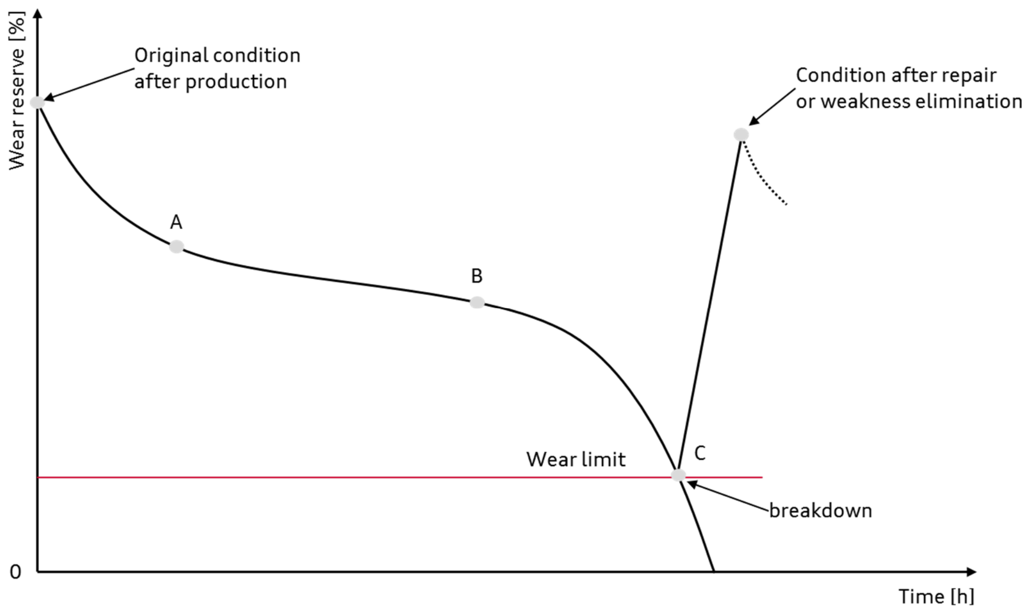


Figure 3: Object condition trend over the time modified from DIN 31051 (2012 p. 8)

In Figure 3 the development of an object condition over time exemplary illustrated. In this diagram, the object condition is defined by the wear reserve. The wear reserve is given in percent and describes the condition of an object. After the installation or production, the object loses very fast its original condition. The highlighted points at the curve mark a normal development for a wear trend. Point A describes the initial point for a potential disturbance. This disturbance in most cases is not recognized at this time. The disturbance further develops to a potential failure. At point B, it is possible to detect the failure. If nothing happens now the failure further develops to a disfunction and causes a breakdown - point C marks this breakdown. Before it comes to a breakdown or goes beyond the wear limit, repair work or weakness elimination should be done. Weakness elimination are activities to improve an object in the way to delay reaching the wear limit if the availability is necessary. (Matyas (2016 p. 125))

2.2. History of Maintenance

Over the time changes in production strategies required an adaption of maintenance strategies. In the early phase and the beginning of maintenance all companies went with the strategy to repair a machine or a component only after a breakdown. By introducing serial production and networked machineries in a flow principle production line, the economic impact of breakdowns got more and more important to stay competitive. (Schenk (2010 p. 1))

Also, the requirements of the skills of maintenance workers changed over the years. At the beginning a normal worker could do the maintenance task beside his normal work. Because of electrification, digitalization, computerization there was a completely new job profile required, compared to that before. A maintenance worker has now to be a specialist for hydraulic, pneumatic and automation. (Reichel (2009 p. 51f))

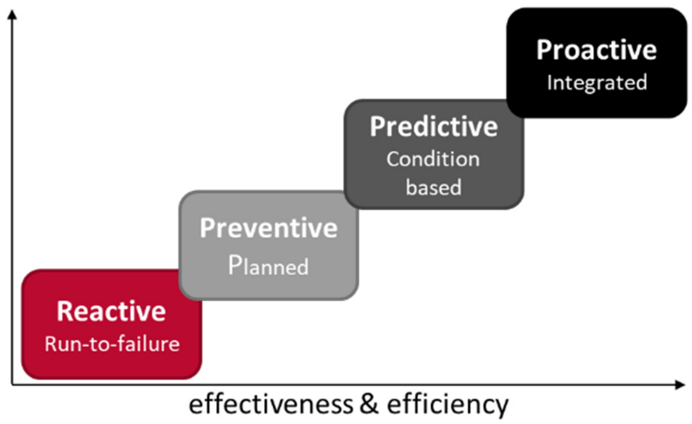


Figure 4: Trends in maintenance modified from Schlussel (2017)

Figure 4 shows a rough overview about the development steps of maintenance strategies over the years. All began with the “run-to-failure” strategy by using very simple not very effective manufacturing systems. Over the years the manufacturing systems got more and more complex and the cost of labor became increasingly significant.

The following generations are defined in the books from Reichel (2009 p. 53ff) and Matyas (2016 p. 29ff)

2.2.1. First Maintenance Generation (1940 – 1960)

The first generation of maintenance is not comparable to the maintenance systems we know nowadays. The structure of the machine system was completely different to the structure of production lines in these days. The complexity of systems and the mechanical parts were very low and the life time of single parts and complete machines was much longer than today. In addition to this a lot of components were oversized. The maintenance strategy in this time was to repair the machine only after a breakdown. The maintenance was only for not planned measures. The strategy at this time was the very simple “run-to-failure” or a so called **reactive maintenance strategy**. The tasks for maintenance in this days were cleaning, inspecting and greasing. (Reichel (2009 p. 52))

2.2.2. Second Maintenance Generation (1960 – 1980)

After the sixties, there was an increase in the demand of industrial goods. This increase caused a better production capacity utilization. In the same time, the mechanical complexity of the machine components got higher and so the impact of downtimes got even more important. This was the starting point of specific maintenance measures and the beginning of preventive maintenance. Furthermore, the impact of the downtimes impacts the economic side of an industrial company because of the high production utilization. (Reichel (2009 p. 52) and Matyas (2016 p. 30))

The cost consideration for maintenance got more and more importance for a company. Due to this change, there was a need for a controllable maintenance, not only in the activities but also in the cost and spare parts sector. At this time, high machine availabilities and long machine life times at low costs were required. To reach this goals companies began to plan their maintenance actions and so the strategy of **preventive maintenance** was created. Preventive maintenance is about maintenance routines and repairing before breakdown occurs. (Reichel (2009 p. 52))

In this period, a big invention in the field of electronics industry lead to a big economic success. The transistor was founded and due to this, this caused an end of the tube technology. Besides the end of the tube technology relay circuits were replaced by electronic circuits. In the 70ties the first programmable logic controllers (PLC) entered the market and this caused a dramatic increase of complexity in the used amount of electrical equipment. The first personal Computer (PC) took over a technical role and so a lot of tasks could be done much faster and more precisely as before. Because of using maintenance planning and controlling software the planning and controlling got more transparent and effective. (Reichel (2009 p. 53))

2.2.3. Third Maintenance Generation (1980 – today)

Caused by the steady improvements in the field of electronics and caused by the highly increasing complexity of the used machine parts, the machines got even more accident-sensitive. Besides the increasing sensitivity regarding to breakdowns the quality of the products got even better and better.

There was not only a change in the used technology of the machines, there was also a change in the requirements for the production workers. PCs and Monitors brought the possibility to visualize complete production system processes and to replace analog displays and instruments with high resolution monitors. Fast computers automated production processes and new software systems could now control the production. This required a quick change of the maintenance system. Now you need specialist workers for hydraulic, pneumatic and automation people instead workers with only mechanical skills. (Reichel (2009 p. 54))

Because of these modern technologies, weakness points in the production process were detected much quicker and this lead to a faster optimization of the whole production process. At this point, besides high availability, it was necessary to ensure a high machine reliability. Furthermore, regarding to the increasing complexity there was also a demand for higher working safety. However, to handle the new upcoming problems innovative technologies in sensor systems or monitoring systems enables an easy implementing of systems in machines to identify the actual machine or machine component condition. Additionally, to the condition monitoring systems machines had to be designed in a more maintenance friendly way. (Reichel (2009 p. 54))

Changes in the organization from a centralized to a decentralized maintenance unit improved the effectiveness too. The increase of the workload and the demand of a fast reaction time required a new way of management thinking. Outsourcing and work contracts became even more popular. To get closer to the production Kaizen, the continuous improvement process (CIP) and total productive maintenance (TPM) were introduced. (Reichel (2009 p. 54))

This generation is strongly depending on **predictive maintenance** strategies like condition-based maintenance.

2.2.4. Fourth Maintenance Generation (future)

More and more areas such as environmental and quality management, energy saving programs, personnel development, delivery dates, risk assessments, spare parts logistic, etc. changed the responsibility to the maintenance department. Strategies like TPM, RCM, preventive or predictive maintenance should ensure the productivity and production. Connected software products and modules like SAP give the possibility to get dependable and quick data and information about the machine conditions and maintenance states. (Reichel (2009 p. 54))

The fourth generation requires - like the third generation - a high machine reliability but also integrated systems. Furthermore, this generation also has the need for self-learning and decision-making systems to get an even higher profitability and a higher effectiveness. This generation is about the **proactive maintenance** strategy and further new strategies. To satisfy the new upcoming requirements a new thinking in kind of web based knowledge systems, database analysis or linked data to the system is necessary. Additional to this, even more and more sensors and embedded actuators should be integrated in machines to determine the actual component condition even more and more precisely. (Reichel (2009 p. 54) and Matyas (2016 p. 30))

In Figure 5 you can see the evaluation of the different maintenance generations regarding to the requirements and the inventions they need to get from one generation to the next generation. It shows the future problems which will occur by generating a lot of data out of a lot of sensors. The problem will be to find the right ways for analyzing the data and to filter out specific information about the condition of machines or single components.

Now, a change in maintenance from a pure cost driver to a company-wide business process is taking place. This change is actively involved in the value added of a company. (Schenk (2010 p. 3))

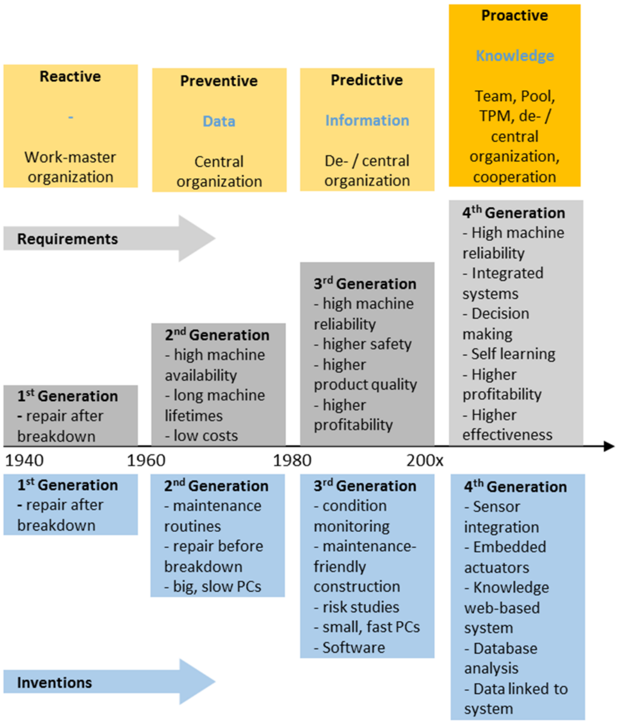


Figure 5: Steps in maintenance development modified from Reichel (2009 p. 53)

2.3. Maintenance Strategies and Policies

Regarding to Strunz (2012 p. 31), to achieve different maintenance goals like:

- Optimizing the lifetime
- Minimizing the downtimes
- Securing the needed functions
- Following safety, environmental and quality standards
- Minimizing the costs

there are different maintenance strategies available.

Maintenance policies represent the general attitude that a company assumes in terms of maintenance problems. To clarify the policies according to departments, machines and economic aspects, there are different strategies available. (Fedele (2011 p. 33))

Maintenance strategies can be understood as a specification or rule. They are necessary to determine the right time frame to do maintenance actions at objects. For making the right decision in case of cost and downtime minimization should consider the influences between profitability, safety and availability. The result of good maintenance should be the fulfillment of the required availability at minimal costs. Choosing the right maintenance strategy strongly depends on each individual company. There is no uniform maintenance strategy available yet. (Fedele (2011 p. 33))

In the DIN standard, the term maintenance strategy is defined as a

> *"management method used in order to achieve the maintenance objectives"* DIN EN 13306 (2010 p. 7)

Regarding to Figure 1 the different strategies and policies have the following meanings:

2.3.1. Unscheduled Maintenance

Unscheduled maintenance is one of the oldest types of maintenance. In this type of strategy, the machinery or object is operating until a failure (breakdown) of a component occurs or a fixed wear limit (as shown in Figure 3) is reached. Normally the target of a strategy is to achieve a planned long-term objective. In proper sense, unscheduled maintenance is no strategy because in this case spontaneity and the very quick reaction to solve a suddenly occurred problem is very important. Dealing with sudden breakdowns specific resources like staff, equipment and spare parts should be available permanently. This is the reason why this type of strategy has the highest downtime of machines and causes very high downtime costs. Another disadvantage is that there is no opportunity to plan maintenance actions.

This strategy is mainly used in following systems:

- Less used machines
- Machines which do not lead to delivery difficulties in case of a machine breakdown
- Redundant machines
- Machines which don't have to meet safety requirements

(Pawellek (2013 p. 130) and Schenk (2010 p. 17f))

2.3.2. Programmed Maintenance

Programmed maintenance is also called time-controlled or time-based maintenance. It is based on the principle that the maintenance activities of components are carried out in event cyclic time intervals. Furthermore, programmed maintenance is divided into two categories. On the one hand, there is the preventive maintenance and on the other hand there is the condition-based maintenance. (Schenk (2010 p. 28))

2.3.2.1. Preventive Maintenance

In the case of preventive (time-based) maintenance, all maintenance activities are connected to a determined time setting. This could be a certain number of operating hours or predefined dates for maintenance. Regarding to Leidinger (2017 p. 16) has the condition of the component no influence on the maintenance plan. Schenk (2010 p. 16) mentioned that the application of this strategy is useful if safety and environmental requirements call for it or if the expected life-time of components is well known Furthermore, preventive maintenance will be applied if condition-based maintenance is not possible or only possible with a high effort (dismounting of machine parts or using destructive methods to determine the actual part condition) or to avoid a part break in case of safety risk requirements. (Pawellek (2013 p. 131))

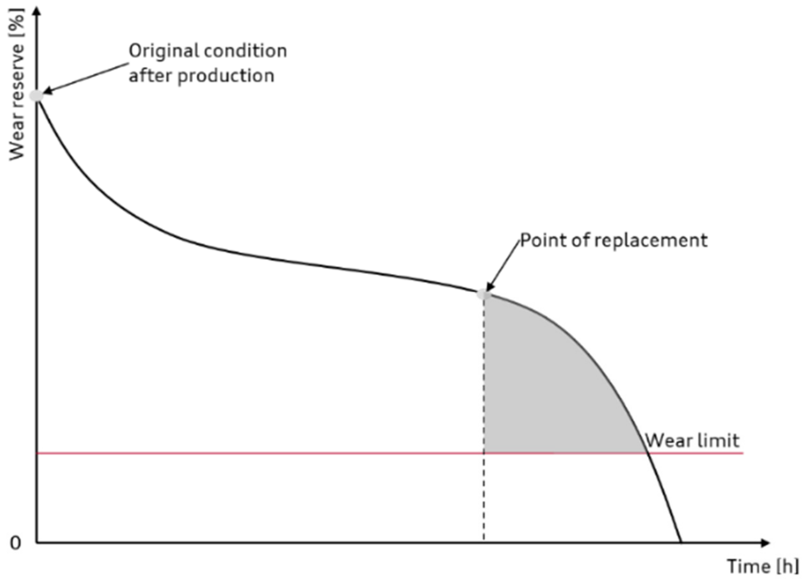


Figure 6: Preventive maintenance modified from Schenk (2010 p. 29)

As you can see in Figure 6, a disadvantage of periodically maintenance could be, that parts will be replaced before they reach their wear limit. This decreases the costs for downtimes but increases the costs for spare parts. If the machine will be used more often than planned, the wear limit is reached earlier and so the gap between the scheduled maintenance actions is maybe too high. This could cause unplanned breakdowns. (Schenk (2010 p. 29))

On the other side, there is the possibility to plan the execution time and to schedule maintenance actions into non-working periods. The working tasks could be prepared and organized in advance and so this reduces the replacement and working time at the machine. A big advantage of this type of strategy is the possibility to guarantee a machine availability. The challenge in realizing preventive maintenance is to deal with the various breakdown behaviors of the different machine components. Each machine unit has another timing to reach the wear limit. To optimize the utilization of the wear range there should be different intervals for maintenance actions classified into functional groups. (Schenk (2010 p. 29))

As a good example for preventive maintenance is an oil change of a vehicle. The setting for service interval is given by the manufacturer and relating to the traveled distance or a defined period. You should e.g. change the oil of your car every 30.000 km or every 12 months. (Leidinger (2017 p. 17))

2.3.3. Condition-based Maintenance

In the case of condition-based maintenance, the repair date is determined based on the technical condition of the component. To identify the actual condition of a part several methods could be used. This could be:

- Inspection
- Non-destructive testing
- Offline
- Online diagnostics

The aim of this method is to expand the use time of components to a maximum without having unplanned breakdowns. (Pawellek (2013 p. 131))

Furthermore, another aim is the possibility to plan the required maintenance actions and put them into production-free times. The point of repair is based on the results of the condition monitoring. (Matyas (2016 p. 125))

Following Fedele (2011 p. 44ff), condition-based maintenance is divided into predictive and proactive maintenance.

Predictive Maintenance

This type of condition-based maintenance, the condition is determined by fixed inspection intervals using visual inspection, non-destructive testing methods and functional tests without disassembling components of the machine Fedele (2011 p. 44). Furthermore, Matyas (2016 p. 125) noted that the maintenance staff can detect a change in the condition but there is no possibility to detect suddenly occurred component failures. Based on the inspection results a maintenance schedule is created. In this schedule, it is defined which components should be repaired or replaced. Additionally, Fedele (2011

p. 45) considered that in this type of condition-based maintenance do not use probability methods to make a forecast of failures. Only trend data of the measured parameters are used to avoid breakdowns.

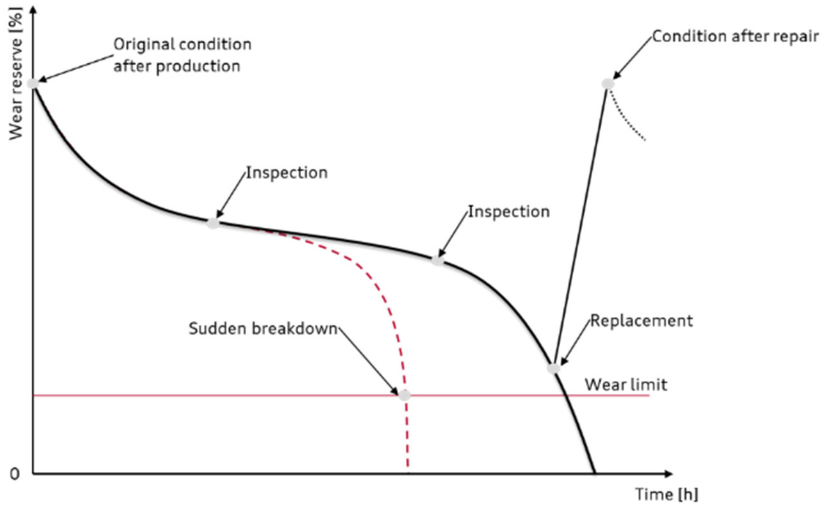


Figure 7: Predictive Maintenance modified from Leidinger (2017 p. 19)

Using this method should improve the availability of a machine and should bring the point of replacement as near as possible to the wear limit. As shown in Figure 7 the main disadvantage is that there is no possibility to detect sudden breakdowns which maybe occur during prescheduled maintenance inspection intervals. (Leidinger (2017 p. 18))

A good example for predictive maintenance are vehicle bake systems. A normal brake pad has a lifetime of 30.000 to 70.000 km. Every year a general function testing and a visible inspection of the brake system is done during the yearly car inspection. The car mechanic identifies approximately the actual condition of the brake and give the costumer a proposal to change the brake pads or not. If the costumer drives a lot with the car, there is the possibility that the brake pad reaches the wear limit before the next inspection. In this case, car manufacturer installed a safety function and an alarm signal will be shown on the display of the car if the brake pads reaches the wear limit. (Leidinger (2017))

Proactive Maintenance

Proactive maintenance is a step ahead and is a strategy which combines all positive aspects of preventive and predictive strategies. The aim of proactive maintenance is to avoid failures or to detect problems early which could lead to a breakdown. Proactive maintenance should provide the maintenance worker with an alert signal with enough lead time to prepare a repair or replacement without having machine downtimes. (Schenk (2010 p. 31))

The main difference to predictive maintenance is the continuous knowledge about the machine condition. To gather continuous information, online condition monitoring systems are necessary. Furthermore, another big part of this strategy is the use of prognosis. Using online condition monitoring systems, a lot of information is gathered and this information could be used to create prognosis. (Fedele (2011 p. 46))

Leidinger (2017 p. 18) considered that the goal is the replacement or the repair shortly before the occurrence of the failure or the fault. With this method, the wear margin could be used in an optimal way.

A good example for proactive maintenance are online condition monitoring systems in car tires. The driver has every time the possibility to get information about the tire condition. The car collects data like temperature, pressure or differences in wheel speed and will give the driver an early information in case of abnormalities. These could be information about a difference in the tire pressures or an alarm signal to stop the car immediately in case of a tire blow-out. The pre-alarm is defined early to give the driver the possibility to make an appointment with a workshop and to repair the tire. The early alarm makes it possible to plan the repair.

2.3.4. Improvement Maintenance

Improvement maintenance is used to determine and eliminate weaknesses in machine systems. Poor components are one reason for sudden breakdowns and weak process stability. They also have an adverse impact to the costs. (Strunz (2012 p. 70))

In DIN 31051 (2012 p. 7) weakness is defined as a failure, which occurs more often than the availability of a component is required and a technical improvement is possible and economical acceptable.

If a technical improvement is not possible and repair is nevertheless justifiable for economic reasons, a repair is done by means of a parts exchange. The improvement of components is closely related to the RAMS method (Reliability, Availability, Maintainability and Safety) and to the CIP. The RAMS method is a further development of the RMS method (Reliability, Maintainability and Safety). According to the definition of EN 50126, RAMS is a strategy that supports the prevention of errors already in the planning phase of projects by incorporating all notes on improvements of all kinds into the specification. (Strunz (2012 p. 70))

2.3.5. TPM

TPM is the abbreviation for “Total Productive Maintenance” and it stands for a fully in production integrated maintenance. TPM is a continuous process and requires the participation of all employees. With using productive maintenance and all employees it leads to an optimal utilization. (AUDI Hungaria Zrt (2012 p. 5))

TPM was developed in the 1960s by the Japanese Seiichi Nakajima. Since the first implementation of TPM, the concept continuously developed from a pure maintenance approach that focuses primarily on improving the effectiveness and extension of machine life times, to a comprehensive management approach that covers all areas of a company. Reichel (2009 p. 79) The concept of TPM is based on a five-pillar model with the focus on the field of maintenance involving all employees (see Figure 8). The motivation for employees is mainly through group work and voluntary commitment. The primary goals of TPM regarding to Pawellek (2013 p. 4) are:

- Maximizing plant efficiency and
- The avoidance of loss of efficiency

Further objectives of TPM are the optimization of quality and reliability of production processes, the elimination and prevention of waste in production processes, the realization of local problem solving and a safe, standardized and organized workflow. (AUDI Hungaria Zrt (2012 p. 5))

TPM effects all production areas of a company. To get an efficient TPM system a good organization is required where tasks, responsibilities and interfaces are clearly defined. Regarding to Manzini (2010 p. 73f) the word “total” in TPM has three meanings:

1. *Total* effectiveness (profitability and economic efficiency)
2. *Total* maintenance approach (breakdown, preventive and condition-based strategies)
3. *Total* participation of all employees (from top management to shop floor worker)

To achieve the required improvements, a few tools in a kind of a toolbox are available. The best way to visualize these tools is the house of TPM and its five pillars as shown in Figure 8. The foundation of TPM on the one side are cleanness, tidiness and discipline and on the other side continuous improvement. The five pillars are sub goals and points of references. They are connected with the roof of target agreement and target tracking systems. (Matyas (2016 p. 232))

To use the toolbox of TPM it is necessary to consider the following guidelines (Matyas (2016 p. 233)):

1. Elimination of waste and losses
2. Individual responsibility
3. Team work
4. Standardization
5. Visualization

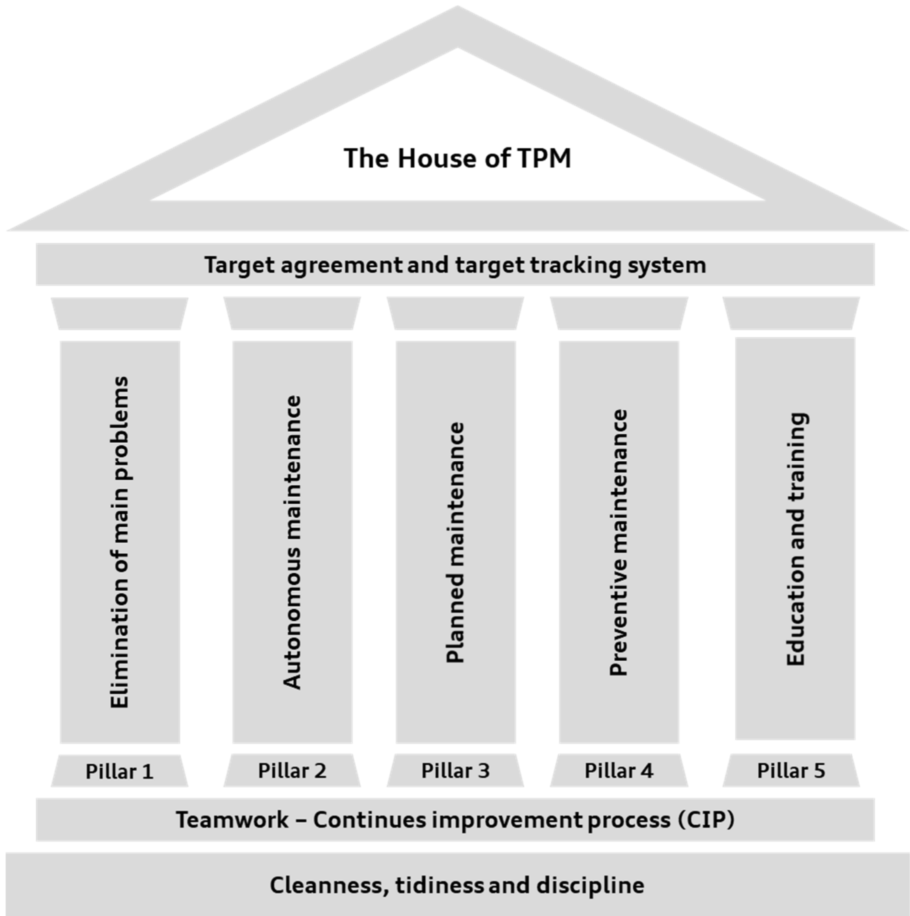


Figure 8: Five pillars of TPM modified from Matyas (2016 p. 232)

Pillar one is about the elimination of main problems and deals with analyzing the machines and identifying their weaknesses. There are some possibilities for analyzing the main problems like the overall equipment effectiveness (OEE) calculation, machine condition analysis or evaluating the information from the machine log book.

The second pillar deals with making the maintenance autonomous. It's about the implementation of autonomous maintenance through all levels of the company.

Pillar three describes planned maintenance activities to make a good and stable set up. It contains machine analyzing to identify costs for spare parts or the evaluation of error distribution.

The next pillar contains tools to early detect weaknesses and optimize them. This began in the phase of development and construction of machines and systems and involves the installation of spare parts, the geometry of working area or the integration of diagnosis systems. At last, pillar five gives the foundation to follow the CIP thinking and gives a good set up for all workers. (Matyas (2016 p. 233ff))

2.3.6. Reliability-Centered Maintenance

Following Matyas (2016 p. 144), RCM was developed by John Moubray and it is a concept that combines the break-down, preventive, condition-based and predictive maintenance in an optimal way. The goal is the compliance of required reliabilities at minimal cost by considering safety and environmental aspects.

Before using this policy, it should be verified if preventive measures are not more expensive than the machine downtime and all related costs to the downtime. An advantage of RCM is the consideration of the different failure behaviors of different components. (Pawellek (2013 p. 7))

The RCM model is a further development of the bathtub curve. The bathtub curve (Figure 9) consists of three different curve areas. The first part is a decreasing curve and includes construction, material and assembling mistakes. The second part is a constant straight with random breakdowns and operating errors. The last part is a progressive one and determined by the increasing wear. (Matyas (2016 p. 42f))

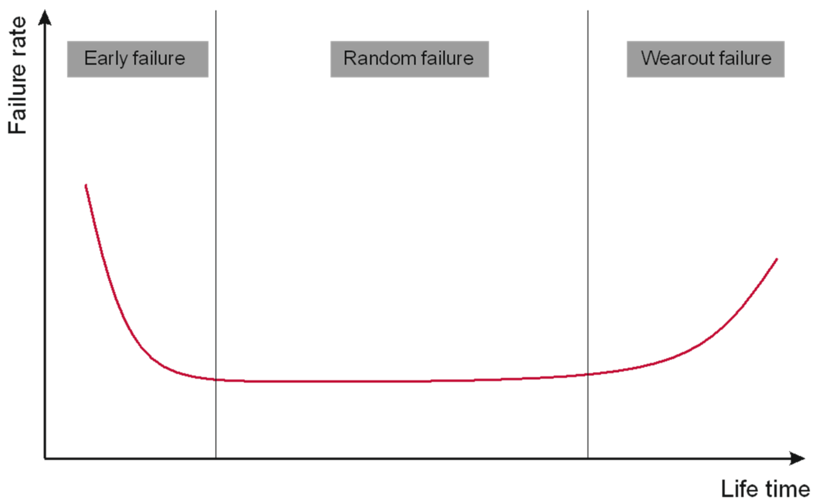


Figure 9: Bathtube curve modified from Matyas (2016 p. 42f)

RCM differentiates between six variants for component or machine breakdowns. The different curves are necessary to investigate and analyze the actual behavior of a system and are shown in Figure 10. (Pawellek (2013 p. 7))

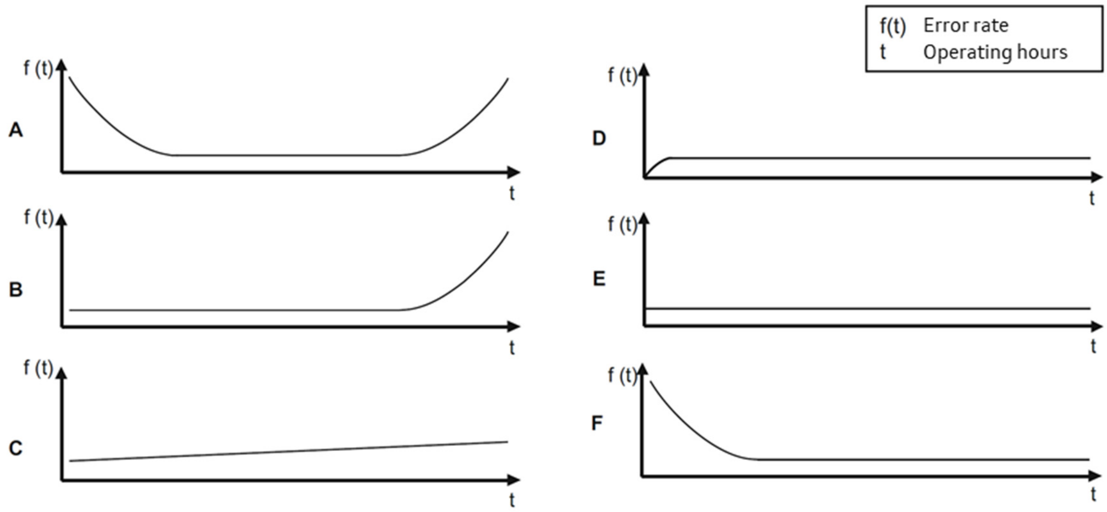


Figure 10: RCM failure curves by Pawellek (2013 p. 8)

The RCM concept deals with the functions of a system, like how the failures indicate and occur, what are the results of a failure and how a failure can be prevented. (Pawellek (2013 p. 8))

2.4. Driving Forces in the Maintenance

Nowadays there are a lot of different driving forces which impact the choice for the right maintenance strategy for a company or an enterprise. In tough times, when the management should cut down the current costs, the influence of the environment to this driving forces cause discussions in management. Very often maintenance is defined for the reason of unpleasant costs and regarding to cut down the current costs, the decision to outsource the maintenance tasks is done by the management. Strunz (2012 p. 9ff) defined eight relevant driving forces in the maintenance:

1. Increasing complexity of machines and single machine parts
2. Permanent increase in maintenance capacity in relation to production
3. Increasing automation
4. Increasing requirements
5. Investments in modernization and improvement

6. Reliability, Maintainability, Safety (RMS)
7. Increasing process speeds
8. New organizational structures

1. Increasing complexity of machines and single machine parts

Modern production systems exist of linked machines with a rising complexity. The process technologies are changing and this causes an increase in the investment costs and an increase in the machine-hour rates. Furthermore, higher complexity and higher utilization have an impact to the wear and the failure rate. The interaction of the machines effects an independency in the production line.

2. Permanent increase in maintenance capacity in relation to production

Over the last years there was a decrease in the number of industrial employees over numerous industrial sectors (for example in chemical industry about 50%). On the other hand, the employment of maintenance staff has risen by 75%. In the United States of America (USA) about ten percent of all working people are working in the field of maintenance. Nowadays, a good maintenance technician must have a solid education and a lot of know-how. Beside this he should widen his knowledge and skills permanently. All these aspects cause increases in the salaries of maintenance technicians.

3. Increasing automation

Regarding to the cost driver I (Increasing complexity of machines and single machine parts) the complexity of maintenance services is increasing dramatically. As a result, the maintenance activities have a higher specific level of difficulty and require a high level of specialist and specialized knowledge. Furthermore, this causes the need for further education and trainings, see cost driver II (Permanent increase in maintenance capacity in relation to production). The increasing automation impacts the growing needs for understanding complex process flows.

4. Increasing requirements

Due to numerous chemical accidents and the enlargement of the European Union (EU) in recent years the legislators have been required to adapt, expand and tighten the governmental regulations on occupational safety and environmental protection. This adaption of the regulation lead to a change of strategy in the maintenance management system. The result was an extension of this system to ensure the protection of occupational safety and health protection and the environmental conditions. At the same time, the increase in regulations cause an increase in responsibilities and need for qualified workers. In addition, companies had to realize additional investments because of upgrading or modifying the existing systems. As you can see in Figure 11 there was a significant increase in the amount of the governmental regulations over the last years.

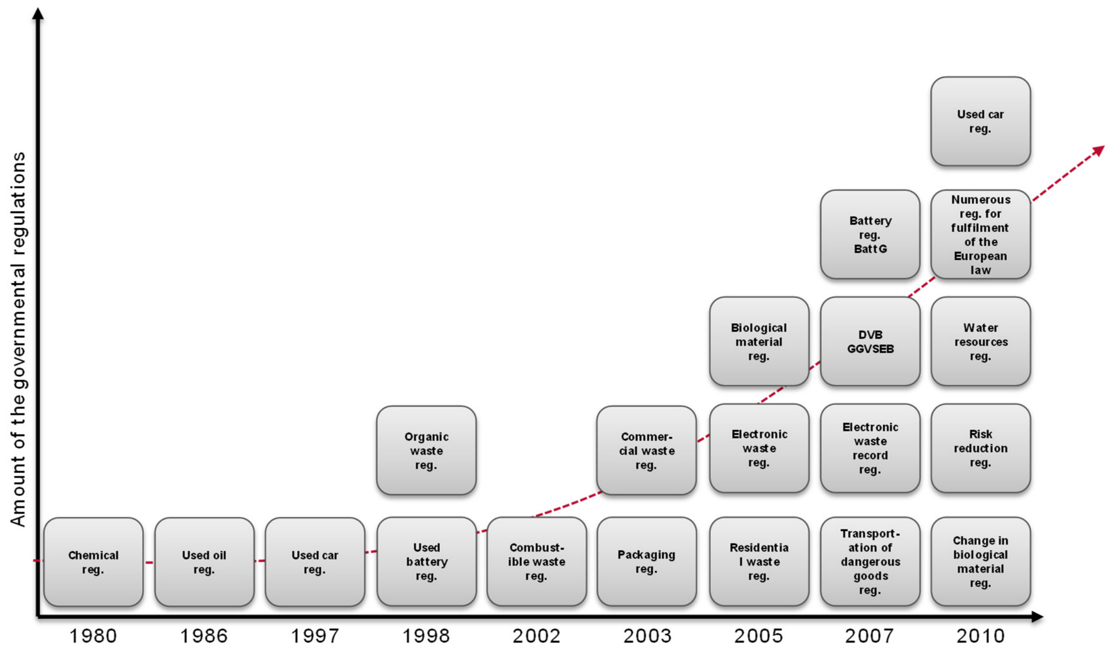


Figure 11: Governmental requirements for maintenance modified from Strunz (2012 p. 10)

5. Investments in modernization and improvement

Rising prices of spare parts and machineries force the need of more investments in modernization and improvement. The increasing replacement costs of worn-out machineries are the reason for the increasing effort to make sustainable modernization and improvement investments. All these activities increase the number of machines to be maintained and the higher amount of more expensive machines increase the fixed assets. Furthermore, another problem are the increasing spare part prices. Machine manufacturers use more often more complex parts, and so the higher complexity of the parts lead to increasing spare part prices.

6. Reliability, Maintainability, Safety (RMS)

RMS is a strategy that is designed to take care of the maintenance requirements in a very early phase of the product development process. Already at the point of designing a machine, this strategy considers several aspects and goals to reach a higher reliability.

This affects an improvement in the availability, maintainability and safety of a machine or system. Furthermore, this approach creates a double benefit. Firstly, machine manufacturers can charge higher prices for their products, secondly the user saves costs during the machine lifetime.

7. **Increasing process speeds**

The growing demand of industrial manufactured goods lead to an increase in process speeds of the machines. This causes a higher fault susceptibility in the technical equipment because materials, surfaces, geometries e.g. are subject to higher loads. The consequences are more extensive maintenance procedures and shorter maintenance cycles. In the last years companies spend a lot of effort and money in research and development (R&D) to eliminate this disadvantages by developing early diagnose systems.

8. **New organizational structures**

The change in organizational structures (connected production, linked factory) and new process oriented production methods (Just in Time, Just in Sequence) determine the sustainability and competitiveness of numerous companies in a long-term view. To realize lean production, it is necessary to have a zero-defect strategy for the processes. This requires comprehensive locally process knowhow. Furthermore, to realize a zero-defect strategy for processes, technological production teams should ensure the system availability. This can only be implemented in combination with continuous further trainings and further qualifications for the transfer of additional tasks within the framework of total productive maintenance (TPM).

3. Condition Monitoring

This chapter describes the basics of condition monitoring (CM), the different types of diagnosis and gives an overview about different monitoring methods like vibration analysis or thermography or oil analysis. As Pawellek (2013) considered in his book, condition monitoring is another approach to discover damages at components or to determine the state of a component. CM can be used to perform a condition-based maintenance strategy. Furthermore, it is used to objectively record and evaluate the actual machine condition. Regarding to the specific task of this thesis, this chapter also deals with bearing vibration analysis methods and other methods for CM.

3.1. Basics of Condition Monitoring

Condition monitoring or also called “condition-based monitoring” is to determine and analyze the actual condition of a machine objectively. Regarding to chapter 2.3.3 this method is used to improve the availability of a machine and to bring the point of replacement as near as possible to the wear limit. However, there are a lot of different possibilities to identify the actual machine condition. Many different parameters should be considered. Depending on the machine and the failure there are several possible fault factors which should be monitored and measured. In Figure 12 you can see some possible diagnostic methods. (Pawellek (2013 p. 122f))

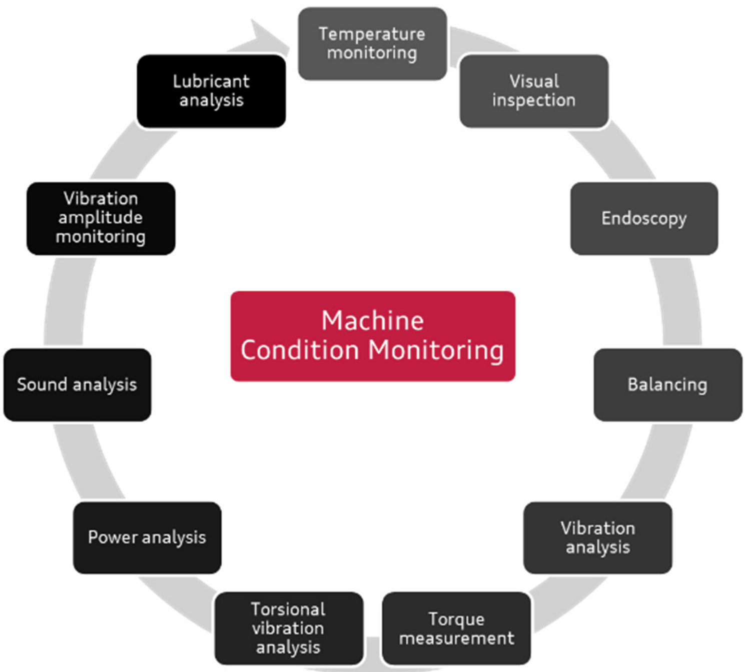


Figure 12: Diagnostic possibilities modified from Pawellek (2013 p. 123)

As the last chapters demonstrated, preventive maintenance is in the most times uneconomic. As shown in Figure 7, preventive maintenance is applied more often than condition-based maintenance. In the case of preventive maintenance, a component is changed before reaching the wear limit. Besides this, there is a risk to damage good components of a machine by dismounting others. Exceptions for useful preventive maintenance could be periodical liquid change, renewing filters and the replacement of components whose repair costs in relation to the failure costs are very low. (Matyas (2016 p. 124))

To detect damage processes to components and to determine the condition of a component, methods and tools for technical diagnostics are used. Technical diagnosis are all activities and processes to determine and evaluate the technical condition of machines. Following Schenk (2010 p. 132), the usage of condition monitoring systems (CMS) supports the maintenance to fulfill the objectives like:

- Monitoring the limit
- Recording the development of damage
- Recognition of potential failures and preventing breakdowns

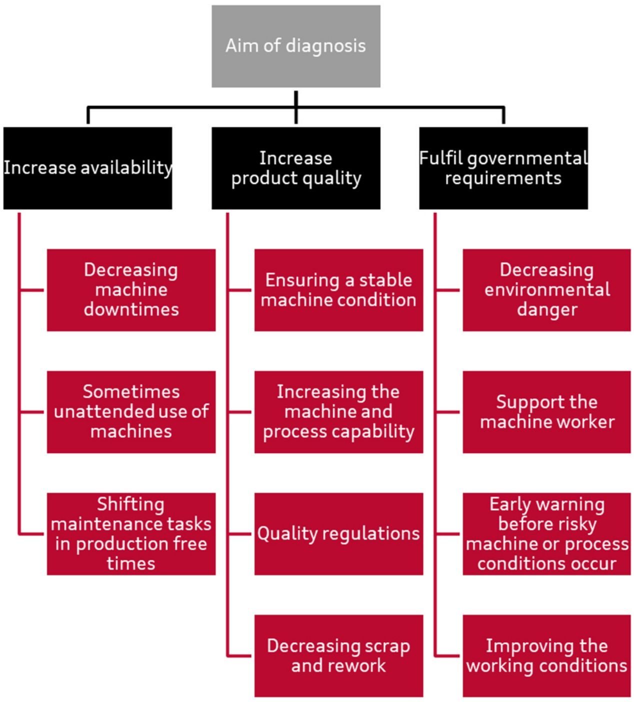


Figure 13: The aim of diagnosis modified by Matyas (2016 p. 127)

By using CMS, it is possible to early detect damages. This gives the possibility to guarantee the machine availability. Furthermore, CMS enables to lower the costs to a minimum. Regarding to Matyas (2016 p. 127), using this method could lower the costs in following areas:

- Operating costs
- Machine costs
- Repair costs
- Breakdown costs

Figure 13 illustrates how condition monitoring and diagnosis systems can increase the cost-effectiveness and process stability in production facilities. The aims of condition monitoring could be classified into aims for the economic success, the product quality and the fulfillment of governmental requirements. In case of economic success, the aims could be decreasing machine downtimes because of early detecting failures or reaching pre-limits. Additional there is the possibility to use machines unattended. Not every machine needs a worker to observe the actual process state. However, a very important aim of condition monitoring is the possibility to shift maintenance tasks into production free times. This reduces the downtime costs a lot and gives the possibility to schedule and plan maintenance actions. (Matyas (2016 p. 127))

To increase the product quality, condition monitoring ensures stable machine conditions, increases the machine and process capability and decreases scrap and reworks. Also, this aim has an impact to the costs. Quality regulations should ensure a safe and stable product quality. (Matyas (2016 p. 127))

The third big aim of CMS is the fulfillment of governmental requirements by decreasing the environmental danger, supporting the machine worker with early warnings regarding the machine and process conditions. These facts improve the working conditions and have a positive impact to the economic success of a company. (Matyas (2016 p. 127))

Regarding to Weck (2006 p. 278) there is a differentiation between process monitoring and machine monitoring.

The focus of **process monitoring** is on the operation process. This could be monitoring of geometrical or technical aspects. A very good example for process monitoring is condition monitoring of tools. The aim of tool monitoring is to early detect tool breaks. With an early detection, it is possible to avoid further damages during the remaining process.

On the other hand, the aim of **machine monitoring** is the protection of the machine and their components. Machine monitoring is to ensure the product quality and the availability of the machine. A good example for machine monitoring is the monitoring of main spindles and feed axis.

Tools and strategies are basically very similar at process and machine monitoring. This is a reason, for using the same sensors for both monitoring types. Also, the approach and problems in case of signal processing and monitoring strategies are very similar. But there are quantitative differences in the specific requirements for sensors, electronics and algorithms. For example, the aim of using sensors is to position the sensor as near as possible exactly to the measured object. Regarding to the differentiation between process and machine monitoring the aim at process monitoring is to mount the sensor as near as possible to the process. In the other case, at machine monitoring the aim is to mount the sensor as near as possible to the monitored component. These objectives should be fulfilled in the best way, because other components maybe will disturb the signal. Table 1 summarizes similarities between process and machine monitoring. (Weck (2006 p. 279))

Table 1: Differences between process and machine monitoring modified from Weck (2006 p. 279)

Distinguishing criterion	Process monitoring	Machine monitoring
Sensor principle	Similar principles	
Sensor parameters	Different sampling rates or signal-to-noise ratios	
Monitoring strategy	Strategies could be similar but most times they are application-specific	
Machine components	Disturbs the signal quality	Monitored object
Start of measurement	Automatically by the process	Specific start is possible to gain specific measurement points
Operating process	Monitored object	Process disturbs the signal quality

Figure 14 shows a schematic layout of a condition monitoring system. In principle, there is no difference in the layout of the system regarding monitoring a process, an object or the environment. At first it is necessary to clarify and determine the variables which should be measured. Afterwards a suitable system should be chosen and installed. After recording, the values should be processed and saved. Furthermore, after processing the values they must be interpreted by an expert or technician with the special know-how. This requires to have a suitable validation model. Based on the validation model or based on the special know-how of the experts or technicians, a decision should be done. (Schenk (2010 p. 133))

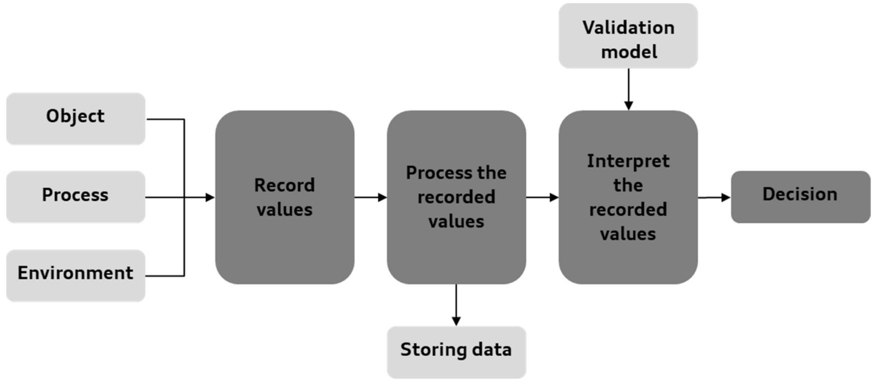


Figure 14: Schematic layout of a condition monitoring system by Schenk (2010 p. 133)

3.2. Types of Diagnosis

To determine the actual condition of a machine or component there are a lot of different possibilities to collect data or information about the object condition. At first there is a differentiation in how to identify the condition. At the one side, and this is the simplest way to get information, you can gather information by doing visual checks with workers. On the other hand, sensors could be used to determine the actual condition. This increases the acquisition costs but reduces the current costs. In the case of sensor monitoring a lot of machine parameters could be monitored. (Matyas (2016 p. 128))

3.2.1. Visual Monitoring

Fedele (2011 p. 64) considered that visual monitoring is the simplest way of monitoring and performed by the operator or worker at the production line. Using visual monitoring requires a skilled worker with a good capability to identify differences in sounds of the machine.

Furthermore, Schenk (2010 p. 132) includes visual inspections to the area of visual monitoring. Visual inspections are checks of machine components which are observable without dismounting parts, done by the operator. The attention is given to geometric changes, corrosion, liquid levels, leakages, temperatures, sounds and vibrations. This type of tests assumes high experience. If the visual inspection is not possible because a lack of accessibility, changes in condition can also be recorded using the endoscopy. With using endoscopes, a visual inspection can also be done at components which are difficult to access.

All visual monitoring activities require experienced and skilled workers. Trained people can detect slightest changes with their sense of hearing. With this ability, it is possible to distinguish variations in the sound of a machine noise from the typical normal sound. The advantage using subjective measuring methods is the possibility to monitor conditions of machines or their parts relatively quickly and without large measuring apparatuses. (Matyas (2016 p. 128))

3.2.2. Sensor based Condition Monitoring

The task of a diagnostic system is to detect the condition of a machine by monitoring certain different measured variables. There is hardly any measured variable that can't be recorded. Due to this there is a large variety in diagnosis sensors and their use must be checked technically and economically before installation. The measured variables are distinct in their physical basis and in the type of the measuring variable. Due to this classification, the corresponding measuring principles are shown in Table 2. Pawellek (2013 p. 123) classified these types for diagnosis as following:

- Vibration analysis (measurement and diagnosis of mechanical vibration)
- Temperature measurement (temperature sensors)
- Thermography (visualization and measurement of the thermal energy dissipated by an object and measured with a camera or a sensor)
- Oil analysis (liquid level measurement, liquid composition measurement, viscosity measurement)
- Power and current consumption (power monitoring)

There are two possibilities to transfer the recorded data from the sensor to the processing unit or to the technician. The first option is a wired and connected method. The second option is using wireless devices. In the area of wireless connection recently a lot of new technologies entered the market. Pawellek (2013 p. 124)

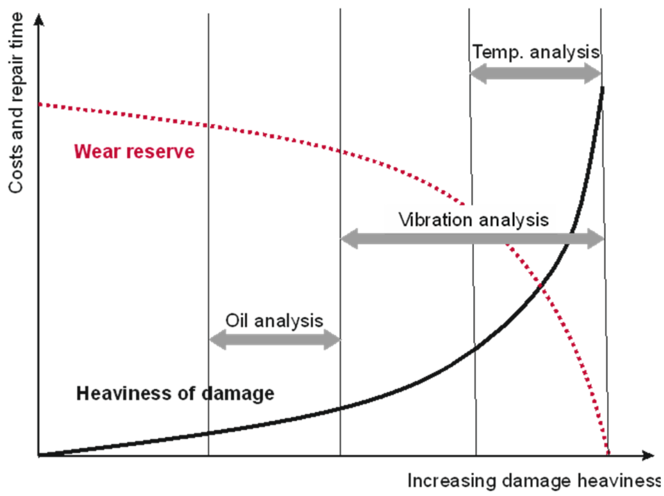


Figure 15: Area of applications of the different monitoring methods modified from Reichel (2009 p. 199)

Figure 15 shows the different areas of application of different monitoring methods. Regarding to the wear reserve and the increasing damage heaviness it is shown, that with oil analysis methods it is possible to detect an error very early. A slightly later error detection is possible with vibration analysis. At the least and in the area with the quickest wear downgrade and with the highest damage heaviness temperature analysis is done. (Reichel (2009 p. 199))

Nowadays there are a lot of similar software solutions available for recording and analyzing sensor measured data. This data could be measurement records from acoustic or thermal sensors. The signals are measured by the sensor, enhanced and transmitted to an A/D converter. Regarding to the measurement setup the digital signals could be buffered and sent afterwards to the analyzing computer. This measuring chain is shown in Figure 16. (Matyas (2016 p. 129))

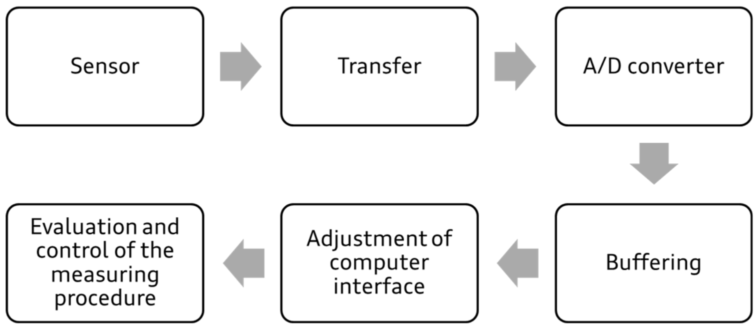


Figure 16: Measuring chain for CM modified from Matyas (2016 p. 129)

Furthermore, Schlieper (2014) distinguished condition monitoring in online and offline systems.

Online condition monitoring systems are permanent monitoring systems with the help of fixed installed sensors in the machine and operating data acquisition of the machine software. They offer the opportunity to get every time information about the condition. Furthermore, using online systems the technician can set alarm limits. If a machine component reaches the predefined limit either the machine shuts down or an alarm is shown. A big advantage of these systems is independency and their low costs for use. On the other hand, the investment costs for sensor systems are very high and are often forgotten during the announcement and specification. Another disadvantage is the relatively high false alarm rate. However, an online CMS could be of advantage, especially in situations where a fast response time is required to minimize the breakdown time. (Schlieper (2014 p. 15) and Reichel (2009 p. 197))

Offline condition monitoring systems on the other hand are systems where the diagnostic data are collected with a portable data collector and then separately evaluated. Between the measurements there is a time range without collecting data. Offline CMS are working aids for the maintenance. The basic idea of this method is that as many systems as possible can be monitored by the simplest means by theoretically anyone. Also, early detections and diagnosis are possible with this type. The decision for a portable system reduces the installation costs, because instead of using wired sensors, the measuring points at the machine are merely equipped with passive sensor adapters. On the other hand, during the operation more staff is needed because operators should measure at predefined points in a defined interval. (Schlieper (2014 p. 15), Reichel (2009 p. 197) and Matyas (2016 p. 129))

On the market, there are many sensors available for monitoring systems. Regarding to Klocke (2008) they could be divided into six physical functional principles:

Table 2: physical functional principles and the measured variables modified from Klocke (2008 p. 387)

Physical functional principle	Measured variable
Mechanical (movement, relocation, stiffness)	Position, acceleration, velocity, force, torque, tension, pressure, etc.
Thermal (kinetic energy of atoms and molecules)	Temperature, specific heat, heat flow, heat conductivity, etc.
Electrical (electrical field)	Current, voltage, charge, conductivity, etc.
Magnetic (magnetic field)	Permeability, magnetically flow, etc.
Radiation (electromagnetic radiation	Energy, intensity, emission, reflection, etc.
Chemical (Forces between atoms and binding energy between molecules)	Chemical components, concentration, etc.

Numerous sensors use the strain of an object as an auxiliary variable for the measurement of forces, torques and accelerations so that in the following sections the functions of strain, piezoelectric, vibration and temperature sensors are explained.

Strain gauge

A strain gauge converts a mechanical strain into a change of the electrical resistance. They are used to measure material elongations on machine parts. The elongation of metallic bodies in the elastic region takes place according to Hook's law in proportion to the load force. Due to this relationship, strain gages can be used for force measurement. The physical function principle of the strain gages is based on the change in the cross-section of a resistance wire or a resistance path because of a longitudinal stretching. (Weck (2006 p. 282))

Piezoelectric force measuring elements

The physical effect of piezoelectric force measuring elements is based on the direct use of the piezoelectric effect. The atomic structure of certain substances causes a shift in the charge under a mechanical load, which can be measured. Piezoelectric elements can be pressed from ceramics into almost any shape or cut from single crystals. Piezoelectric force measuring elements based on quartz have a wide temperature range, high stiffness, large measuring range, and very small strain can be measured. (Weck (2006 p. 286) and Klocke (2008 p. 390))

Structure-borne sound and acceleration sensors

These sensors are used to detect vibrations in the manufacturing process or defective machine elements, such as rolling bearings, gears, shafts, etc. changes in the process could be detected by changes in the amplitude or frequencies. Piezo-electric accelerometers have a high priority due to their linearity over large frequency ranges. They can be attached to the existing machine structure without the need for major structural changes. Some sensors are especially suitable for the harsh operating conditions inside machines and can be installed without causing damage to the sensors due to coolant, oil or chips. Over the time, the condition of tools or machines changes regarding to the use. This change in the condition leads to a change in the structure-borne sound and airborne sound signal. This change in amplitude and frequency can be seen in the spectrum. More details to vibration analysis are given later. (Weck (2006 p. 290ff))

Temperature sensors

Temperature sensors are used in machines for monitoring the operating or working temperature. They could be used for monitoring a liquid temperature like the oil temperature of the hydraulic oil or could be used for monitoring the bear ring temperature of the main spindle. Usually, touching sensors are used. Temperature sensors could be divided into resistance, semiconductor resistance and IC sensors. Resistance sensors change their electrical resistance as a function of temperature. Metals are used as the resistance material for this purpose (platinum or semiconductor). A typical type for a platinum sensor is a PT100 element. Semiconductor resistors have a positive (PTC element) or negative temperature coefficient (NTC element). (Weck (2006 p. 297ff))

Another monitoring technique, which is increasingly used nowadays, is monitoring by means of a thermographic camera. The wear of machine components can be measured by the heat radiation. Thermography is explained later in chapter 3.4. (Klocke (2008 p. 403))

Current and power measurement

Each movement requires a power which must be applied by a drive. A movement for example could be the move of a spindle or the move of a feed. As a result, changes in the manufacturing process must also effect changes in the consumption of electrical power. Various principles are used to measure the engine current consumption. Due to these changes in the power consumption, fault causes and malfunctions can be detected. (Weck (2006 p. 293f))

Table 3: Advantages and disadvantages of different condition monitoring methods modified from Pawellek (2013 p. 126)

Type of diagnosis	Advantages	Disadvantages	Requirements for realization	Requirements for analysis
Vibration analysis	• High developed • Low investment costs • Early warning • High success rate	• Experts are required for analysing the data and understand the root failure cause	Technical knowhow required	Expert knowhow required
Thermography	• Flexible useable (handset) • Low costs • understandable	• Difficult to automate • Late warning • Short reaction time	Average	Technical knowhow required
Oil analysis	• Good identifying of the cause of failure • Early warning • Identifying of complex failure connections	• Not automatable • Analyse has to be done under laboratory conditions • Very expensive • Experts are required	Low	Expert knowhow required
Power monitoring	• Good for implantation in existing systems • Low costs	• Experts are required • Late warning • Limit knowledge required	Technical knowhow required	Technical knowhow required
Liquid level monitoring	• Effective • Good automatable • Easy to use • No expensive tools necessary	• Not very precise • No detection of the error cause	Low	Expert knowhow required

Table 3 illustrates advantages and disadvantages of different condition monitoring methods and describes the different requirements for realization and for analyzing. This is a very rough overview about the different methods. The next chapters will give a deeper understanding of the three most important monitoring methods to determine machine condition. The three most important methods are vibration analysis, thermography and oil analysis. In this table, it is shown that a lot methods requires technical or expert knowhow for realization or for analyzing the results. This are reasons why it is so difficult and cost expensive to implement condition monitoring systems to already existing machines.

Regarding to the aim of this thesis, chapter 3.3 deals with the basics of vibration analysis at gives a deeper look into the basics of bearing vibration analysis.

3.3. Vibration Analysis in Machining Centers

In this chapter, a basic definition of the term "vibration" is given at the beginning. Afterward, the most important vibration parameters are explained. Furthermore, several types of vibrations in machining centers and their development are briefly shown. Additionally, this chapter also explain the acquisition and analysis of the measured raw data. Finally, a small insight into the possibilities and limitations of vibration analysis regarding to the analysis of bearings is done.

The vibration analysis or diagnosis is primary used to monitor the measured value of body vibrations and to determine stresses in the form of unbalance, misalignments, hitting or loose parts, fitting issues, shaft damages, gearing damages or damages of bearings. For this purpose, the vibration signal generated by the system is recorded and analyzed with using modern analysis techniques. These techniques could be a fast Fourier transformation (FFT) for converting a time signal into a frequency signal and visualized in a spectrum. With this it possible to identify characteristic frequencies which do not occur to undisturbed operation. The effective (RMS) values of the signals can be an indicator for the degree of damage. If, in addition, the kinematics of a system are known, such as rotational speed, installed rolling bearings, or the number of teeth of the gear stages, it is possible to assign which components are damaged. (Schenk (2010 p. 133f))

Due to the various influencing factors which affect a technical system, the description of the active damage processes still depends very much on the knowledge and experience of the user (the expert or technician). This is caused by the fact that very experienced worker with a long operating experience can describe the damage and its effects on the machine condition without technical diagnosis equipment. As mentioned in chapter 3.2.1 these workers are used and very important for visual inspections. (Schenk (2010 p. 134))

3.3.1. Definition of Vibration

A variable is oscillating when oscillation (vibration) occurs regularly. The oscillation could be random or periodic. For example, a periodic oscillation could be the motion of a pendulum. On the other hand, a random oscillation could be the movement of a tire on the road. Vibrations can be observed everywhere in nature and in all areas of technology.

In technology, periodic oscillation whose state variables $x(t)$ are repeated after a period or oscillation, the oscillation period τ plays a significant role. Figure 17 shows a typical periodic oscillation and all-important variables like displacement, amplitude and period. (Magnus (2013 p. 1))

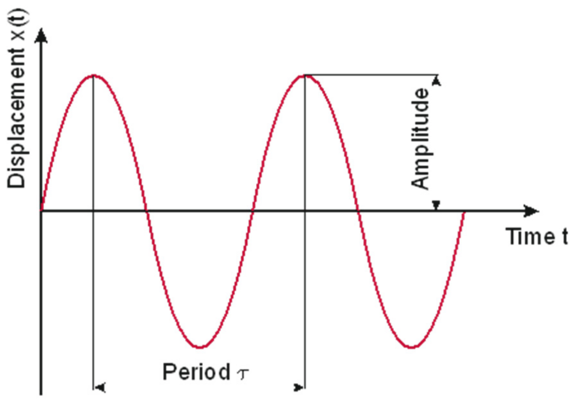


Figure 17: Periodic oscillation

At machine condition monitoring, periodic vibrations are of importance. If the following periodicity condition applies, the oscillation is a periodic oscillation:

$$\boldsymbol{x(t) = x(t+\tau)\ [m]}$$

Equation 1: Oscillation displacement

The frequency f of a vibrating system expresses the number of vibrations in one second:

$$f = \frac{1}{\tau}\ [Hz]$$

Equation 2: Frequency

Another important variable is the number of oscillations in 2π seconds and is given by the angular frequency ω and calculated as follows:

$$\omega = 2\pi * f = \frac{2\pi}{\tau} \; [rad * s^{-1}]$$

Equation 3: Angular frequency

The amplitude of an oscillation is the maximum value of a vibration during an oscillation period. This should not be mixed with the displacement, which indicates the actual value of the oscillation variable. The amplitude is therefore a measure of the intensity of a vibration and is given by the formula sign $\hat{x}$.

(Kollmann (2006 p. 2ff) and Magnus (2013 p. 1f))

3.3.2. Types of Vibrations in Machining Centers

This section briefly explains the three types of vibrations (free damped oscillation, forced oscillation and self-excited oscillation regarding to Magnus (2013)) occurring in machining centers. Also, Uhlmann (2008) classified these three types of vibration as the most important types for machining centers. The classification regarding to Uhlmann (2008) is shown in Figure 18.

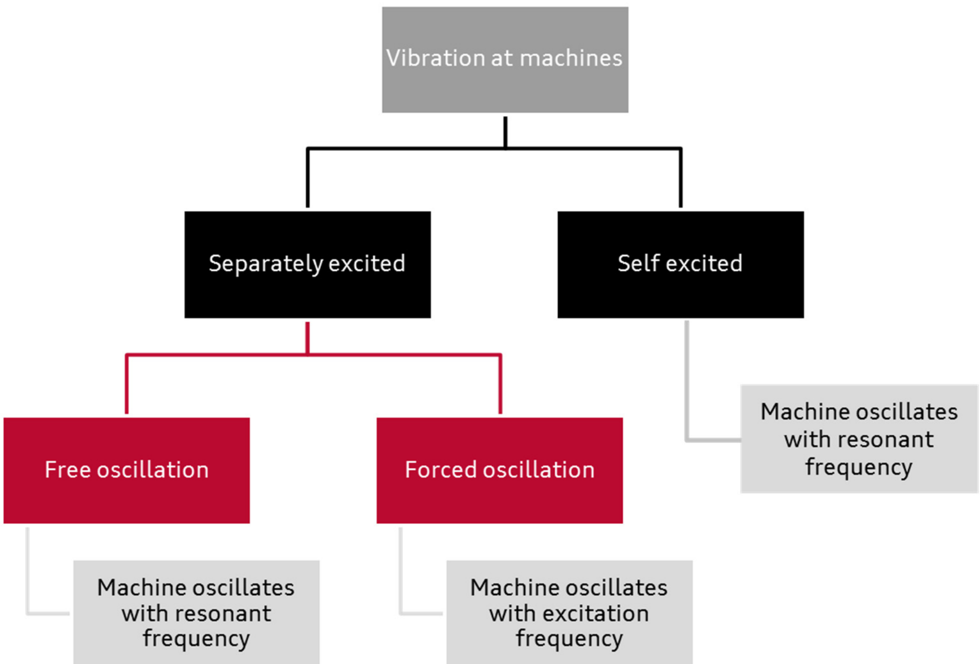


Figure 18: Types of vibration at machine centers modified from Uhlmann (2008 p. 17)

Free damped oscillation

In case of a free damped oscillation, the body produces a free oscillation with a single deflection and no other external actions. No further energy is supplied form outside and the systems oscillates in the body specific Eigen frequency and Eigen form. Over the time, the amplitude decreases due to system damping. An example of this kind of oscillation is a child is swinging on a child swing. If an external person forces the child one time the rest of the swings are a free damped oscillation. The oscillation is damped due to the mechanical friction of the swing. (Brecher (2017 p. 598f))

The difference between free and free damped oscillation is shown in Figure 19. A free oscillation has a constant amplitude over the time. Regarding to a free damped oscillation the amplitude decreases over the time due to external impacts like friction etc.

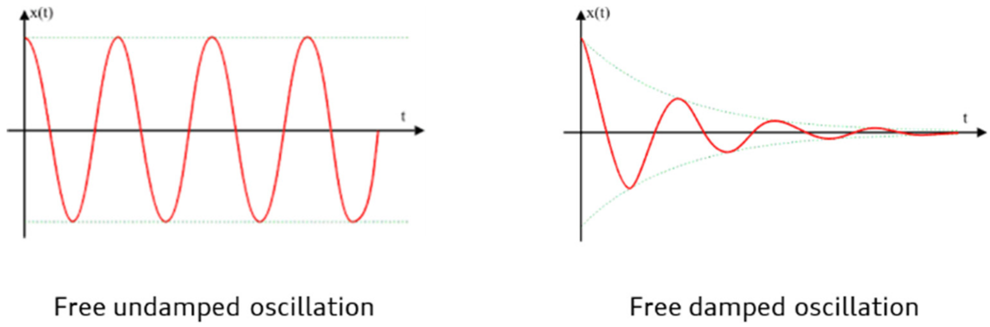


Figure 19: Difference between free and free damped oscillation modified from Leitner (2017)

Forced oscillation

The processing center is stimulated from the outside or by the drive or cutting process and vibrates at a certain frequency. The amplitude of the oscillation depends on the excitation force, the exciter frequency, the static stiffness of the machine, the mass and the damping. If the excitation frequency is near the resonant frequency resonance may occur. In this case the amplitudes increase very fast. It is necessary to quit the process rapidly to avoid damages. An example for this type of vibration is the excitation of a machine due to a vibration induced by the foundation of a motor with imbalance. (Brecher (2017 p. 598f))

Figure 20 shows a forced oscillation and all relevant variables like the excitation frequency and the amplitude over the time.

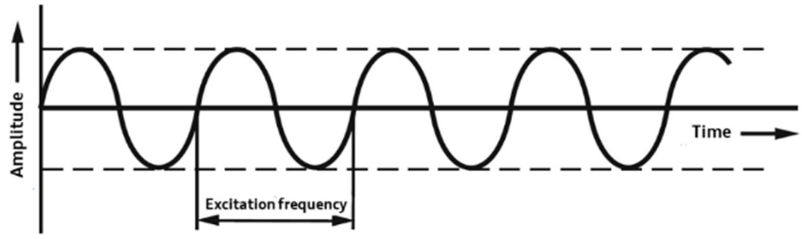


Figure 20: Forced oscillation by Hirsch (2016 p. 88)

Self-excited oscillation

This type of oscillation is caused by internal alternating forces and the instability of the overall system. Self-excitation mechanisms are found in the machine behavior and in the operating process. If - for example - the regenerative effect occurs, the affected machine component vibrates with their resonant frequency. (Brecher (2017 p. 598f))

The regenerative effect is the repeated cut of a tool into a previously produced waviness of a work piece and shown in Figure 21 (Uhlmann (2008 p. 19)).

Therefore, resonance easy occur and vibrations could take significant dimensions. One example could be a turning process, which oscillates damped due to cutting force fluctuations regarding to workpiece inhomogeneity. (Schlieper (2014 p. 20))

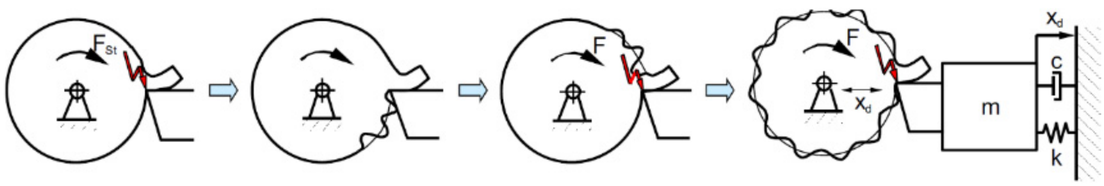


Figure 21: Regenerative effect based on a turning process by Uhlmann (2008 p. 19)

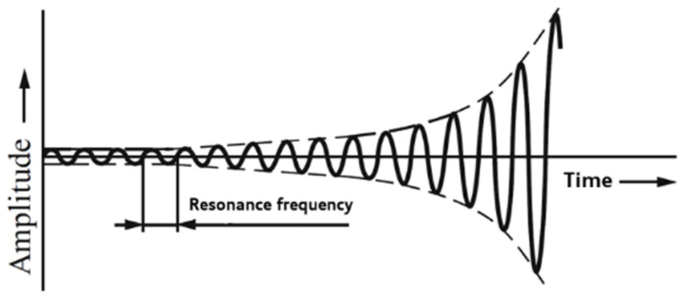


Figure 22: Self-excited oscillation by Hirsch (2016 p. 88)

3.3.3. Development of Vibration in Machine Center

Machining centers convert electrical energy into mechanical energy. Besides inaccuracies in the manufacturing and assembling of the machine and the physical and material effects, the energy transformation process is essentially responsible for the vibration generation. Therefore, the vibration graph provides information about the technical condition of a machine. In addition, vibrations generated outside can also be initiated and can disturb the processing process. These external influences should be filtered out for a vibration-based condition monitoring. A reason for stimulating machining centers to oscillate could be alternating forces or shocking pulses. Causes of alternating forces could be (Hirsch (2016 p. 88)):

- Unbalanced machine parts
- Forces of tooth mashing in case of concentricity or tooth shape failures
- Failures in geometry or components of bearings
- Belt-structure or belt tension failures
- Hydraulic pumps
- Process-related disturbances like interrupted cuts or different offsets

A damage in rolling bearings, spindles, gearboxes or on housings generates shock impulses. This shock impulses are a result of a periodical overrun of the damage with constant speed. For instance, a bearing rolls over a damage in the inner race every rotation. This is an example for a periodically shock impulse every rotation.

Bearing Vibrations

Regarding to the aim of this thesis bearing vibrations are very important. Every main spindle of machining centers contains bearing packages. The structure of a spindle is explained later in chapter 4.1.

A new rolling bearing produces only a high-frequency, wide-band noise of low level. If the wear of a bearing increases this level of frequencies also increases but remains broadband and high-frequency. With an accelerometer, these frequencies could be measured in a very good way. (Gasch (2006 p. 649))

Bearing damages on the outer race, inner race, gage or on the rolling elements cause shock pulses. These frequencies are multiples of the rotation speed. A very good way to visualize this shock pulses is using the vibration spectra. How to get from an acceleration measurement to a spectrum is explained later in this chapter.

Figure 23 shows the components of a typical bearing used for main spindles. Felten (2017) classified the types of rolling elements into a ball, a roller, or a tapered roller.

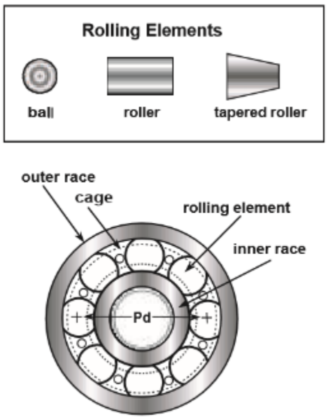
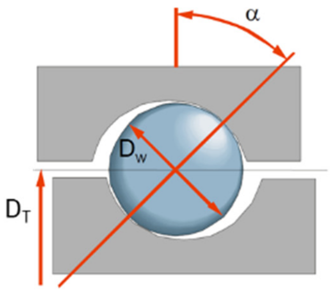


Figure 23: Components of a bearing by Felten (2017)

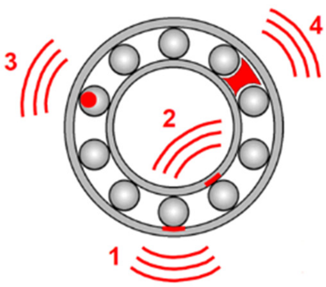
From the bearing geometry, the exciter frequencies can be determined, which occur when a failure is rolled over from the outer ring or inner ring or its rolling element. Figure 24 shows the main dimensions of bearings. (Gasch (2006 p. 649))



α	Angle of contact	[degree]
D_T	Pitch diameter	[mm]
D_W	Rolling element diameter	[mm]
z	Number of rolling elements	[-]
n	Shaft speed	[s^{-1}]

Figure 24: Main dimensions of bearings by Gasch (2006 p. 649)

Regarding to Felten (2017 p. 2), Gasch (2006) and to Weber (2017) they defined the fundamental defect frequencies as follows:



1	Damage at the outer ring
2	Damage at the inner ring
3	Damage at the rolling element
4	Damage at the cage

Figure 25: Damage possibilities at bearings from db Prüftechnik (2017 p. 26)

Fundamental Train Frequency (FTF) is the frequency of the cage:

$$FTF = \frac{n}{2} * (1 - \frac{D_w}{D_T} * \cos(\alpha))\ [Hz]$$

Equation 4: Fundamental Train Frequency

The shaft speed is measured in revolutions per seconds.

The next failure frequency could be the Ball Spin Frequency (BSF). This is the fault frequency of rolling elements:

$$BSF = \frac{D_T}{2 * D_w} * n * \left(1 - (\frac{D_w}{D_T} * \cos(\alpha))^2\right) [Hz]$$

Equation 5: Ball Spin Frequency

Furthermore, the Ball Pass Frequency of Outer Race (BPFO) is defined as following:

$$BPFO = \frac{z}{2} * n * \left(1 - \frac{D_w}{D_T} * \cos(\alpha)\right) [Hz]$$

Equation 6: Ball Pass Frequency of Outer Race

The last definition is the Ball Pass Frequency of Inner Race (BPFI). BPFI is defined as following:

$$BPFI = \frac{z}{2} * n * \left(1 + \frac{D_w}{D_T} * \cos(\alpha)\right) [Hz]$$

Equation 7: Ball Pass Frequency of Inner Race

All these definitions are frequencies caused by rolling over damages in the bearing and requires constant speed. However, it should be noted that the calculation formulas assume ideal rolling. Under real conditions this requirement is very often not fulfilled. In practice, slippage of the rolling element can occur and so ranges around the calculated frequencies should be defined. (Schlussel (2017 p. 21))

A method to classify rolling bearing damages is the envelope analysis. It is an essential tool if complex rolling bearings are installed in the machine and different noises from various sources (e.g. transmissions) are indicated. (Weber (2017))

Figure 26 shows the difference between a time related raw signal, the frequency spectra and the envelope spectra.

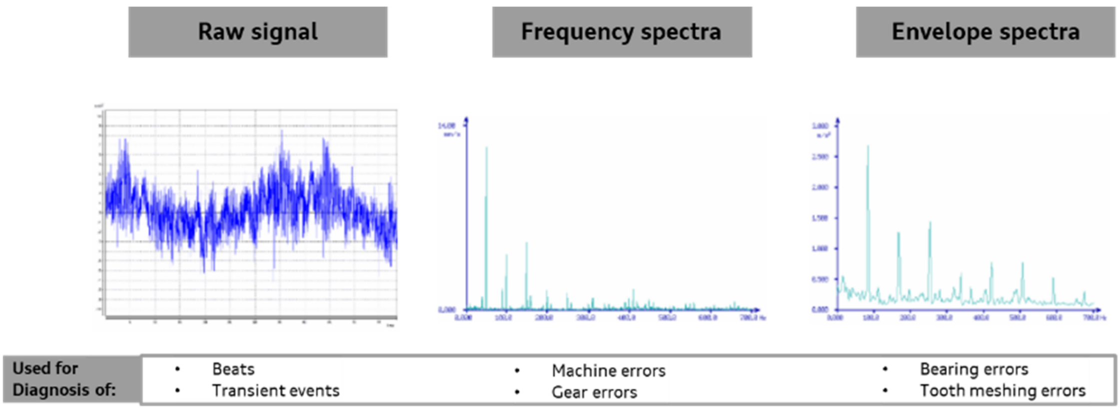


Figure 26: Difference between Raw signal, frequency spectra and envelope spectra modified from db Prüftechnik (2017 p. 22)

The aim of the envelope analysis is to identify the defective bearing component. This is performed by visualizing the shock impulses caused by damages. An intact bearing produces a broadband vibration, if defects occur in the bearing, this uniform oscillation is stimulated by the periodic impacts. The method of the envelope analysis effects a demodulation which extracts the shock repetition sequences (damage frequencies). An envelope analysis regarding to Weber (2017) can be performed as follows:

- High-pass filtering of interference signals
- Equalization of the remaining signal
- Formation of the envelope curve
- Performing a Fast Fourier transform

So, the bearing overruns the damage periodically and this shock impulses are measured with an accelerometer. This process is shown in Figure 27. The raw signal is a graph which contains the acceleration (on the y-axis) over the time (x-axis).

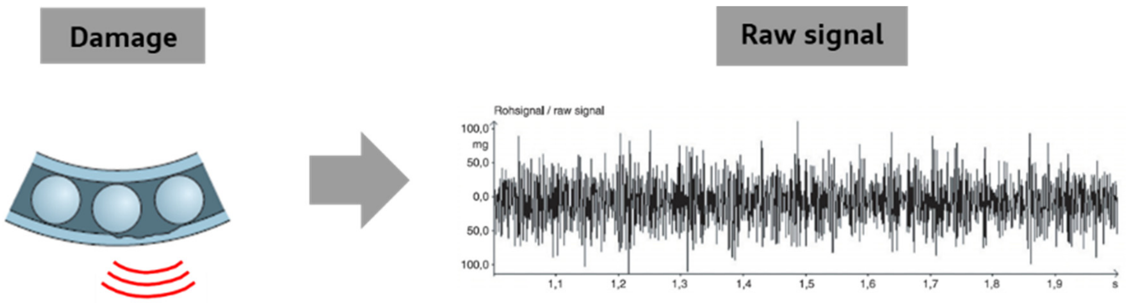


Figure 27: Bearing damage to raw signal

The measured raw signal is a composition of a lot of different oscillations, caused by different machine parts (bearings, transmission, etc.) and the process. To lead this raw signal over to a frequency spectrum a Fast Fourier Transformation (FFT) is done.

A **Fast Fourier Transformation** is a mathematical method to easily decompose a complicated waveform into its frequency components. The FFT is based on the model of the Discrete Fourier Transformation (DFT) which is a calculation rule for the determination of the spectral components of periodic oscillation. It is merely a very easy form of the DFT calculation. (Kopetz (2017 p. 27))

Before the transformation, the signal must be decomposed in time. Therefore, the original signal is divided into several blocks with N samples. This is the so-called decomposition. In the time-dependent analysis (FFT over time), the results of the individual blocks are mapped in a spectrum. (Head Acoustics (2017 p. 1))

Figure 28 shows how a FFT works. A FFT transforms complicated waveforms into a series of discrete sin waves and evaluates each individually. (IMV CORPORATION (2017))

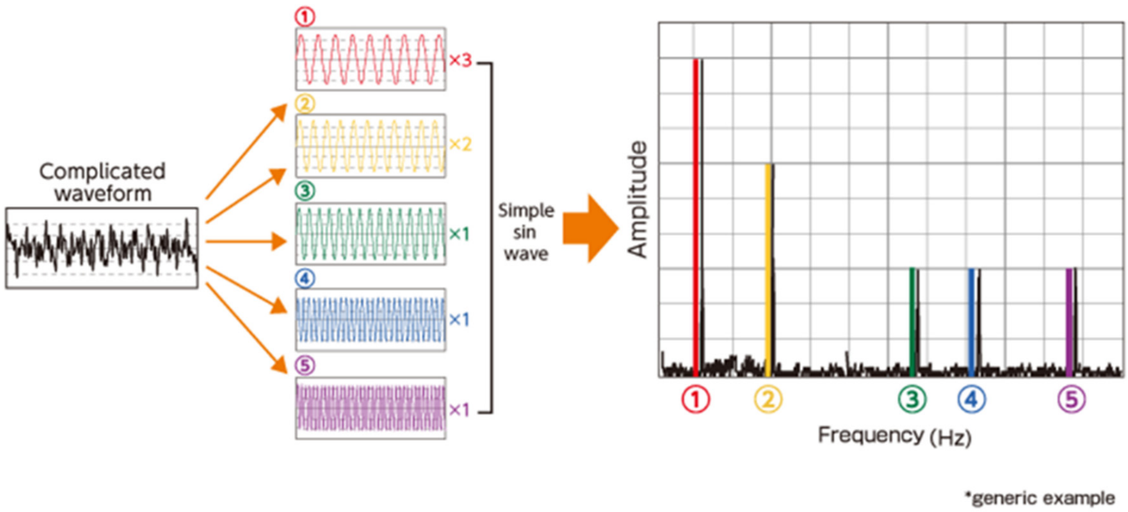


Figure 28: Fast Fourier Transformation by IMV CORPORATION (2017)

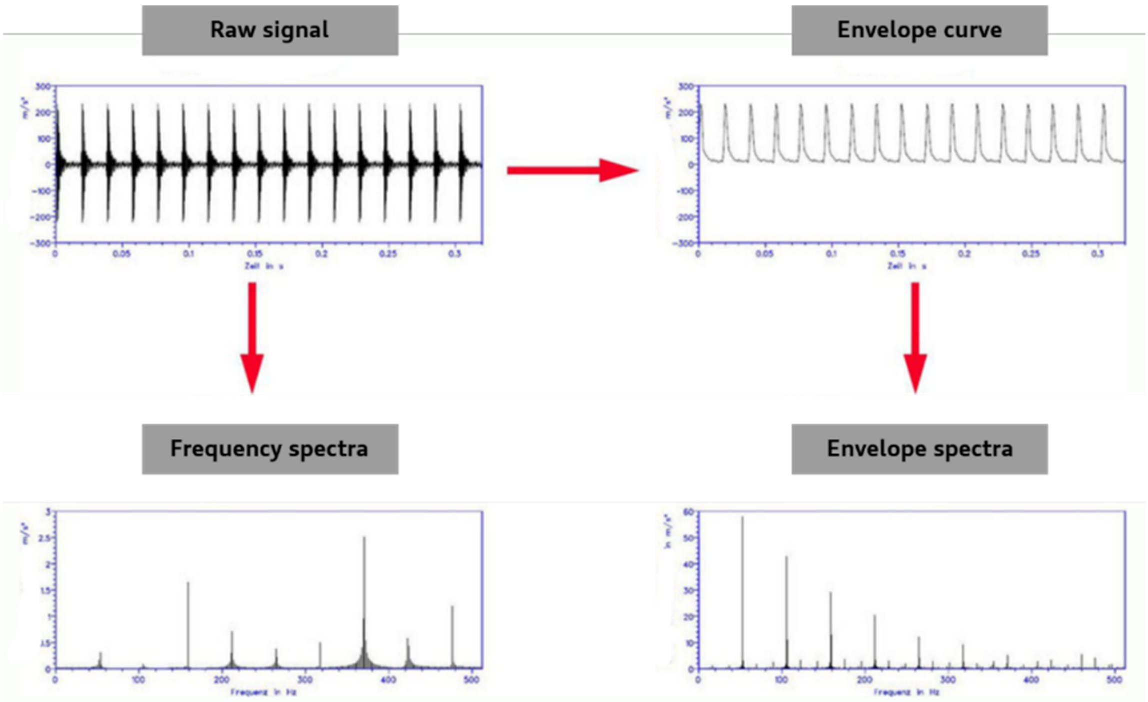


Figure 29: Envelope curve and envelope spectra modified from Wirth (1998 p. 4)

The detection of shock impulses is reliably achieved in the envelope spectrum. At first the envelope curve is extracted from the raw (time) signal. This is shown in Figure 29. This can be done in several ways. Analogue equalization and high-pass filtering are just as suitable as digital equalization, data reduction and high-pass filtering. However, data reduction should be done every time. Afterwards, the amplitude spectrum of the envelope curve is formed with FFT. (Wirth (1998 p. 4))

With the envelop spectra it is possible to allocate specific component frequencies and enables to do diagnosis and draw conclusion to the reason of the failure. The damage frequencies are already included in the original signal, but they are much harder to extract and recognize. (Weber (2017))

At last regarding to Weber (2017) a short example will visualize the complete process. In Figure 30 a bearing is shown with a damage in the outer race. In case of an outer ring damage, there are defects on the running surface of the outer ring. These occur in the load area of the bearing and are therefore a local rolling element damage. Typical defects are e.g. scratches, breakouts, stoppage marks or peelings. A shock pulse is generated at each overrun of the rolling element over the damage (see Figure 30). By means of these periodic excitations and the geometric dimensions of the bearing, the external ring damage in the envelope curve can be detected.

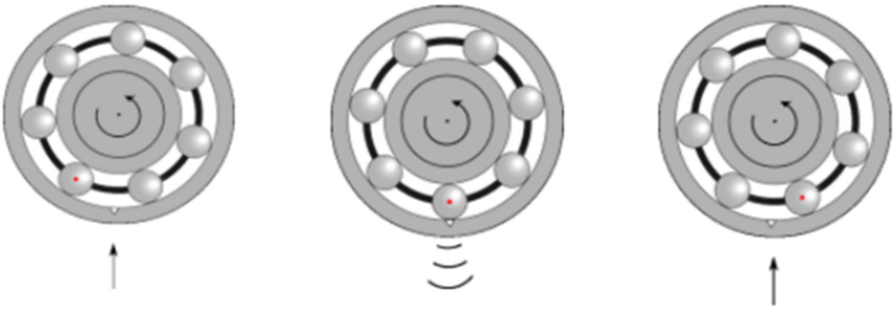


Figure 30: Outer race damage by Weber (2017)

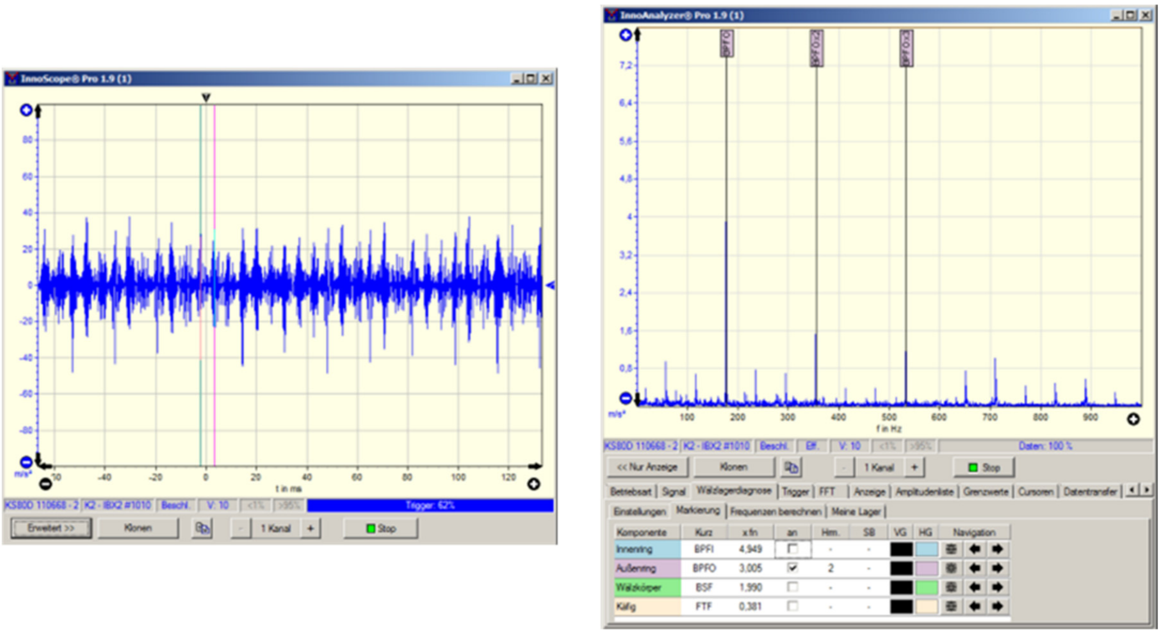


Figure 31: Raw signal and envelope spectra of an outer bearing damage by Weber (2017)

The time signal contains very high periodic signals. The amplitude is a multiple of the values of the undamaged bearing. This suspicion can be confirmed using the envelope analysis. Large peaks appear, which fits to the roll-over frequency of the outer ring and its multiples. In addition, there are frequency bands with smaller amplitudes. In Figure 31 you can see the marked lines BPFO, BPFOx2 and BPFOx3. BPFO represents the outer ring frequency calculated with Equation 6. BPFOx2 and BPFOx3 are the multiples of BPFO. (Weber (2017))

3.4. Thermography

Thermography is a method to measure a temperature of an object contactless. Very often it is not possible to measure a temperature using touching temperature sensors. In these cases, temperature devices like thermography cameras are a good option. (Brecher (2017 p. 503))

Following Klocke (2008 p. 89) a pictorial temperature distribution is determined in thermography.

Their strengths are especially in applications with very high temperatures, in measurements on bodies with very low thermal conductivity and heat capacity, in the case of moving bodies (spindles) and in the case of difficult-to-reach measuring points. The temperature on the objects surface is determined from the emitted heat radiation. However, the measurement is strongly dependent on the emission characteristics of the surface and can lead to incorrect results if the measuring instruments are not used correctly. Moreover, these methods do not reach the accuracies of the contacting sensors. They are within a range of ± 1 K. (Brecher (2017 p. 503)

Thermographic cameras are flexible to use, not so expensive and easy to handle. Disadvantages of this monitoring method are the problem that the measuring is very hard to automate. In case of detecting an increasing temperature most of the time the failure is already far advanced and so there is very less time to react and to fix the failure. To interpret the measuring results expert knowledge is needed. However, this is another disadvantage that experts are needed and they cost a lot. (Pawellek (2013 p. 126))

Furthermore, a disadvantage of thermographic cameras is the handling of the camera. To get consistent results a basic setting (distance to the object, ambient temperature, etc.) must be done. Regarding to this setting the measurement should be done depending on the predefined values (distance, temperature, etc.).

In addition to the thermography cameras, color pyrometers are used. They are used to measure the temperature at a single surface point, which means that the measured temperature is not visualized, but displayed as a numerical value on the measuring instrument. In principle, pyrometers can be distinguished in single-color and two-color pyrometers. The essential difference between these characteristics is the number of measured wavelengths for determining the temperature. In the case of the single-color pyrometer, the radiation emitted from the object to be measured is measured at a wavelength and converted into a temperature (Brecher (2017 p. 504))

3.5. Oil Analysis

Regarding to Figure 15 oil analysis is a very important part of condition monitoring. Oil analysis is to monitor the condition of tribological systems such as gears and bearings for the early detection of damage. Another area of use is the determination of the oil level for the decision for an oil change. The oil is used as an information medium to evaluate the condition of the friction point such as bearings, gear pairings, and sliding pairs. Oil analysis is used to identify certain elements in the used oil, which are not present in the fresh oil but originate from the friction point. It is for deciding on the exchange of a machine component after reaching a certain wear limit. Furthermore, oil analysis is used to reach an early warning of damage and to do preventive maintenance. (Bartz (2017 p. 4ff))

Fedele (2011 p. 92) described in his book that following methods should be done to measure a machine condition:

1. *Analysis the fluid properties*
2. *Analysis of pollutants*
3. *Analysis of debris from wear*

Analysis the fluid properties is a very important method to get information about the level of oil quality. It’s a method which compares the used oil with the property of a new oil. Analysis of pollutants is also important and it’s about the humidity, calculate the particles in the oil or doing glycol tests. At last, the analysis of debris from wear is a method of analyzing which can give direct information about the machine condition. Fedele (2011 p. 92)

Considering to Pawellek (2013 p. 126), he mentioned the advantages and disadvantages in his book. Using oil analyzing it is possible in a very good way to identify the root cause of a damage. Furthermore, this method gives user early information about existing damages and it is possible to recognize complex damage contexts. However, on the other hand there also exist some disadvantages. Nowadays it is not possible to automate this method. In addition to this the analysis is very expensive, because analyzing the oil a laboratory with very expensive devices is needed. Doing laboratory analysis also requires expert knowledge.

4. Feasibility and Verification

Condition monitoring of machines and their components with vibration analysis is nowadays well established in manufacturing areas. It is already used for monitoring component conditions in large wind parks, at hydraulic pumps and electric engines but in the area of monitoring spindle conditions or more precisely bearing conditions, vibration analysis is not often used yet. This chapter illustrates the existing potential for implementing condition monitoring in machining centers to collect information about the spindle (bearing) condition. At first this chapter gives a little insight about the structure and layout of main spindles. Afterwards, it will show the difference in signals between measuring a new or a used spindle. Regarding to the verification part, this chapter gives an overview about existing systems on the market and the evaluation process to determine the best system for the experiments.

A very tough task at AH was the determination of the several types of existing machines at the whole factory site. Reaching the goal to find a system which fits into every machining center was a really challenging task. Regarding to an analysis which was done during to this work, there are different types of main spindles from several manufacturers existing at AH.

Regarding to the aim of this thesis, only condition monitoring systems to identify the main spindle condition are of interest. To achieve this goal, this chapter describes a new system, which was found during the technology screen and was firstly implemented at AH.

4.1. Structure of Main Spindles

Main spindles are used in mechanical machining centers. This machining centers are essential machines for the mechanical production steps and are used for the engine production at AH. A few hundred of these machines are currently in use. Every machining center consists at least of one main spindle. Figure 32 illustrates a typical structure of a mechanical machining center. Normally, it consists of a workpiece changing table where the workpiece is fixed on it, a machine base, a tool magazine for different tools, one or two main spindles and a control panel. (Weck (2005 p. 180))

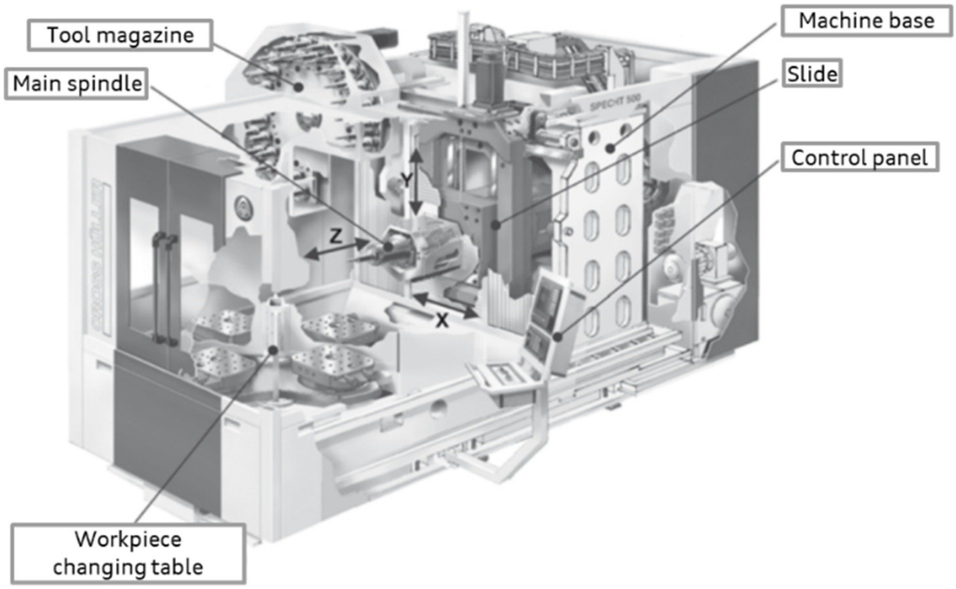


Figure 32: Mechanical machining center regarding to Weck (2005 p. 180)

The main spindle is the last shaft of the main drive. It is directly connected to the workpiece, tool or to the tool holder. The direct proximity of the main spindle to the machining process and to the workpiece assumes specific requirements for design, manufacturing and assembling to ensure the quality of the workpieces. (Hirsch (2016 p. 188) and Neugebauer (2012 p. 291f))

Regarding to Abele (2017 p. 781) the main tasks of main spindles are:

- Turn the tools (grinding, milling, drilling) or the workpiece (turning) precisely
- Transfer the necessary energy to the cutting zone of the tool to remove metal
- Generate the cutting speed
-

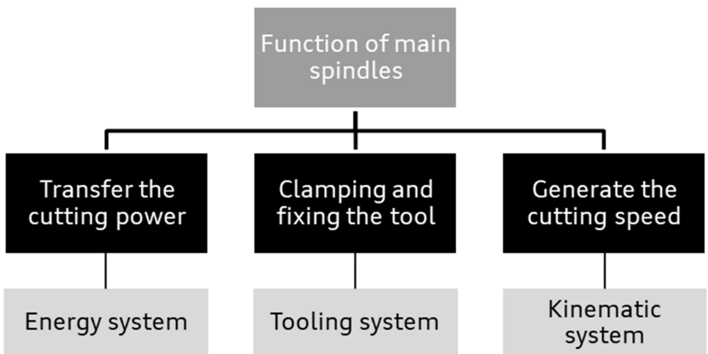


Figure 33: Functions of main spindles modified from Uhlmann (2017 p. 3)

As Neugebauer (2012 p. 292) considered and as shown in Figure 34, a main spindle consists of:

- Main spindle as component
- Bearings for radial and axial position determination and force transmission
- Sealing elements
- Components installed on the main spindle for the drive realization
- Tool or workpiece receiving surfaces
- Functional components of the control and automation system

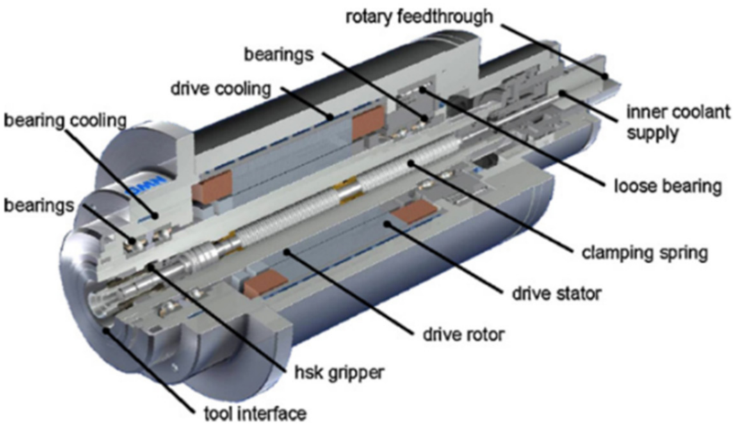


Figure 34: Structure of a main spindle by Abele (2017 p. 782)

Following Hirsch (2016 p. 189), the requirements for this module are:

- Executing a required rotation in a certain speed range and transmitting this movement to a workpiece or tool
- Grabbing and forwarding of the forces and moments (machining, weight and centrifugal forces) necessary for the machining from the work piece or tooling fixture into the frame or to the drive element
- Grabbing the necessary clamping tools
- Securing the intended position of the workpiece or tool even under static, dynamic and thermal stresses.

The front bearing package consists of a radial and an axial bearing. The near position to the machining process particularly requires a very high demand on accuracy and stiffness to ensure the quality of the workpieces. The rear radial bearing is the secondary bearing. Therefore, the front bearing package must absorb all forces. So, the front bearing should be replaced very often to avoid unplanned machine breakdowns. (Neugebauer (2012 p. 292))

4.2. Potential Analysis

Before doing the comparison of existing technologies, it was necessary to determine the overall potential for using vibration analyzing methods, to evaluate the main spindle condition. Therefore, existing data from the spindle repair workshop were used.

At AH, there is an own department in the field of technical services, which is specialized on repairing and overhauling main spindles of machining centers. They can repair and overhaul about 250 spindles per year. Each repair or overhauling process begins and ends with a vibration measurement. To measure the vibrations, the department has their own test bench installed. They do the tests with a condition monitoring system from SKF as shown in Figure 35. They use this system offline, only for measure the vibrations of the bearings. To measure the vibrations of the front and back bearings they use three SKF CMSS 787A accelerometers. Two of them are used at the front bearing to measure the horizontal and vertical vibrations and one is mounted in the near of the back bearing. The measured data is saved locally on a PC in the area of the test bench. The technician uses the software package (@pitude Analyst) from SKF to analyze the measured values.

Figure 35: Used SKF (2017) system for the test bench

Table 4: SKF iMX device explanation

Device	Used for
SKF Multilog Imx	Measurement unit
SKF CMSS 787A	Accerlerometer
SKF @pitude Analyst	software solution for diagnostic and analytic

To evaluate the potential of bearing vibration analysis, two spindles got measured before and after their overhauling. The bearings were replaced during the overhauling process. They come to the spindle repair workshop in case of different fault causes.

4.2.1. Measurement Setup

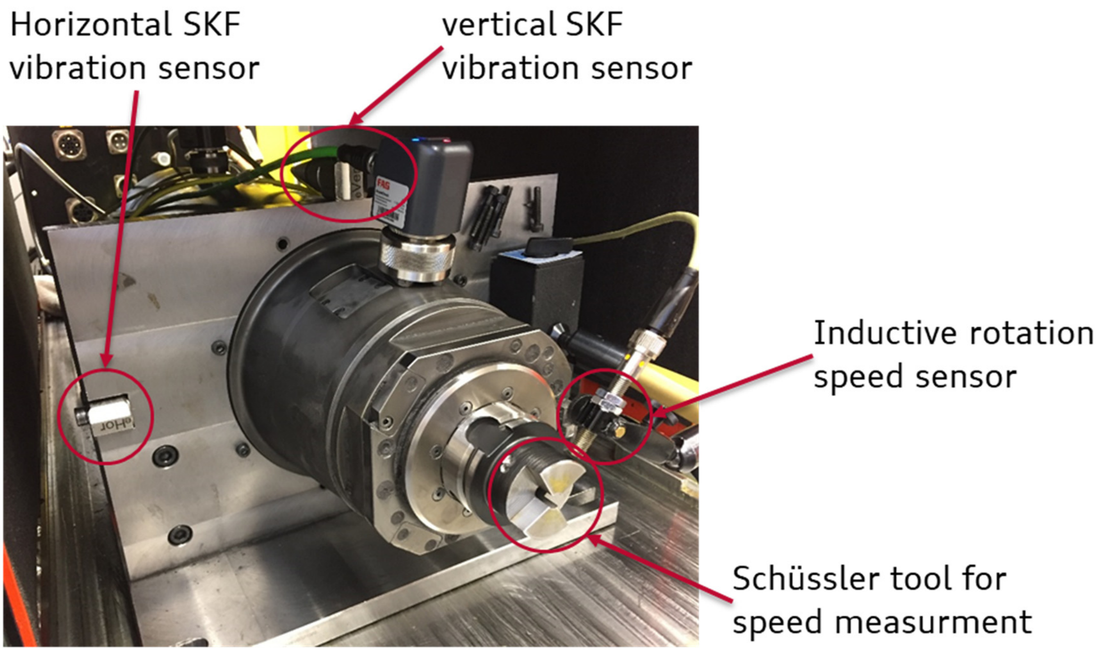


Figure 36: Measurement setup for potential evaluation

Figure 36 shows the setup of the measurement system and sensors at the test bench regarding to the measurements for the potential evaluation.

4.2.2. Procedure

Two spindles manufactured from Kessler were measured before and after the overhauling. During the overhauling process, all bearings were replaced. The measurement was done regarding to a fixed measurement procedure with different speeds and lasted 10 min per measuring. The speed was measured with an inductive rotation speed measurement device. The vibration sensor data was saved and processed by the processing unit from SKF and analyzed with the software @pitude.

Table 5: Experiment parameters for potential evaluation

Aim	General evaluation of the potential of vibration analysis methods
Spindle type	Kessler DMS 112.AM.4.FOS
Spindle serial number	**Spindle 1:** SNo.: 181 090 **Spindel 2:** SNo.: 204 187
Spindle damage cause	**Spindle 1:** low clamping force **Spindle 2:** bearing failure
Tool	Schüssler - No.: 9606399-11
Test parameter	**Speed:** Different rotation speeds **Duration:** 10 min.
Sensors	2 pcs. SKF CMSS 787A front bearing 1 pcs. SKF CMSS 787A back bearing 1 pcs. Inductive rotation speed sensor
Processing unit	SKF Multilog IMx
Software solution	SKF @pitude Analyst

ResultTable 6 illustrates the results of the acceleration measurement of the two different spindles types. This test carried out and showed the differences in measuring vertically or horizontally and draws a conclusion for the optimal sensor position. Table 7 is a summary of all measured values and illustrates the existing potential for vibration analyzing systems.

The results show, that the difference of the emitted vibrations from bearings between an overhauled and a used spindle are in a rage from 50% to 60% measured vertically. Furthermore, the results show only a small difference (approximately 15%) in horizontal direction. The analysis was done regarding to the acceleration measurement with peak to peak values. Afterwards, an average over all these values was calculated.

Table 6: Results of potential evaluation

				Acceleration ACT [g]			
				Peak to Peak		Average	
				Value	Difference	Value	Difference
Spindle 181 090 (clamping force)	FR	vertical (CH1)	Used	0,1414	-23%	0,0079	-75%
			Overhauled	0,1092		0,0020	
		horizontal (CH2)	Used	0,0776	26%	0,0044	-66%
			Overhauled	0,0975		0,0015	
	BK	vertical (CH3)	Used	0,2306	-70%	0,0087	-80%
			Overhauled	0,0684		0,0017	
Spindle 204 187 (bearing damage)	FR	vertical (CH1)	Used	0,4217	-60%	0,0066	-55%
			Overhauled	0,1678		0,003	
		horizontal (CH2)	Used	0,1652	-22%	0,0047	-22%
			Overhauled	0,1288		0,0037	
	BK	vertical (CH3)	Used	0,376	-50%	0,0066	-53%
			Overhauled	0,189		0,0031	

Table 7: Potential analyzing result summary

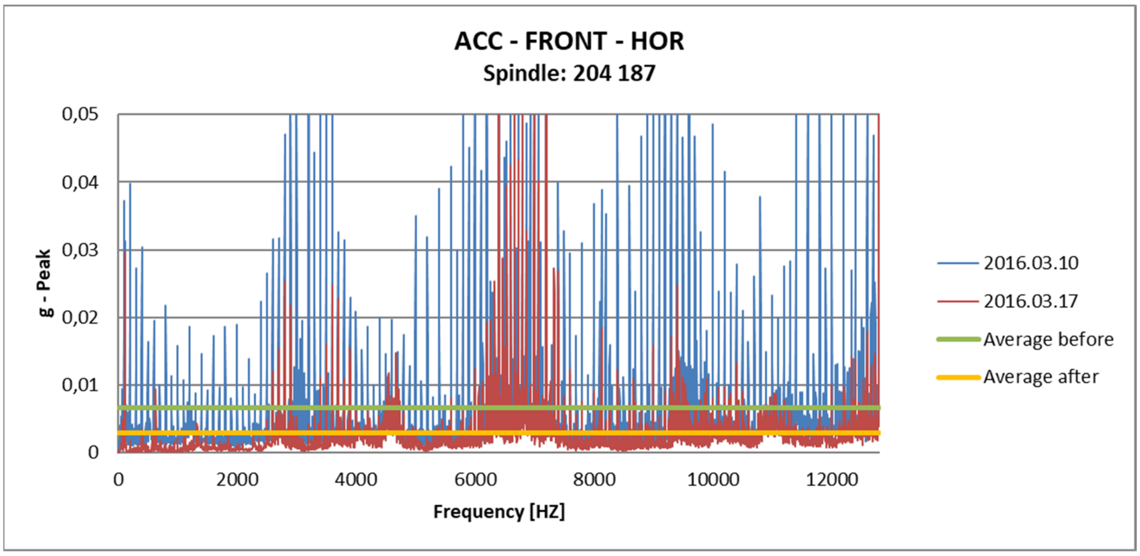
	Acceleration ACT [g]		
	Peak to peak	Average	Average
vertical FRONT	-41%	-65%	**-53%**
horizontal FRONT	2%	-29%	**-14%**
vertical BACK	-60%	-67%	**-63%**

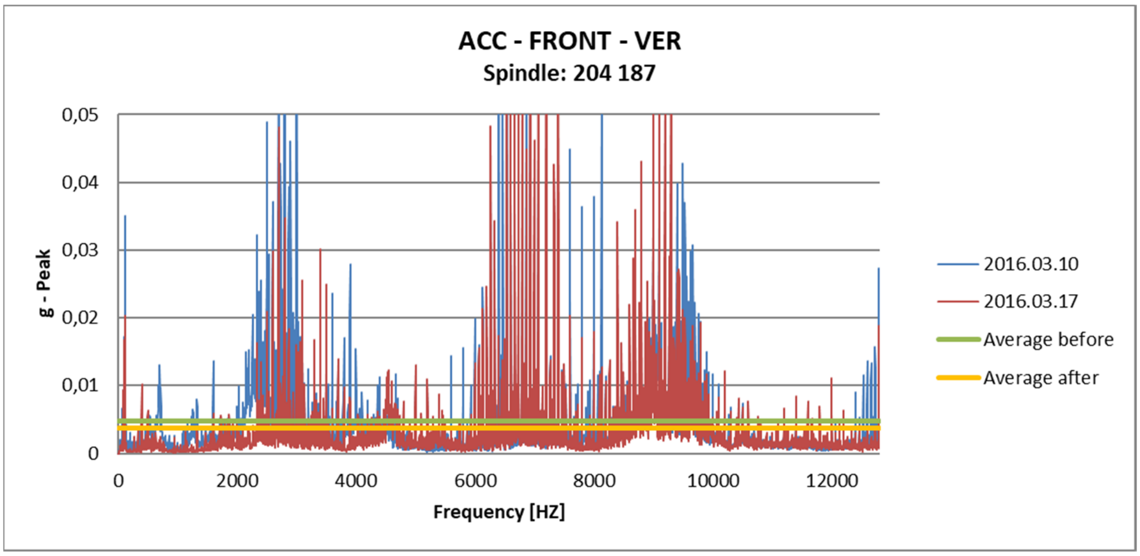
Furthermore, the tests also showed, that even used spindles, which are not overhauled because of damaged bearings, show improvements in the frequency spectra after an overhauling. Figure 37 is a visualization of the results from Table 7. You can clearly see the difference in the averaged values. Only at the vertical measurement, the difference is not so high. Regarding to these tests, the optimal sensor position is vertically.

Figure 37 illustrates two measurements. The spectra of the measurement before the overhauling is marked with the blue color. The red color illustrates the spectra from the measurement after the overhauling. The green line indicates the average before the measurement and the orange line after the overhauling. On the x-axis, you can see the frequencies. The y-axis contains the deflection peak values.

These tests were done to evaluate the potential of vibration analyzing methods. They weren't done for finding possible failure root causes!

Appendix 1 shows the results of the second spindle measurement (spindle 181 090)





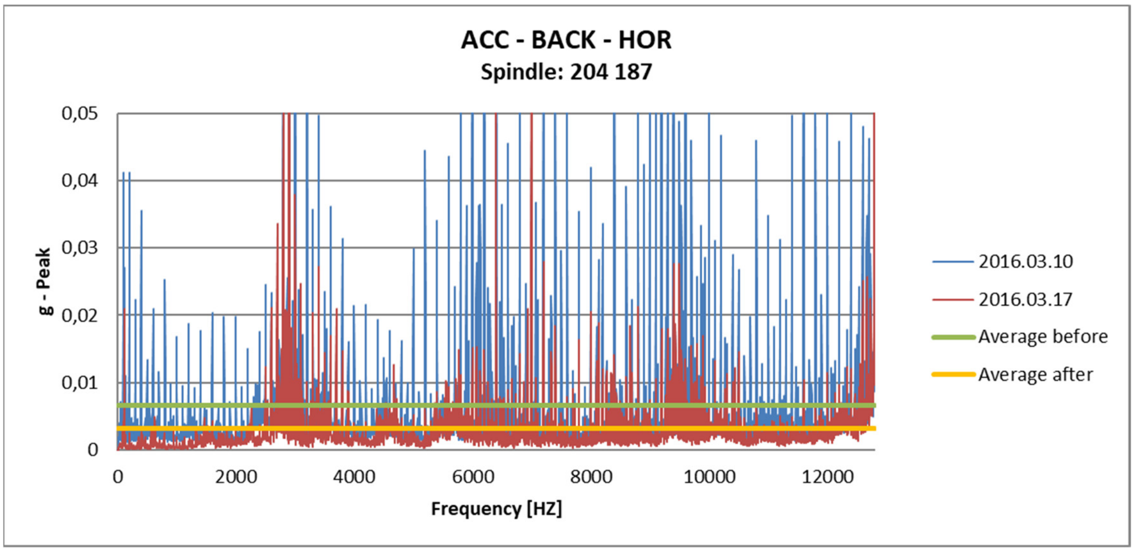


Figure 37: Measuring results potential analysis from spindle 204 187

4.3. Effort Estimation for Machine Upgrading

As shown in chapter 4.2, the potential to implement condition monitoring systems to the main spindle of a machining center is very high. Due to this, this chapter describes the different possibilities to implement such systems. As already mentioned in the introduction of chapter 4, AH uses a lot of different manufacturers with several spindle types for their machining centers. Figure 38 gives an overview about the used manufacturers.

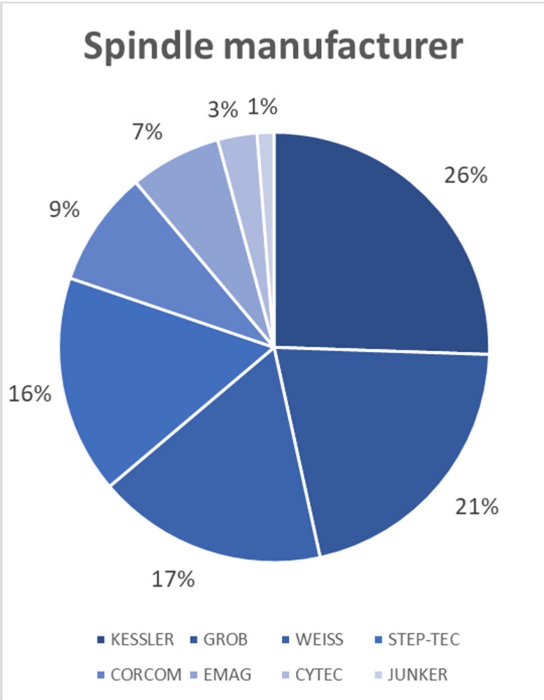


Figure 38: Different spindle types at AH

Caused by these several manufacturers, every type of spindle is different in the geometry, dimension, material, component, design etc. Some spindles already have integrated sensors to measure the spindle condition. These sensors could be measurement sensors for temperature or acceleration sensors for measuring the vibration.

An investigation showed, that a considerable number of spindles already include platinum temperature sensors (PT100) to measure different temperatures inside the spindle. About 95% of all spindles include temperature sensors to measure the motor coil temperature. Three-quarter of all spindles are equipped with temperature sensors at the front bearing. One quarter of all spindles have already installed temperature sensors for measuring the back-bearing temperature. Furthermore, ten percent have installed vibration measurement sensors. A less number of Kessler spindles have a preliminary space to mount vibration sensors.

These results are visualized in Figure 39 and shows potential places for upgrading the existing machining centers using monitoring systems with front bearing sensor and vibration sensors.

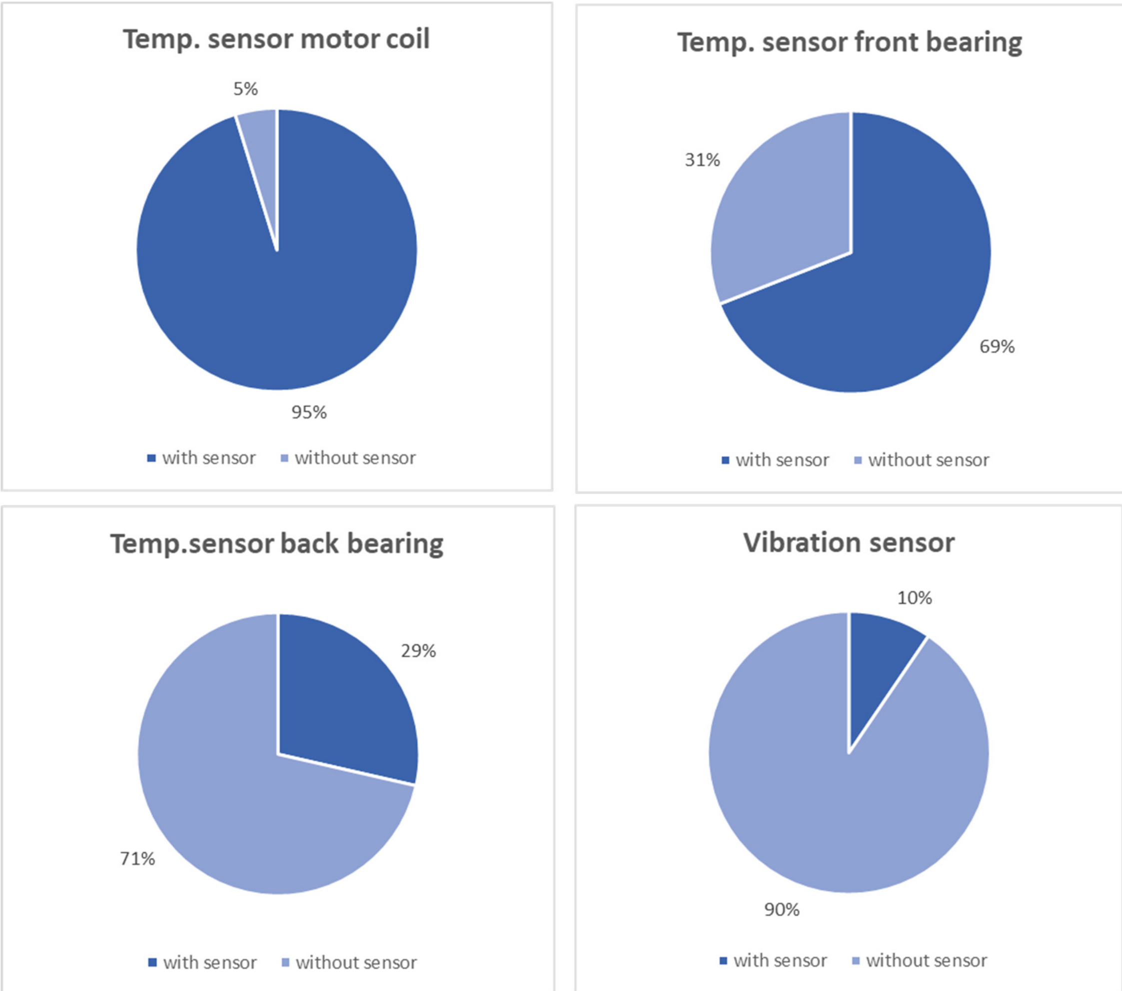


Figure 39: Existing sensor systems for spindle monitoring at AH

A deeper analysis showed, that the already integrated sensors are assembled in the spindles but not used and not wired in the machining centers at AH. For instance, at the production line ZK4, an installed Specht 600 DUO machining center already uses a vibration measurement device form IFM. (see Figure 40). But this CM system is only implemented in the machine and not used at for collecting condition information. Figure 41 and Figure 42 show the existing vibration sensors at Corcom spindles and the preliminary space at Kessler spindles.

Figure 40: Already installed diagnosis system

Figure 41: Corcom spindle with integrated IBIS accelerometer

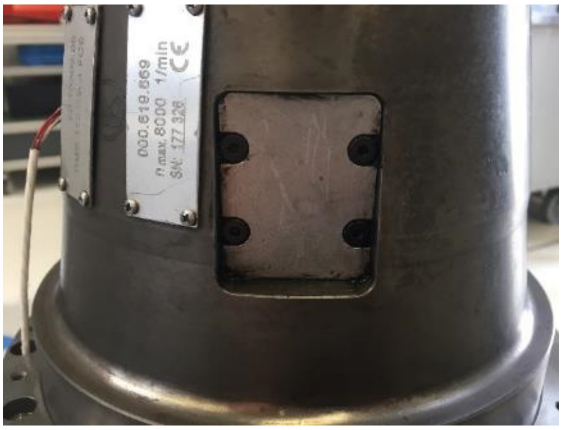


Figure 42: Kessler spindle with preliminary space to implement an accelerometer

This analysis showed, that the effort to implement temperature monitoring of the coil temperature is very low. Also, the effort to realize temperature monitoring at the front bearing is manageable. Implementing or using the installed systems at Kessler and Corcom spindles for monitoring the bearing vibrations is not a very tough task. Using the already installed systems with temperature and vibration monitoring sensors and the spindles with preliminary space (Kessler) for implementing sensors will cover about half of all machines at AH.

A central question that needs to be addressed in this context is the possibility to install and implement processing units in machining centers. Due to the use of a production data acquisition (PDA) system, all machines are already connected to the network and therefore using online systems will be the best option.

4.4. Comparison of Technologies & Benefit Analysis

After evaluating the potential for using monitoring systems at machining centers, it is possible to draw a first conclusion: The use of monitoring systems is useful and manageable! This chapter describes the way from the market analysis to the choice of three systems.

Regarding to the goal of this thesis, a market research in the field of online condition monitoring systems was done. A lot of systems are already available on the market but most of them don’t fulfill the requirements for monitoring the condition of main spindles in machining centers. A large number are used for monitoring the condition of bearings in wind parks or at machines which are used stationary (with constant speed) or for monitoring the operating process. The requirements for monitoring the spindle conditions are:

- Online measurement system
- Interface to connect at least two accelerometers with a sensitivity of 100mV/g
- Interface to connect at least two temperature sensors (PT100)
- Possibility to implement the processing unit and the sensor to the machining center
- Assembly space to integrate vibration sensors in the spindle
- Digital input to start and stop a measurement (trigger signal)
- Possibility to export the raw data to the PDA system

4.4.1. Market Research

The market research has shown that the following systems are possible condition monitoring systems to monitor the spindle condition. These systems are compared and evaluated later in chapter 4.4.2. Now the different components and insights to the abilities and specifications of each component are explained.

SKF

SKF offers two possible products to monitor spindle conditions with accelerometer sensors. The first product (shown in Table 8) consists of a processing unit mounted in a separate control unit. It is possible to connect sixteen analog and eight digital sensors to one processing unit. The combination with SKF CMSS 787A vibration sensors is already in use at the test bench at AH. This was the reason why this type of sensor was chosen for the comparison. Also, other standard vibration sensors could be used with this processing unit. To visualize and analyze the measuring data a software package from SKF called @pitude was taken. Also, this software package is already in use at the test bench. The big advantage of this system is the existing knowledge about the usage and handling. Furthermore, the software package gives the possibility to use a database with bearing defect frequencies (as discussed in chapter 3.3). This database is limited to frequencies only for SKF bearings.

Table 8: SKF Multilog IMx-S with SKF CMSS 784A Sensor and SKF @pitude Analyst software package by SKF (2017)

Processing Unit	SKF Multilog IMx-S  **Figure 43: SKF (2017) Multilog IMx-S**	• Multilog online system • Dimensions: 500 × 400 × 155 mm • Analog inputs: 16 • Digital inputs: 8 • Data storage on time, event, or alarm condition • Ethernet	• Signal processing: - FFT - Acceleration enveloping - Time waveform
Vibration sensor	SKF CMSS 787A  **Figure 44: SKF (2017) CMSS 787A**	• For use in hazardous areas • Optimal for use with SKF on-line system • Dimensions: 53x25,2x26mm • Meets stringent CE, EMC requirements • Rugged, corrosion resistant and hermetically sealed	• Sensitivity: 100 mV/g • Sensitivity precision: ±5% at 25 °C • Frequency range: - ±10%: 1,0 to 5 000 Hz - ±3 dB: 0,7 to 10 000 Hz • Voltage source: 18 to 30 V DC
Software package	SKF @pitude Analyst  **Figure 45: SKF (2017) @pitude Analyst**	• One software program to manage asset condition data from portable and on-line devices • Diagnosis and analysis: - Spectrum - Time waveform • Different alarm types	• Graph displays: - Trend - Spectrum - Time domain - Waterfall • Live view

The second product offered from SKF is a combination of a sensor, data collector and transmitter in one device. As shown in Table 9 this is a wireless product without a need of an external power source. The power comes from an internal battery and offers power for 5 years without changing or charging the battery. Due to the easy installation SKF promises very low installation costs. A big disadvantage of this system are the dimensions. The system has a height of 100mm. Regarding to the specification of analytic possibilities and frequency range it is like the first SKF product. The software package is the same than before. Therefore, there is no difference in the analytic possibilities. Another disadvantage of this product is the problem that there is no ability to connect external sensors like temperature sensors to the processing unit. The device offers no inputs.

Table 9: SKF CMWA 8800 with SKF @pitude Analyst software package by SKF (2017)

Processing Unit + vibration sensor	SKF CMWA 8800  **Figure 46: SKF (2017) CMWA 8800**	• combines a sensor, data collector and radio • Reduced installation costs – no wires • Dimensions: D35 × 100 mm • Analog inputs: 0 • Digital inputs: 0 • Data storage on time, event, or alarm condition • Wireless communication	• Signal processing: - FFT - Acceleration enveloping - Time waveform • Sensitivity: 100 mV/g • Sensitivity precision: ±5% at 25 °C • Frequency range: 10 Hz to 1 kHz • Voltage source: Internal 3.6 V battery
Software package	SKF @pitude Analyst  **Figure 47: SKF (2017) @pitude Analyst**	• One software program to manage asset condition data from portable and on-line devices • Diagnosis and analysis: - Spectrum - Time waveform • Different alarm types • Bearing database included	• Graph displays: - Trend - Spectrum - Time domain - Waterfall • Live view

IFM

Using the IFM VSE 100 processing unit offers the possibility to use sensors from different manufacturers. The processing unit offers the ability to mount the device directly into the electric cabinet of a machining center. Furthermore, the device can be mounted on a DIN-rail. The chosen sensor IBIS AE100.942 is a special sensor and is suitable to mount into the predetermined space at Kessler spindles. The software package from IFM has an included database for bearing defect frequencies. It should be considered that IFM is not a bearing producer, therefore the existing database is very small. However, the software offers no possibility to start and stop the measurement by an external trigger signal. The record button must be pressed by hand to start and stop a measurement. This is a very big disadvantage of this system.

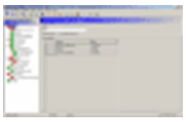
Table 10: IFM VSE 100 with IBIS AE100.942 vibration sensor and IFM efector octavis software package by IFM (2017) and IBIS (2017)

Processing Unit	IFM VSE 100  **Figure 48: IFM (2017) VSE 100**	• Online system • Dimensions: 50 × 105 × 114 mm • Inputs: - 4 dynamic - 2 static • Output: - 2 digital - 1 analog • Data storage on time • Ethernet	• Operating voltage: 24V DC • Sampling rate: <100 ksamples
Vibration sensor	IBIS AE100.942  **Figure 49: IBIS (2017) AE100.942**	• Accelerometer for vibration and bearing condition monitoring • Heavy Duty design • Dimensions: 25x25x22mm • Designed for conditions inside the machining center	• Sensitivity: 100 mV/g • Sensitivity precision: ±10% at 25 °C • Frequency range: - 0,5 - 10.000 Hz • Voltage source: 18 to 28 V DC
Software package	IFM efector octavis  **Figure 50: IFM (2017) efector octavis**	• One software program to manage asset condition data from portable and on-line devices • Bearing database included • Different alarm types	• Data monitoring • Counter monitoring • I/O monitoring • Spectrum monitoring • Raw data monitoring • History monitoring

FAG

Also, FAG offers two product lines to monitor a spindle condition. The first product line is a multichannel condition monitoring system called **ProCheck** and gives the opportunity to connect several sensors to one processing unit. Due to the big dimensions of the processing unit it is hard to implement it in a machining electric cabinet. Like the IFM system, different sensors can be used with the FAG system. A disadvantage of this product is the old software package. It is limited in the range of function, has a very old user interface and offers no bearing database.

Table 11: FAG (2017) ProCheck with IBIS(2017) AE100.942 vibration sensor and FAG software package

Processing Unit	FAG ProCheck  **Figure 51: FAG (2017) ProCheck**	• Online system • Dimensions: 400 × 300 × 190 mm • Inputs: - 8 analog • Output: - 8 analog - 16 digital • Ethernet	• Operating voltage: 24V DC • Measurement functions - Time signal - spectrum - demodulated signal - acceleration (RMS) - velocity (RMS) - displacement (RMS)
Vibration sensor	IBIS AE100.942  **Figure 52: IBIS (2017) AE100.942**	• Accelerometer for vibration and bearing condition monitoring • Heavy Duty design • Dimensions: 25x25x22mm • Designed for conditions inside the machining center	• Sensitivity: 100 mV/g • Sensitivity precision: ±10% at 25 °C • Frequency range: - 0,5 - 10.000 Hz • Voltage source: 18 to 28 V DC
Software package	FAG ProCheck software  **Figure 53: FAG (2017) ProCheck Administrator**	• Configuration Manager • Remote Server/Data Link/ E-Mail Link/Transfer Link • Bearing database included	• Trend analysis • FFT analysis • Waterfall diagram and sonogram • History monitoring

The further development and a very new product of FAG is the **SmartCheck**. The SmartCheck is a compact, innovative and modular on-line measuring system for permanent decentralized machines and process parameter monitoring. FAG SmartCheck is suitable for the early detection of rolling bearing damage, unbalance and alignment errors. It is a plug and play system and offers an automatic alarm adjustment using a self-learning mode. FAG (2017)

Furthermore, FAG offers the possibility to get a complete palette of services out of one hand (consulting, launching, remote service, maintenance contracts and training). Additionally, it is possible to implement SmartCheck into the existing process landscape (e.g. SAP). This is shown as an example in Figure 54. (Schaeffler Technologies AG & Co. KG (2017 p. 1f))

Another advantage of the system is the possibility to connect other external sensors to the device. On the other side, very significant disadvantages are

- the big dimensions of this product and
- the used materials (plastic). It is not possible to mount this device inside a machining center in the working area. Coolant and chips can damage the unit very easily.

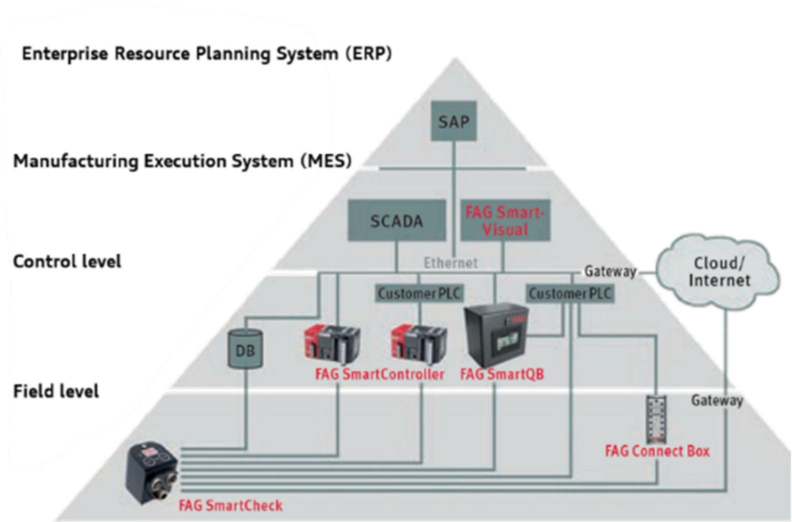


Figure 54: Integration of SmartCheck in the process landscape by Schaeffler Technologies AG & Co. KG (2017 p. 2)

For this device, FAG developed a new software with integrated database for bearing defect frequencies and very good options for visualization and user handling. The database also includes bearing types from external manufacturers like SKF. It is possible to connect a smartphone with the SmartCheck. Therefore, FAG developed their own app. In this app, the actual condition of the observed machine component is displayed.

Figure 55: FAG (2017) SmartCheck App

Table 12: FAG (2017) SmartCheck with SmartUtility

Processing Unit **+** **vibration sensor**	FAG SmartCheck  **Figure 56: FAG (2017) SmartCheck**	• Combines sensor and processing unit in one device • Dimensions: 44 x 57 × 55mm • Input: - 2 analog - 1 digital • Output: - 1 analog - 1 switch output • Data storage on time, event, or alarm condition • Ethernet communication	• Measuring functions: - Acceleration - Velocity (Integration) - Temperature - Process parameters (pressure, speed) • Signal processing: - Time signal - Envelope curve - Spectra - Trend analysis - Rotation speed • Frequency range: 0,8 Hz - 10 kHz • Voltage source: 11-32V DC
Software package	FAG SmartUtility  **Figure 57: FAG (2017) SmartUtility**	• Diagnosis and analysis: - Spectrum - Time waveform • Saved history • Different alarm types • Bearing database included	• Graph displays: - Trend - Spectrum - Time domain - Waterfall • Live view

Sequoia

Normally, Sequoia offers products in the field of condition monitoring for process monitoring. Especially for the purpose to visualize the main spindle condition, they further developed the existing process monitoring to a monitoring system for spindles. The combination of "SeTAC TK Full Interface" as the processing unit and "SeTAC TK sensor" should cover a new area for the company. It is possible to mount the interface into the machining center electric cabinet. The interface is very small and fits to a DIN-rail. On the other hand, the system doesn't offer a possibility to connect other sensors like temperature sensors to the processing unit. Table 13 shows that the functionality of the software package is very low. There is no opportunity for trend analysis or visualizing the vibrations in a spectrum. This software is rather designed for process monitoring than condition monitoring.

Table 13: Sequoia (2017) SeTAC TK Full Interface with SeTAC TK vibration sensor and SeTAC Machine Airbag software package

Processing Unit	SeTAC TK Full Interface  **Figure 58: Sequoia (2017) SeTAC TK Interface**	• Online system • Act as a machine black box • Dimensions: 400 × 300 × 190 mm • 2 digital inputs • 3 relay outputs • Ethernet	• Operating voltage: 24V DC • logging and time-based cataloguing of: - collisions - vibration overloads • calculate spindle effective hours of operation
Vibration sensor	SeTAC TK  **Figure 59: Sequoia (2017) SeTAC TK**	• Accelerometer for spindle condition monitoring • Heavy Duty design • Dimensions: 30x55x15 mm • Triaxial • Sturdy, shock resistant and compact	• Sensitivity: 100 mV/g • Frequency range: - 0 – 2500 Hz • Voltage source: 18 to 26 V DC
Software package	SeTAC Machine Airbag	• Individual alarm setting • Implementing filters • Event log	• FFT analysis • No bearing database

4.4.2. Technical Benefit Analysis – Scoring

Regarding to the shown possibilities examined in the market research, it was necessary to analyze and evaluate these possibilities. The aim of this analysis was to determine the best three products for later and deeper analysis on the test bench. Only the technical aspects like space requirements, functionality, effort for technical integration, usability and quality were considered in this technical analysis. The best and easiest way to determine the three best products was the use of a benefit analysis.

The benefit analysis is to compare decision alternatives based on qualitative factors. The guiding principle is the fragmentation of a questionnaire into individual criteria, which are assessed afterwards for their own. This makes it possible to compare alternatives in an objective way. The result is the score (benefit) of each considered alternative. (Kühnapfel (2013 p. 87))

The procedure for the benefit analysis regarding to Kühnapfel (2013 p. 87ff) is standardized and contains following steps:

1. Establish the target system and any secondary constraints
2. Selection of decision alternatives
3. Determination of criteria
4. Weighting of the criteria
5. Choosing a rating scale
6. Evaluation of the criteria
7. Mathematical calculation of the benefit values
8. Sensitivity analysis

Regarding to this procedure, the scoring model as shown in Table 17 was created. The systems used for scoring are systems like described in chapter 4.4.1. The main criteria are classified in functionality, technical integration, handling and support. The weighting of the criteria are shown in the following table:

Table 14: Weighting of criteria

Criteria	Weighting
Functionality	**30%**
Technical integration	**40%**
Handling	**20%**
Support	**10%**

Due to this weighting, sub criteria were defined and even weighted in relation to the main criteria. An example is given in Table 15.

Table 15: Example with sub criteria and their weighting

Criteria		Level 1	Level 2	Relevant
Functionality		**30%**		
	Features		50%	15,00%
	Product maturity		15%	4,50%
	Complexity		35%	10,50%

Afterwards, all criteria and single systems were evaluated and ranked independently with a scholar grading system as shown in Figure 60.

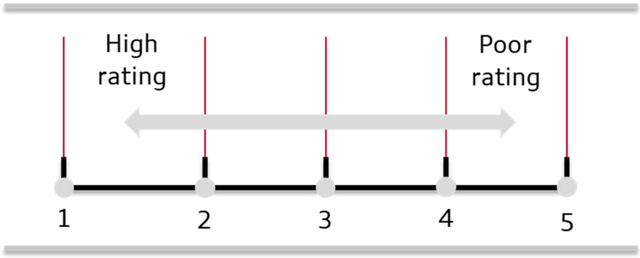


Figure 60: Scholar rating system modified from Kühnapfel (2013 p. 96)

After the grading, the mathematical calculation offers the result for the best three systems. The order of these systems is:

Table 16: Results of technical benefit analysis

System		
FAG SmartCheck	IFM - VSE100 + IBIS AE100.942	SKF iMx + SKF Sensor CMSS 787A
1	2	3

Result

The benefit analysis is the base for further tests performed on the test bench. The analyze determined that **FAG SmartCheck** is the best system for use regarding the assumed criteria and weighting. Using this system brings the problem, that the available space in the machining centers is not big enough to implement the SmartCheck. Furthermore, this system has a bad resistant against coolant and chips. A better option will be the IFM VSE100 with the IBIS AE100.942 accelerometer. It is possible to integrate the sensor in the predetermined space at Kessler spindles. Additionally, the processing unit is easy to handle and mount into the electric cabinet. The third - already existing system in the test bench area - is the SKF iMx with the CMSS 787A sensor. Parameters like handling, external signals for starting-stopping measuring jobs and the usability of the software are not primary part of this evaluation. They are taken into consideration later in the experimental tests.

Discussions with the experts from FAG - and this is the reason why the SmartCheck is even used for the evaluation – filtered out, that there is a new product in development which is based on the SmartCheck but further developed especially for the needs at AH. This new product (prototype) is described deeper in the next chapter.

Table 17: Technical scoring model for different monitoring systems

				System											
				FAG SmartCheck		FAG ProCheck + IBIS AE100.942		SKF CMWA 8800		SKF iMx + SKF Sensor CMSS 787A		Sequoia SeTac TK Full Interface		IFM - VSE100 + IBIS AE100.942	
	Weighting														
Criteria	**Level 1**	**Level 2**	**Relevant**	**Points**	**Total**	**Points**	**Total**	**Points**	**Total**	**Points**	**Total**	**Points**	**Total**	**Points**	**Total**
Functionality	**30%**														
Features		50%	15,00%	1	0,15	3	0,45	2	0,30	3	0,45	3	0,45	3	0,45
Product maturity		15%	4,50%	3	0,14	3	0,14	4	0,18	1	0,05	3	0,14	1	0,05
Complexity		35%	10,50%	1	0,11	3	0,32	3	0,32	3	0,32	2	0,21	2	0,21
Sum					**0,39**		**0,90**		**0,80**		**0,81**		**0,80**		**0,71**
Technical integration	**40%**														
Integration to the machining center / space requirements		40%	16,00%	4	0,64	3	0,48	4	0,64	2	0,32	2	0,32	2	0,32
Connectivity to the machine		10%	4,00%	5	0,20	3	0,12	5	0,20	3	0,12	2	0,08	3	0,12
Connectivity to the PDA		10%	4,00%	1	0,04	1	0,04	1	0,04	2	0,08	1	0,04	1	0,04
Effort to integrate into the network		10%	4,00%	2	0,08	2	0,08	1	0,04	2	0,08	2	0,08	2	0,08
Technical effort for integration		15%	6,00%	2	0,12	2	0,12	1	0,06	2	0,12	3	0,18	3	0,18
Protection class / robustness		15%	6,00%	3	0,18	1	0,06	4	0,24	1	0,06	2	0,12	1	0,06
Sum					**1,26**		**0,90**		**1,22**		**0,78**		**0,82**		**0,80**
Handling	**20%**														
Software - analytic possibilities		40%	8,00%	1	0,08	1	0,08	1	0,08	1	0,08	1	0,08	1	0,08
Usability		30%	6,00%	1	0,06	3	0,18	1	0,06	3	0,18	2	0,12	3	0,18
Quality		10%	2,00%	3	0,06	1	0,02	3	0,06	1	0,02	2	0,04	1	0,02
Sensor assembling		20%	4,00%	2	0,08	3	0,12	2	0,08	3	0,12	3	0,12	3	0,12
Sum					**0,28**		**0,40**		**0,28**		**0,40**		**0,36**		**0,40**
Support	**10%**														
Manufacturer publicity		20%	2,00%	1	0,02	1	0,02	1	0,02	1	0,02	3	0,06	1	0,02
Support / Remote-Control		60%	6,00%	1	0,06	1	0,06	1	0,06	1	0,06	3	0,18	3	0,18
Product description / details availability		20%	2,00%	1	0,02	1	0,02	2	0,04	2	0,04	2	0,04	1	0,02
Sum					**0,10**		**0,10**		**0,12**		**0,12**		**0,28**		**0,22**
Total points:	**100%**		100%		**2,030**		**2,300**		**2,415**		**2,110**		**2,255**		**2,125**

Mark note: 1 = very good; 2 = good; 3 = satisfying; 4 = enough; 5 = not enough

Place	FAG SmartCheck	FAG ProCheck + IBIS AE100.942	SKF CMWA 8800	SKF iMx + SKF Sensor CMSS 787A	Sequoia SeTac TK Full Interface	IFM - VSE100 + IBIS AE100.942
	1	**5**	**6**	**2**	**4**	**3**

4.5. Prototype FAG SmartCheck

Due to different conversations with experts from FAG (Schaeffler) it turned out that the already existing prototype can be used with little modification for monitoring the spindle condition in machining centers. The system is based on the already existing SmartCheck but the processing unit is now separated in an own device. Using the prototype gains the possibility to use a multichannel system. It is possible to use more than one and different sensors (temperature, digital signals, vibration sensor, etc.) from different manufactures. Figure 61 shows the system and the electronic components of the system mounted in an electrical box.

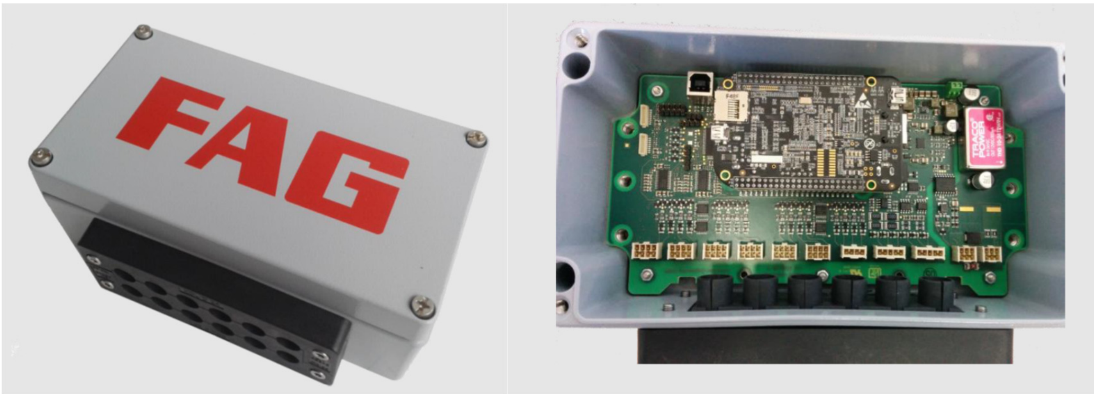


Figure 61: FAG SmartCheck Prototype
by Schaeffler Technologies AG & Co. KG (2017 p. 3)

Regarding to the specific use at AH, Schaeffler customized the prototype to the requirements regarding to an implementation into a machining center. Therefore, they changed one temperature input from a PT1000 to a PT100 input. Furthermore, only 2 inputs for accelerometers and only 2 inputs for digital speed are available. Referring to the normal SmartCheck there is no difference in the measuring possibilities. Also, the software package is the same with same functionalities. The main difference in using the prototype is the possibility to use different vibration sensors with one processing unit. This gains the opportunity to connect the integrated IBIS100.942 sensor with the processing unit. Table 18 gives an overview about the different system components.

Table 18: FAG SmartCheck prototype with IBIS AE100.942 Sensor and FAG SmartUtility

Processing Unit	FAG SmartCheck prototype  **Figure 62: FAG SmartCheck prototype by Schaeffler Technologies AG & Co. KG (2017 p. 3)**	• Online system • Dimensions: 220 × 120 × 80 mm • Inputs: - 6 temperature (PT1000) - 6 vibration - 2 digital speed • Output: - CAN • Ethernet	• Operating voltage: 24V DC • Measurement functions - Time signal - spectrum - demodulated signal - acceleration (RMS) - velocity (RMS) - displacement (RMS)
Vibration sensor	IBIS AE100.942  **Figure 63: IBIS (2017) AE100.942**	• Accelerometer for vibration and bearing condition monitoring • Heavy Duty design • Dimensions: 25x25x22mm • Designed for conditions inside the machining center	• Sensitivity: 100 mV/g • Sensitivity precision: ±10% at 25 °C • Frequency range: - 0,5 - 10.000 Hz • Voltage source: 18 to 28 V DC
Software package	FAG SmartUtility  **Figure 64: FAG (2017) SmartUtility**	• Diagnosis and analysis: - Spectrum - Time waveform • Saved history • Different alarm types • Bearing database included	• Graph displays: - Trend - Spectrum - Time domain - Waterfall • Live view

Figure 65 shows the logical structure of the processing unit and illustrates the use for condition monitoring in machining centers. Therefore, regarding to Hamers (2017) six inputs for vibration sensors and two for digital speed measurement are planned to use.

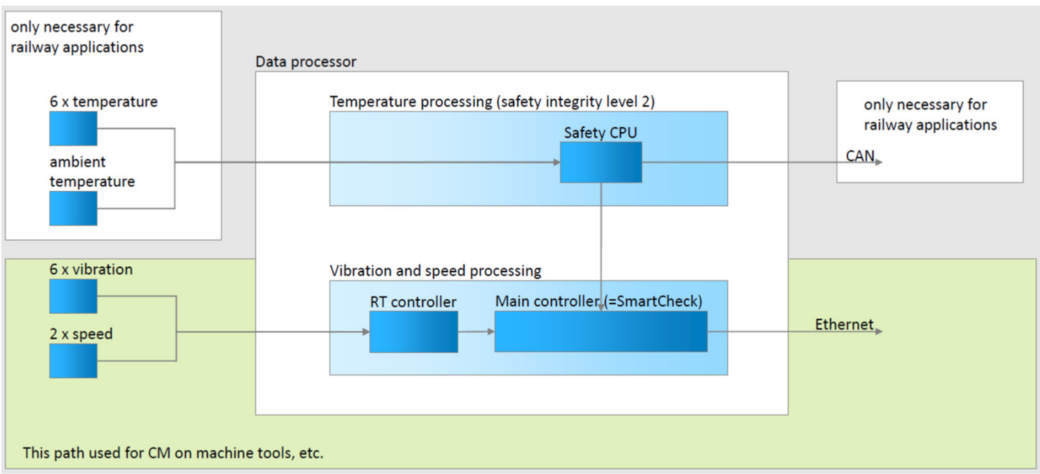


Figure 65: Logical structure of the processing unit (SmartCheck prototype) by Hamers (2017)

5. Experiments

As already discussed in chapter 3.3, vibration monitoring is often used for monitoring the spindle condition in machining centers. Due to the results from chapter 4.2 it has turned out, that it is affordable and useable to implement condition monitoring systems into machining centers.

Besides this thesis, two other theses were written in cooperation with the Technical University Graz and A. These theses dealt with monitoring the tool condition using either thermography cameras (Habich (2017)) or vibration sensors (Altziebler (2017)) to monitor the operating process.

The aim of these experiments was to implement a spindle condition monitoring system to a machining center at the production line of AH and to collect data over a period of time (four months). Furthermore, the experiments should visualize the actual condition and should show a trend in the condition graph which illustrates the change in the condition over the time.

Figure 66 shows such typical wear graph for spindles. As shown in this graph, the beginning illustrates the "running in" phase. The "running in" of a spindle is done during the manufacturing or after an overhauling. The area in the middle of the graph describes the wear behavior of a spindle. At the beginning, the wear doesn't increase very fast. Only at the end, the condition of the spindle gets worse very quickly. This leads to the problem, that it is extremely difficult to determine the actual condition without having knowledge about the spindle (already produced number of workpieces, time of installation, etc.)

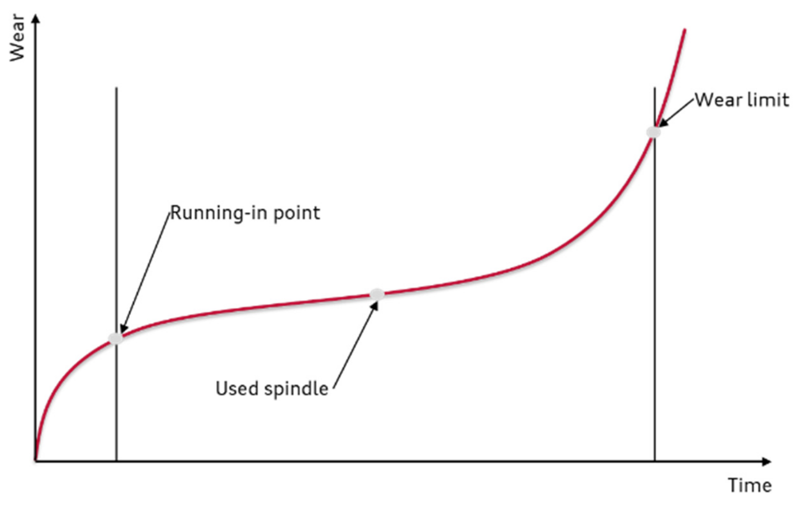


Figure 66: Typical wear graph for spindles modified from Klocke (2008 p. 234)

Primary, two different experiments were done:

- Experiments under laboratory conditions
  The primary aim of these experiments under laboratory conditions was to determine the sensor mount ability and the optimal sensor position. Furthermore, the measuring results of different systems were compared.
- Experiments under production conditions
  The aim of these experiments under production conditions was to determine the effort for implement a condition monitoring system in a machining center, to collect data over a period of time and finally to draw a conclusion between the wear curve and the development of the spindle condition over the time.

Based on the market research and benefit-analysis (see chapter 4.4), FAG SmartCheck, the system from SKF and the system from IFM were used for the experiments under laboratory conditions. For the experiments under production conditions, the FAG SmartCheck prototype and the system from IFM were used. The tests were performed with different processing parameters caused by different objectives of the tests.

The experiments were all done with a Kessler spindle. This type of spindle was used, because this spindle is installed on one third of all machines at AH. On the other hand, this spindle is used at the production line in which the experimental tests under production conditions were performed and they have a possibility to integrate a sensor.

5.1. Experiments under Laboratory Conditions

The objectives of the experiments under laboratory conditions were to get information about the necessary effort for sensor implementation in the spindle, finding the optimal sensor position and evaluating differences in the measured signals. The tests were done at the already existing test bench placed in the spindle repair workshop. As described in chapter 4.2, AUDI uses this test bench to measure spindles before and after their overhauling, to find imbalances and to run-in the spindle after repair. Furthermore, differences in the measuring results between the front and the back bearing were searched.

Besides the tests for vibration monitoring, also the temperature was measured at the front bearing. Therefore, a measurement system with a transducer form PHOENIX CONTACT (MINI MCR-SL-PT100-UI -NC) had to be implemented to the test bench Figure 68. The measurement of the temperature was done in connection with the SKF processing unit iMx-S.

5.1.1. Measurement Setup

The tests were done with the following systems:

Table 19: System overview test bench

SKF	**Processing unit:** SKF Multilog IMx-S **Sensor:** SKF CMSS 787A **Software package:** SKF @pitude Analyst
FAG	**Processing unit:** SmartCheck **Sensor:** SmartCheck **Software package:** SmartUtility
IFM	**Processing unit:** IFM VSE100 **Sensor:** IBIS AE100.942 **Software package:** IFM octavis efector
Temperature	PT100 with MINI MCR-SL-PT100-UI - NC transducer
Power supply	Siemens LOGO!Power 24V DC

Figure 67 and Figure 68 show the setup of the measurement systems and sensors at the test bench.

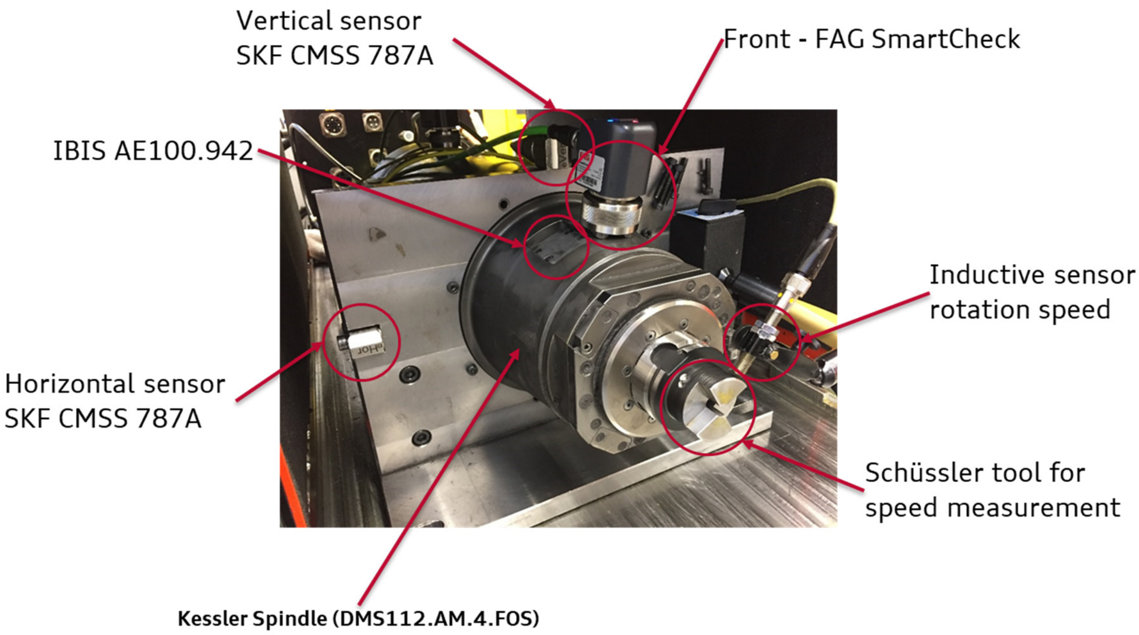


Figure 67: Measurement setup for test bench (front view)

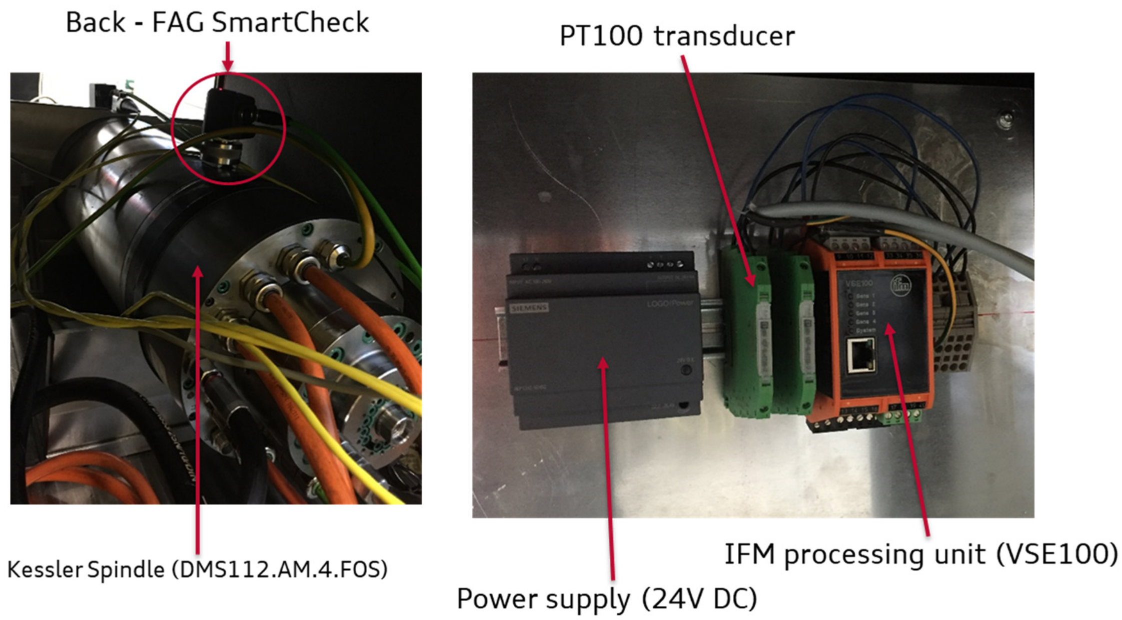


Figure 68: Measurement setup for test bench (back view & electrical installation)

5.1.2. Procedure

At first, the effort to integrate an IBIS sensor into the spindle was determined. Therefore, as shown in Figure 69, a wire was pushed from the backside of the spindle through the spindle. This was done at an assembled spindle to simulate the condition in a machining center and to ensure the possibility to integrate the sensor without doing a lot of disassembling work.

After the integration test of the sensor to the spindle, two measurement experiments at the test bench were performed. Each test lasted ten minutes. Information about the optimal sensor position and about the vibrations were gained out of the measuring results. The measurement procedure is shown in Table 20.

Figure 69: process to determine the effort for sensor integration

Table 20: Experiment parameters for test bench tests

Aim	finding optimal sensor position and differences in the measurements
Spindle type	Kessler DMS 112.AM.4.FOS
Spindle serial number	219 803
Bearing type	**Front:** FAG HCB71916-E-2RSD-T-P4S-UL **Back:** SKF N 1011 KPHA/SP
Spindle damage cause	**Spindle 1:** low clamping force
Tool	Schüssler - No.: 9606399-11
Test parameter	**2 Tests** **Speed:** 5000 rpm **Duration:** 10 min. per test
Sensors	2 pcs. SKF CMSS 787A front bearing 1 pcs. SKF CMSS 787A back bearing 2 pcs. FAG SmartCheck front bearing 1 pcs. FAG SmartCheck back bearing 1 pcs. Inductive rotation speed sensor 1 pcs. IBIS AE100.942 1 pcs. PT100 front bearing
Processing unit	SKF Multilog IMx FAG SmartCheck IFM VSE 100
Software solution	SKF @pitude Analyst FAG SmartUtility IFM efector octavis

The FAG SmartCheck was mounted at the spindle with a magnetic stand. The IBIS sensor was mounted with four screws into the preliminary space at the Kessler spindle and the SKF sensors were mounted with screws at the fixation unit of the spindle to the test bench.

Furthermore, the temperature of the front bearing was measured with a PT100 sensor. This PT100 sensor is implemented in every Kessler spindle at the front bearing. No further work was necessary to implement this sensor. Only an adaption of the SKF processing unit and a transducer was needed to implement the temperature into the measuring process.

5.1.3. Result

Sensor integration

The test showed, that the effort to integrate an IBIS AE900.142 into a Kessler spindle is not very high. It was very simple to push the cable from the backside through the fully assembled spindle and to mount the sensor. The sensor is fixed with four screws inside the spindle. After the sensor mounting, the cover should be sealed and fixed with another four screws. The test figured out, that it is easily possible to implement a sensor in an assembled spindle without much effort. To push the cable through the spindle and to mount the sensor lasts approximately ten minutes.

Sensor position

The first potential evaluation (see results from chapter 4.2) figured out, that the optimal sensor position is in vertical position. Also, the preliminary space at Kessler spindles and the integrated sensors in Corcom spindles are in vertical position. As you can see in Figure 72, there is a difference in the signals between measuring horizontally or vertically. Additionally, the tests at the test bench - run with the SKF systems - figured out, that the vibrations are higher if they are measured vertically and this leads to the statement that the optimal sensor position is vertically. The highlight in Figure 72 illustrates the higher deflections and the differences between the average before and after the overhauling. The vertically installed SKF sensor is marked in orange illustrates higher deflections than the horizontally sensors (blue line).

Furthermore, the tests showed differences in measuring at the front and the back bearing. As shown in Figure 70 and Figure 71, there are no similarities in the spectra. Therefore, the statement can be made that there is no influence between the bearings. Caused by the limited possibilities to implement sensors at the back bearing and caused by the fact that the front bearing is much more stressed, it’s of more interest to monitor the front bearing. These experiments should only visualize the differences in sensor positioning. They don’t give an association to the condition of the bearings and a possible failure cause.

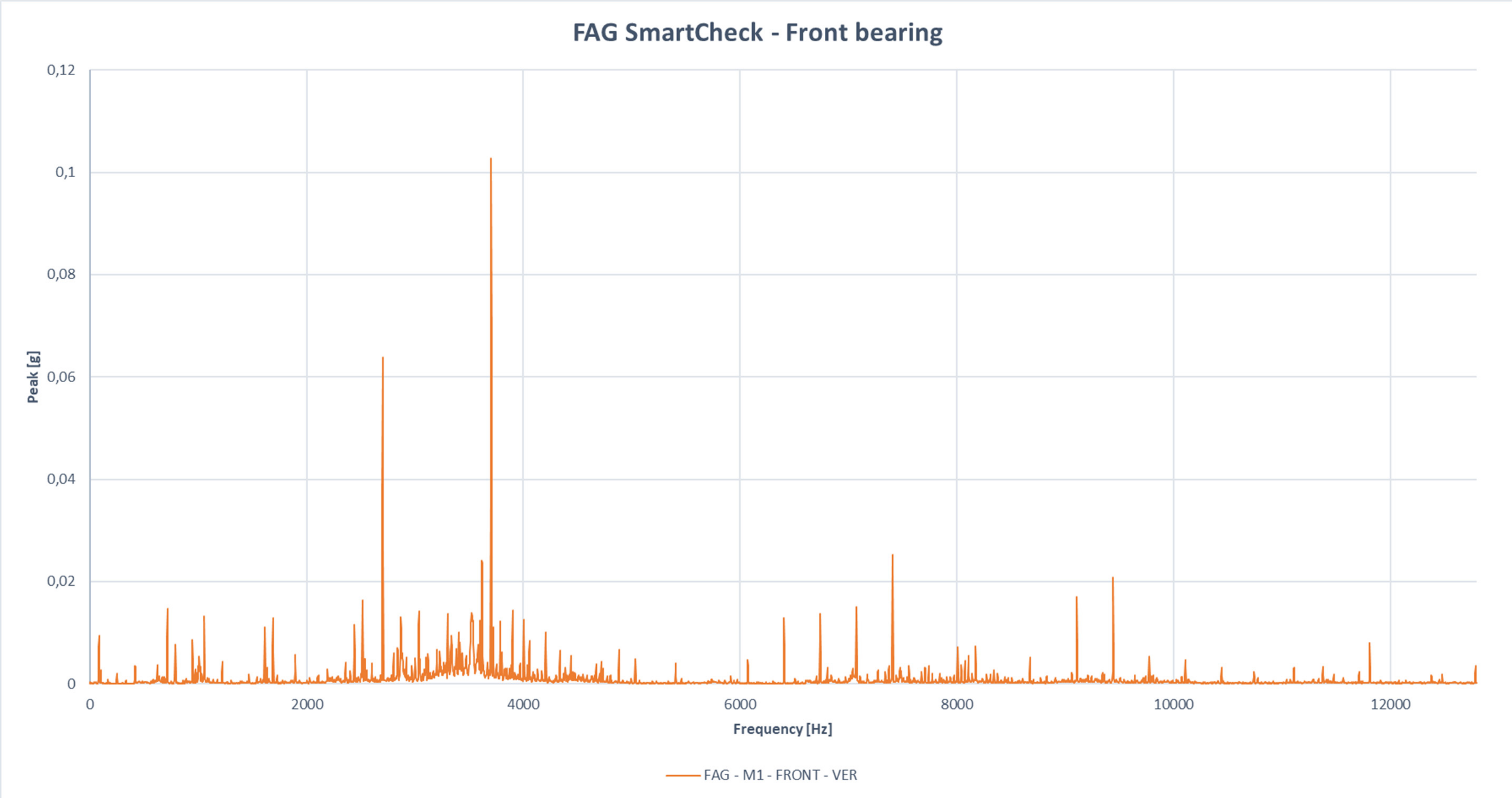


Figure 70: SmartCheck front bearing

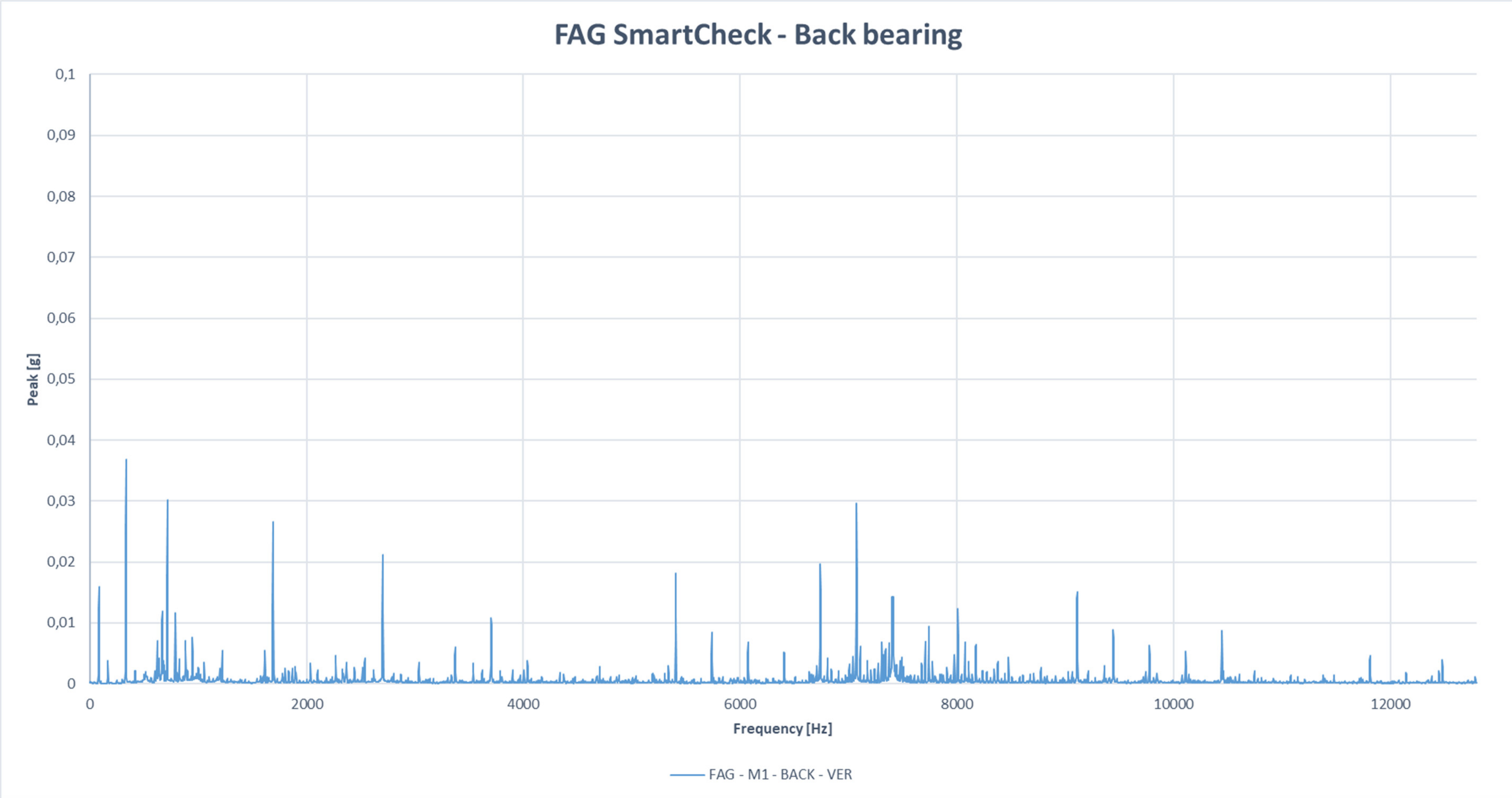


Figure 71: SmartCheck back bearing

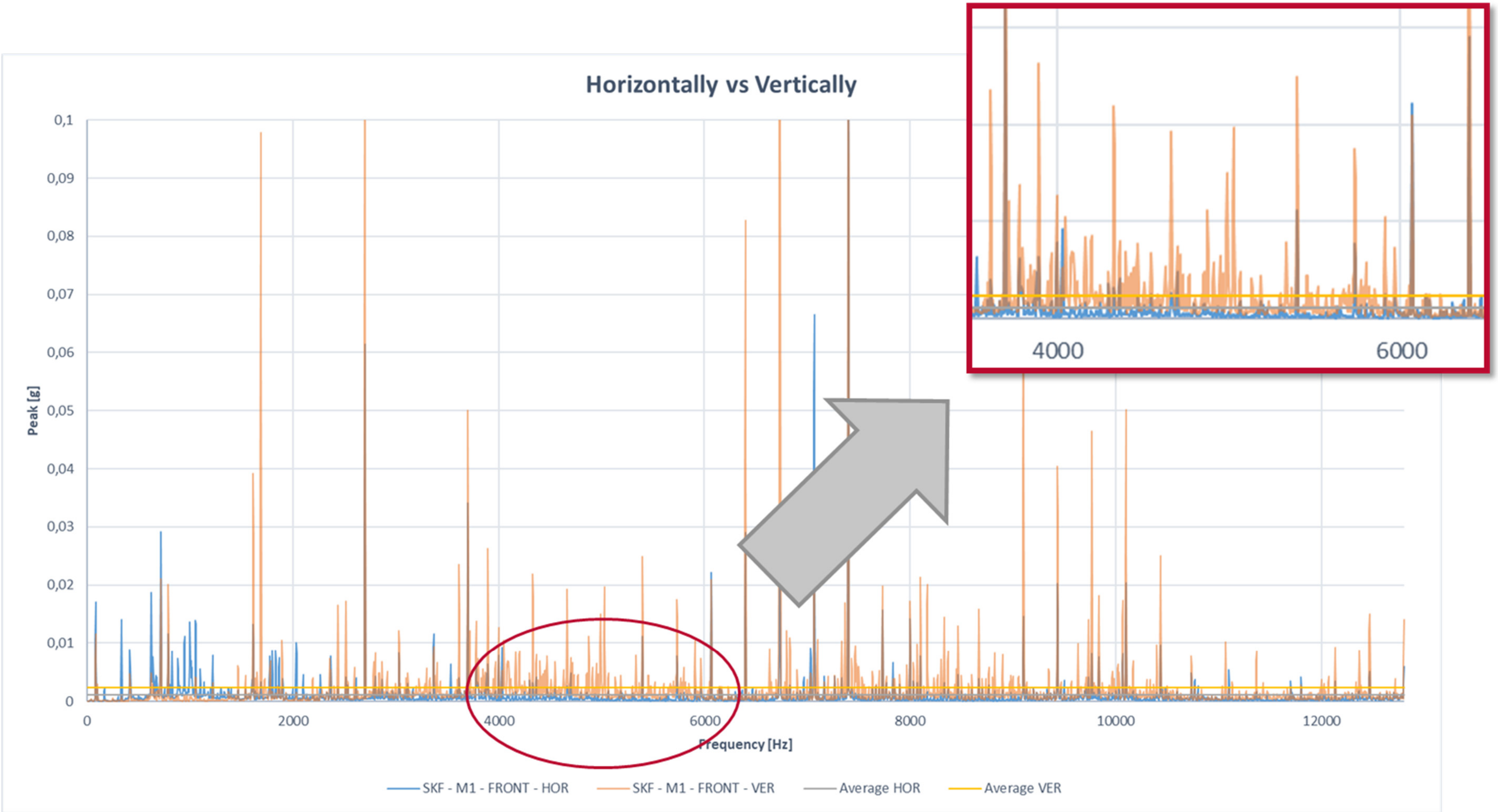


Figure 72: Optimal sensor position

Differences in the measured results

As explained in the procedure, two tests were done at the test bench. Each test lasted ten minutes and was performed at a speed of 5000rpm. The used systems for these tests were the discussed systems from FAG, SKF and IFM (chapter 4.4). All these systems recorded and measured the acceleration over the time and led these measurements over to a spectrum using the FFT calculation method as explained in chapter 3.3.

The experiments figured out, that there are almost no differences between the measuring results from FAG and SKF system. Only the IFM system showed differences in the signals.

These differences could be caused by different issues. At first, recording the parameters with the IFM system was not that easy than recording the parameters with the SKF and FAG systems. Using the IFM system you have to manually start and stop the record of the measurement. The other systems measure permanently and save the data in a predefined time interval. This interval is a measurement point every minute. This setup could not be done at the IFM system. Furthermore, there was the opportunity to visualize the measurement in two ways. The first opportunity (done in measurement one) was to use the FFT visualization. The second opportunity (done in measurement two) was to use the envelope FFT visualization. As shown in Figure 73 and Figure 74, the measured data from the IFM system is completely different to the other systems. Furthermore, the IFM system only measures up to a frequency of 10.000Hz.

Senosor mounting

There are differences in the first and the second measurement between the results of the FAG and the SKF systems. This leads to the conclusion that there is an enormous influence on the results using a magnetic foot or screws to mount the sensor to the spindle. On the other hand, this difference could also regard to the mounting distance between the sensor and the bearing. The SKF sensor was mounted at the top of the fixing unit as shown Figure 67. The FAG system was directly placed above the bearing on the spindle and the IBIS sensor was directly located at the bearing. Especially, as shown in Figure 73 and Figure 74, there is a signal difference in low frequency regions. Only in the range from 2000 to 4000Hz the data is nearly the same. The fix mounted SKF and IFM system shows higher deflections than the magnetic mounted FAG systems. The values are only higher but not located at other frequencies. This leads to the conclusion that the sensor should be mounted with screws to the spindle.

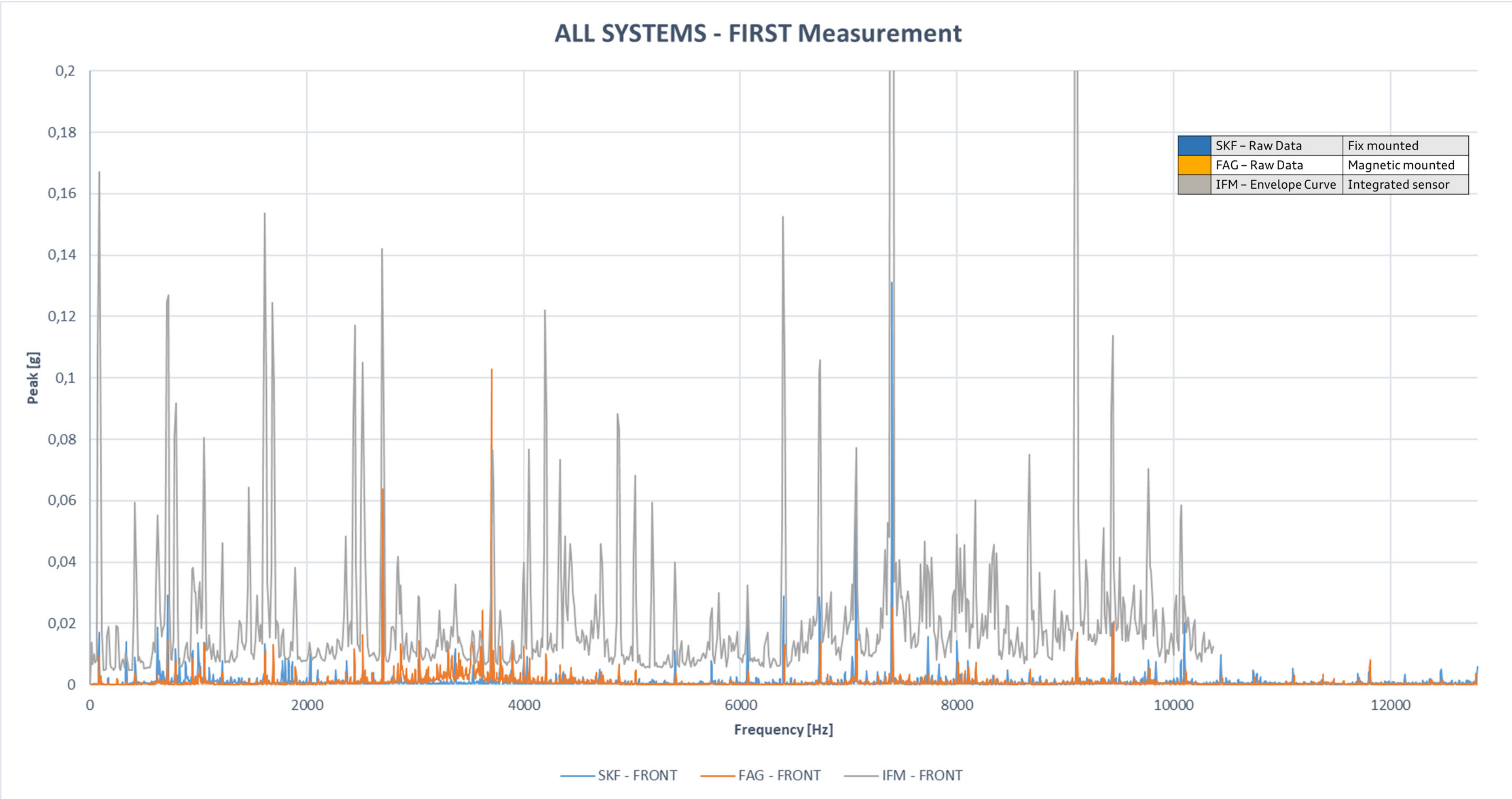


Figure 73: Test bench test one - all systems

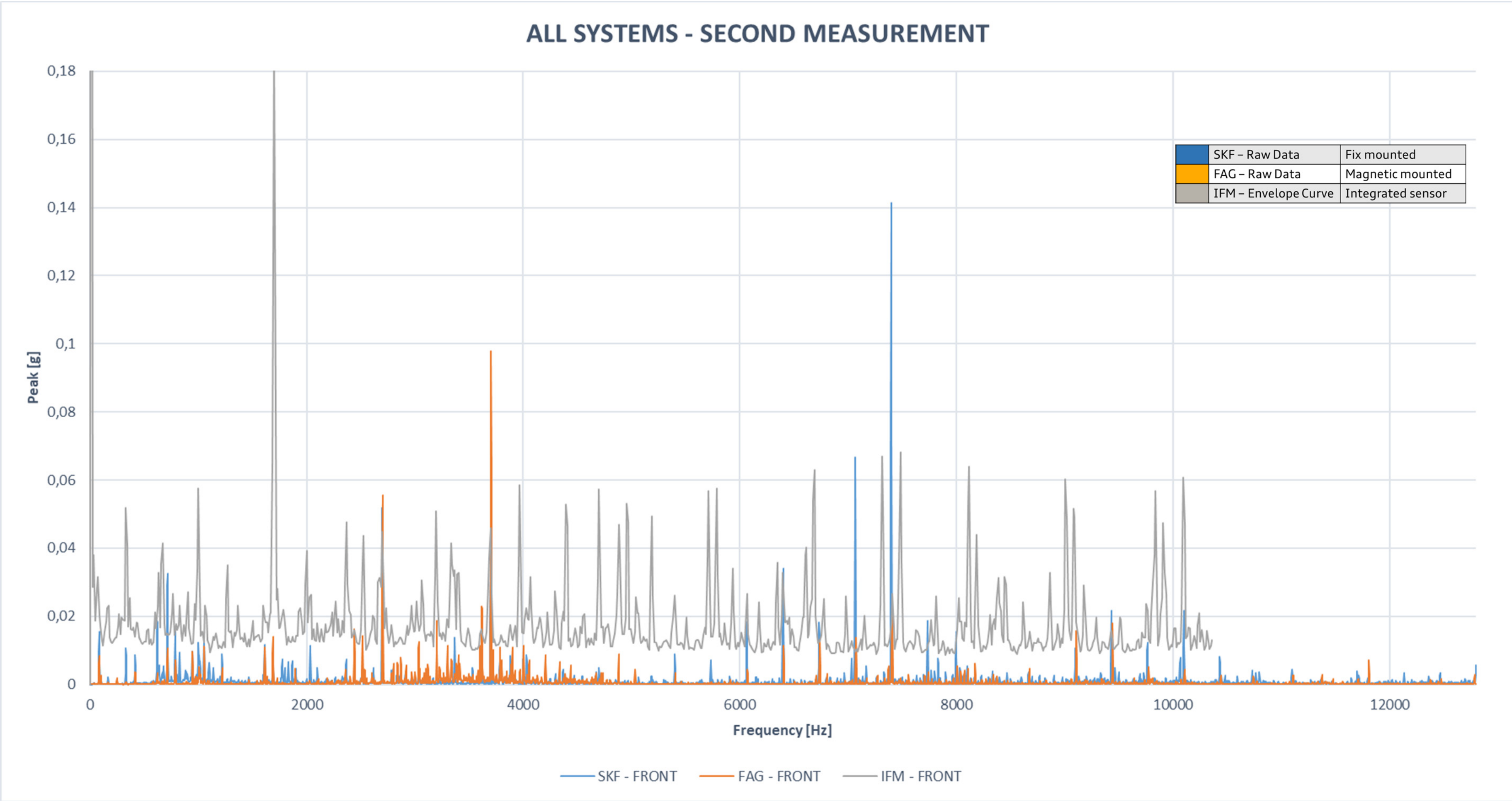


Figure 74: Test bench test two - all systems

Temperature

During the two experiments, there was no meaningful change in the temperature (illustrated in Figure 75). The temperature stays constant in the range from 22,5°C to 23°C. This is caused by using a spindle with bearings in good condition. A measurement at a spindle with bad conditions was not done.

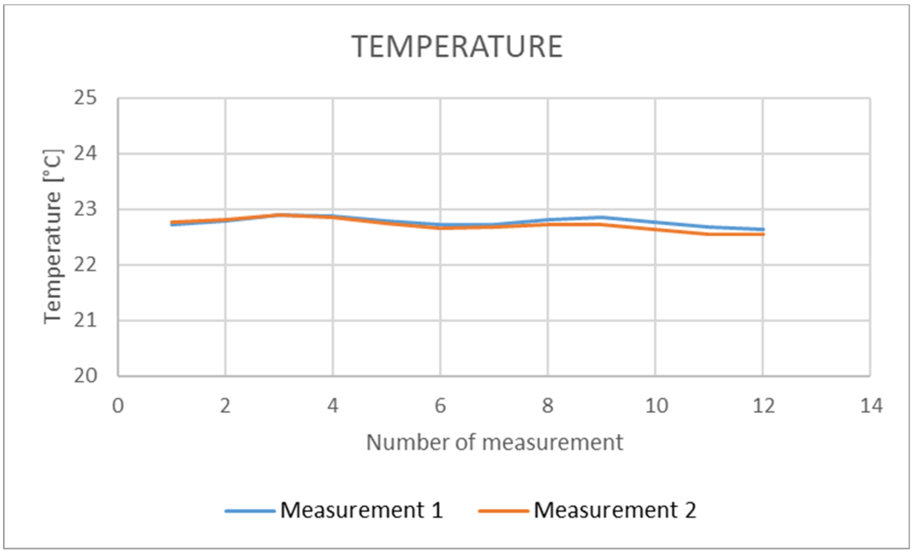


Figure 75: Temperature profile of the two experiments

5.2. Experiments under Production Conditions

After the first tests at the test bench and the knowledge about the existing potential, the aim of the experiments under production conditions was to collect data about the spindle condition over a longer period. A further aim was to find the effort for integrating such a system in a machining center and to compare two systems.

To do measurements under production conditions, a machining center of the production line from the four-cylinder diesel engine (P5 ZKG AF230/7) was chosen. This machining center stands for a center which is very often used at AH. The machining center is produced by the company GROB and has two main spindles. It is a five axis CNC machine (GROB 520). This type of machine is one of a few used in this line for different mechanical operations at the engine crankcase. The work sequence 230/7 was chosen because the two spindles have nearly the same date of installation and these spindles are in good condition. Furthermore, this work sequence consists of seven machines which all do the same operating step. Regarding to this and regarding to the available capacity it is not a big problem if one of these seven machines has a short downtime.

Figure 76: GROB 520 machining center by GROB-WERKE GmbH & Co. KG (2017)

The integration of the systems requires a stop of the machine for a few hours because the sensor has to be pushed through the spindles and the monitoring units have to be installed and wired. Therefore, it was necessary to clamp into the operating room to dismount the cover of the preliminary sensor space (Figure 77) and push the cable through the spindle into the electrical cabinet.

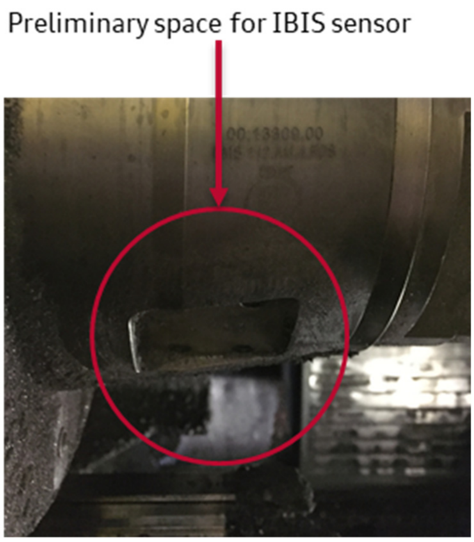


Figure 77: Preliminary space for IBIS sensor at the machining center

To shift the machine downtime to a production free period, the installation of the system was done in the time of summer holidays. Due to this, there were no unexpected machine downtimes and no further costs for a lower output were generated.

As described in chapter 4.5, company Schaeffler made it possible to use a completely new system (FAG SmartCheck Prototype). With this prototype, it was possible to separate the processing unit from the sensor and to use the SmartCheck with the SmartUtility software package.

To integrate the FAG and IFM system it was necessary to install a continuous power supply, mount the processing units, do the wiring for the sensors (temperature and accelerometers) and integrate a measuring procedure into the numerical control (NC) program.

Furthermore, to start and stop the measurement an external trigger signal from the NC must be send to the SmartCheck. Only the SmartCheck has the possibility to use external trigger signal for starting and stopping measurements. Therefore, a connection from the NC to the SmartCheck input had to be installed.

5.2.1. Measurement Setup

The long-term tests were done with the following systems:

Table 21: System overview experiments under production condition

FAG	**Processing unit:** SmartCheck prototype **Sensor:** IBIS AE100.942 **Software package:** SmartUtility
IFM	**Processing unit:** IFM VSE100 **Sensor:** IBIS AE100.942 **Software package:** IFM octavis efector
Temperature	PT100 with MINI MCR-SL-PT100-UI - NC transducer
Power supply	Siemens LOGO!Power 24V DC

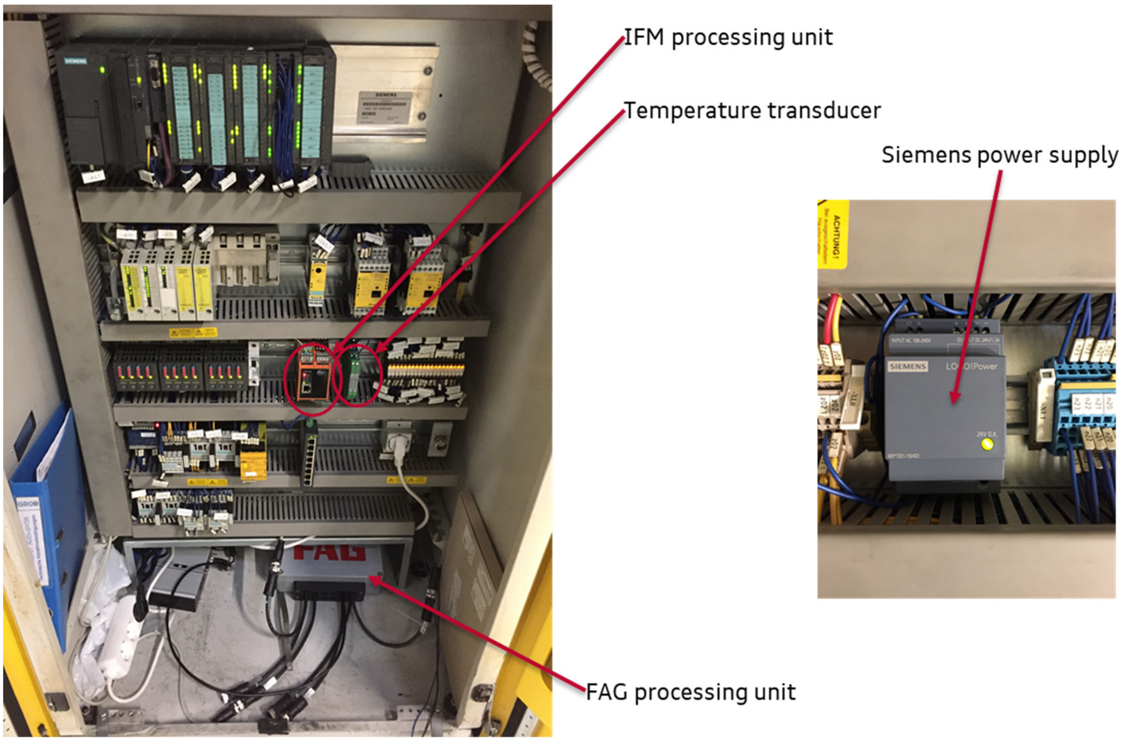


Figure 78: Measurement setup for the experiments under production conditions

5.2.2. Procedure

At the beginning, the effort to integrate a CM system to a machining center was evaluated. Therefore, two systems (FAG & IFM) were integrated into one machining center. To integrate a system in a machining center an external power supply had to be installed. This external power supply was necessary because the FAG SmartCheck prototype doesn't have a battery inside to save the predefined settings. The machine is sometimes switched of via the main switch in case of maintaining or troubleshooting. A constant power supply was installed using a Siemens LOGO! Power 24VDC unit.

Furthermore, the IBIS AE100.945 accelerometers had to be implemented and wired to the electric cabinet. Also, the already existing PT100 sensors had to be wired to the new installed temperature transducers and connected with the processing units from FAG and IFM.

To start and stop a measurement as described before, a wire had to be laid from the PLC to the FAG input. Furthermore, a measurement procedure had to be programmed and integrated into the existing NC program. At the beginning of the tests only one measurement over ten minutes was done in the morning of every working day. To ensure a consistent repeat accuracy of the measurement, an addition into the greasing program was done. The measuring procedure lasts every day ten minutes and was performed with a speed of 4000rpm and no tool was clamped in the spindle. Due to the use of the FAG prototype it was not so easy to integrate an external trigger signal with the system to start and stop a measurement. Two problems came up: The first problem was that the prototype was not wired correctly inside the system. Using the input one, didn’t give a signal to the system. Only the use of the second input gave a signal but was shown in the software as the signal from input one. This phenomenon was not able to be changed because it was a prototype version and predefined from the manufacturer. The second problem was, that the inputs required a digital triggered speed signal (Figure 79).

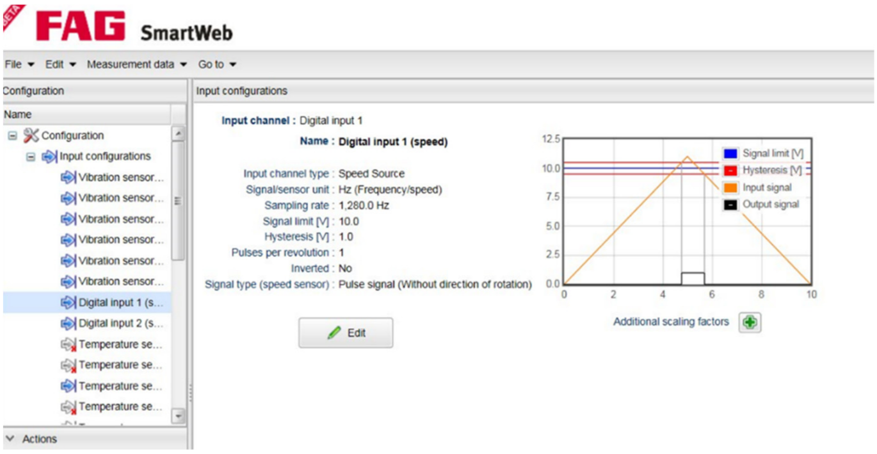


Figure 79: FAG digital triggered input speed

Therefore, the output signal from the PLC was programmed with interruptions to simulate a triggered speed signal. The original FAG SmartCheck has the possibility to use “normal” digital input signals to trigger a measurement. Only the FAG system gives the possibility to use a signal to trigger the measurement. This can be done using a measurement trigger in the FAG software as shown in Figure 80.

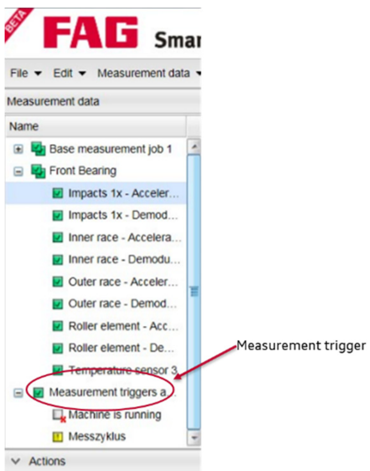


Figure 80: FAG measurement trigger

After the integration of the first measurement procedure into the NC program a second measurement procedure was integrated. The second procedure was done in the afternoon, has the same parameters (speed: 4000rpm, no tool clamped) but lasts only five minutes.

Using a GROB 520 machining center with two spindles created the possibility to use two different systems at one machine. Therefore, spindle one and temperature sensor one were connected to the IFM system. Furthermore, spindle two and temperature sensor two were connected to the FAG SmartCheck prototype. Figure 81 shows the location of the spindle in a GROB machining center.

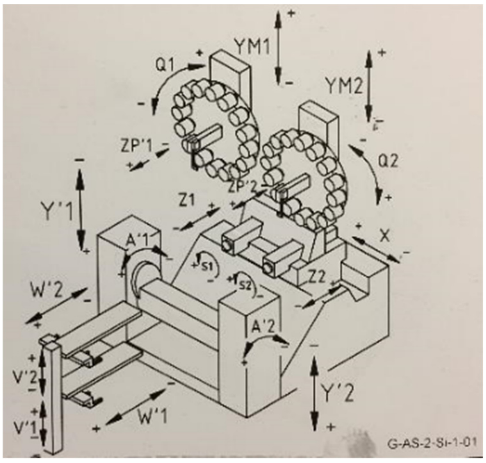


Figure 81: Spindle position in GROB 520 machining center by GROB-WERKE GmbH & Co. KG (2017)

After the installation, the settings of the systems had been done. To display the bearing condition the right bearings had to be chosen and bearing measurement jobs had to be implemented to the measurement routines.

Figure 82: FAG bearing measurement job

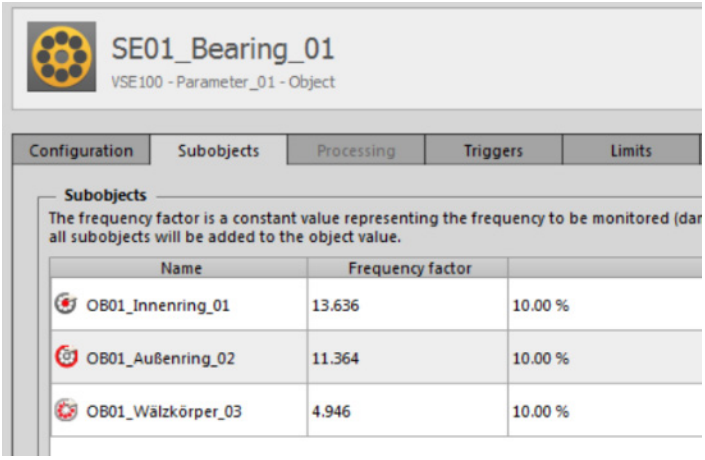


Figure 83: IFM bearing measurement job

FAG gives the possibility to use a database with different bearing defect frequencies. The IFM system also had a database, but the FAG bearings mounted in the Kessler spindle were not included. There was the possibility to insert the bearing defect frequencies manually. The values from the FAG system were inserted. These values are shown in Table 22.

Table 22: Defect frequencies of FAG spindle bearing

Bearing defect frequency	Value
BPFI	13,6359 Hz
BPFO	11,3641 Hz
BSF	4,9457 Hz
FTF	0,4546 Hz

Regarding to these values, both systems recommend individual alarm settings. These alarm settings are the same. The alarm for the pre-alarm was at 0,7g and for the main alarm at 1g. Furthermore, the alarm for the temperature was defined as follows: The pre-alarm starts at 40°C and the main alarm starts at 45°C.

At both systems, the setting for the accelerometer had been done. A vibration sensor with the type IEPE with a scaling from 100V/mg was chosen. Also, a constant speed trigger with 4000rpm was created at both systems because no external speed signal was used and regarding to the measurement procedure the speed was constantly 4000rpm.

The measurements were done over a period of one month. At the beginning only one measurement per day (in the morning) was performed. At half of the measuring period, a second measurement procedure in the afternoon was added.

5.2.3. Results

System integration

The tests showed, that the integration of condition monitoring systems to a machining center is not much effort. Especially at GROB machining centers which uses Kessler spindles with preliminary space for IBIS accelerometers. The effort evaluation for other machining centers was not task of this experiments. To integrate the systems, only the vibration sensors, a new continuous power supply and the processing units had to be integrated. The already existing temperature sensors could be used and only the wiring to the processing unit had to be done. At the first time, the effort to implement was much higher, because the technicians didn't know how to do it, and the NC programs had to be adapted completely new. With the new collected knowledge and the already changed NC code, it could be estimated that two skilled technicians are able to implement a condition monitoring system to a machining center in **approximately two hours**.

It is possible to lay the wires in the existing cable channels in the machine to get from the spindle to the cable cabinet. In the cable cabinet, there is enough space to insert new wires and to install the processing units. The IFM processing unit could be installed at the DIN rail. The FAG processing unit couldn't be installed to the DIN rail, because the prototype is implemented in a prototype box without any mounting opportunities. The FAG processing unit was placed at the bottom of the electrical cabinet. Also caused by using a prototype the plugs of the FAG unit were very big. They use standard M12 connectors to connect the processing unit to the sensors and to the power supply.

Difference between IFM and FAG system

Regarding to the problem that the IFM system can't use external triggers to start and stop measurements, further results are only considered from the FAG system. However, the IFM system was installed and used, but no good statement could be made about the spindle condition. Furthermore, the IFM system is not able to show trends, because each record of a measurement must be started manually. The IFM software gives the possibility to visualize the actual spindle condition as shown in Figure 84. Additionally, the usability of the IFM software is even more complicated than compared to the FAG system. Every use of the system requires a manually connection to the device. With the FAG software feature called SmartWeb, it is possible to visualize the actual condition and the history of the maintenance in a web based platform. Also changes in the system settings can easily be implemented.

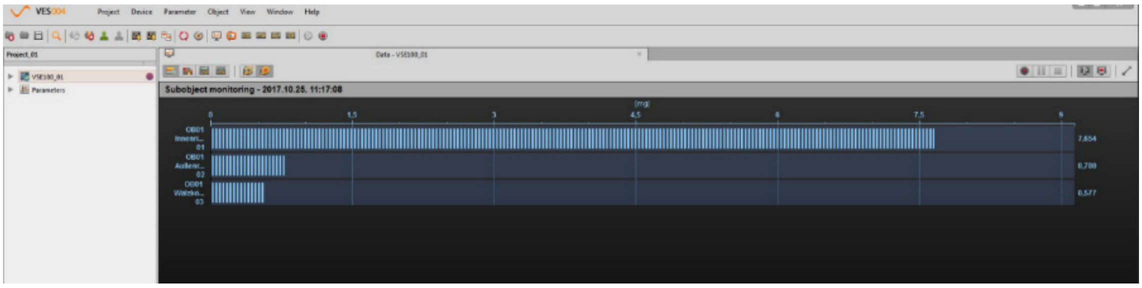


Figure 84: IFM spindle condition visualization

The IFM software package offers different types to visualize the monitored data. Using history monitoring requires a manually starting and stopping of the measurements.

	Data monitoring
	Counter monitoring (only VSE)
	I/O monitoring
	Spectrum monitoring (only VSE)
	Raw data monitoring (only VSE)
	History monitoring

Figure 85: IFM (2017) software package analyzing opportunities

Regarding to the missing functions in the IFM system and regarding to the missing opportunity to start and stop measurements with external trigger signals, no further comparisons were done. Only the use of the FAG SmartCheck prototype was further evaluated.

However, both systems meet the requirement to export the measured data. This could be done by exporting the data to a Microsoft Excel csv file. This file could be used to send the data to a PDA system or make further analysis with it. Besides this, FAG provides the opportunity to send the data to a team of experts. These experts will give support to the technician in case of troubles and they are able to use a knowledge database.

FAG SmartCheck prototype results

Using the SmartCheck prototype with the SmartUtility software package created the possibility to connect via a web based platform to the SmartCheck. This is the so-called FAG SmartWeb platform. Figure 86 illustrates the structure of the SmartWeb platform. This platform is live connected to the SmartCheck processing unit and the processing unit can be integrated to the company wide network. Regarding to the high effort to integrate the processing unit to the company network during the experiments, the connection to the SmartCheck was done via an industrial notebook. However, there is no difference in the functionality and only an integration to the network must be done. The integration of the system is not complicated due to the wiring, but the process of integrating a device into the AUDI network is very complicated from the IT side.

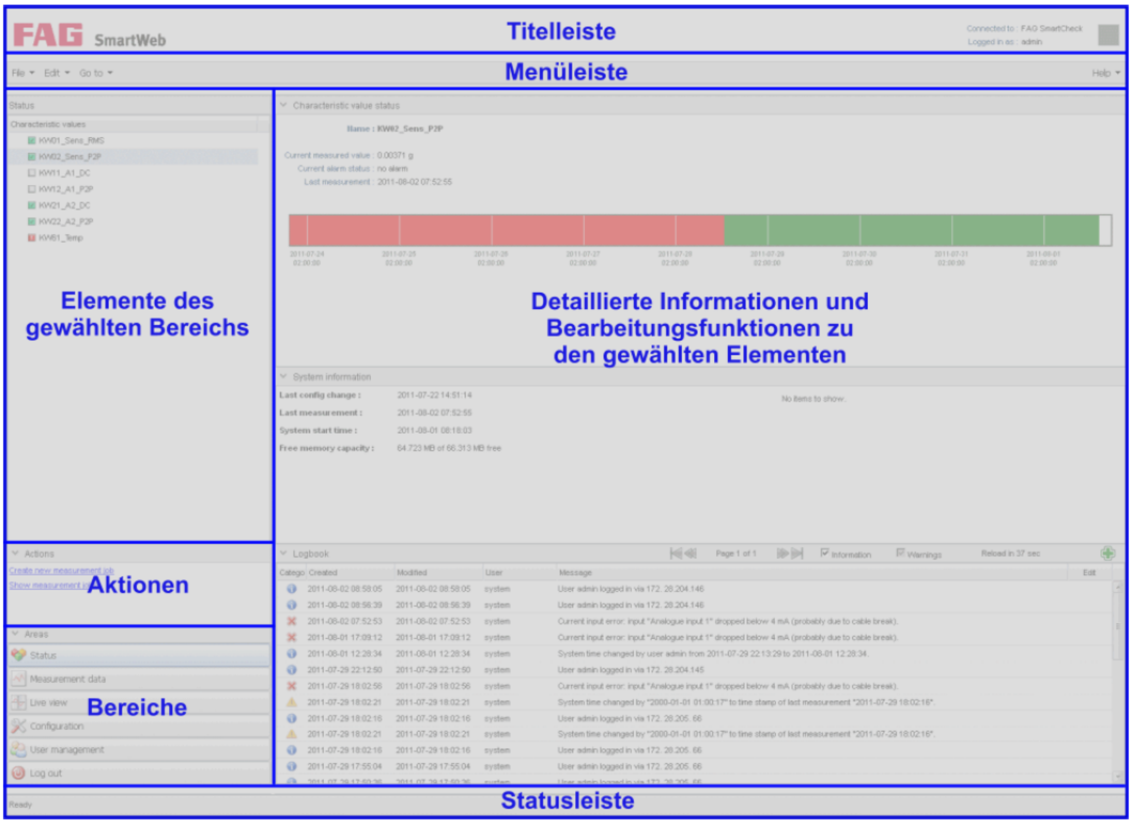


Figure 86: FAG SmartWeb overview by FAG (2017)

On this platform, the user has different possibilities. The user can choose between illustrating the actual condition (Figure 88), showing the history of the measurement as a trend visualization (Figure 90) or displaying the live signal from the sensors (Figure 91). Furthermore, also configurations could be done live in the SmartWeb application.

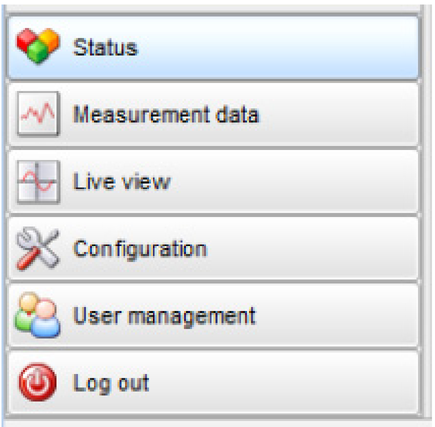


Figure 87: Possible areas to choose on the SmartWeb platform

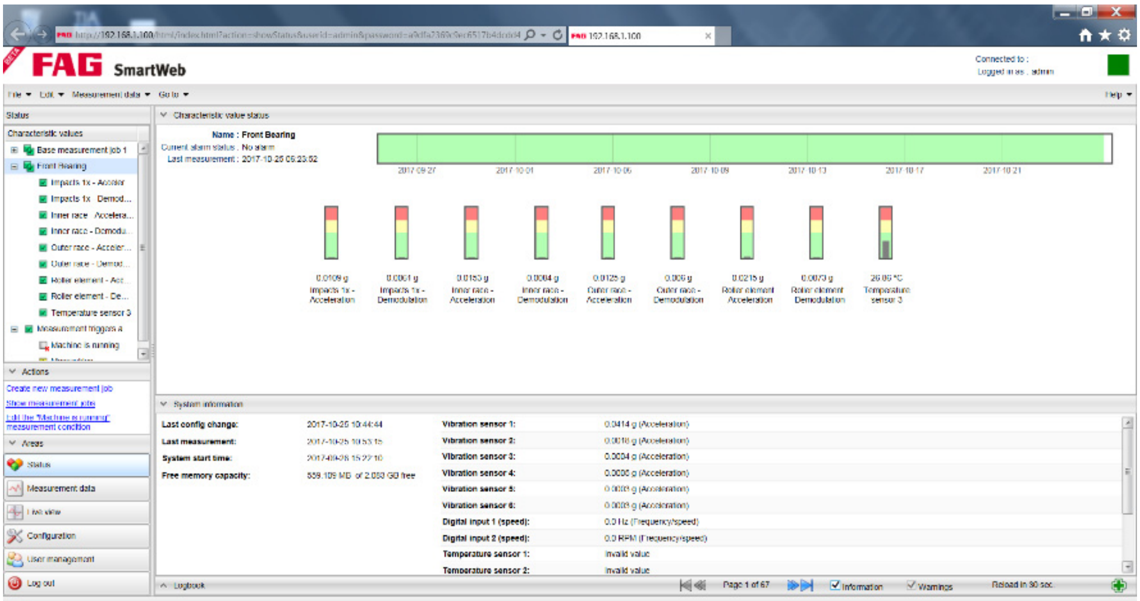


Figure 88: SmartWeb – Status

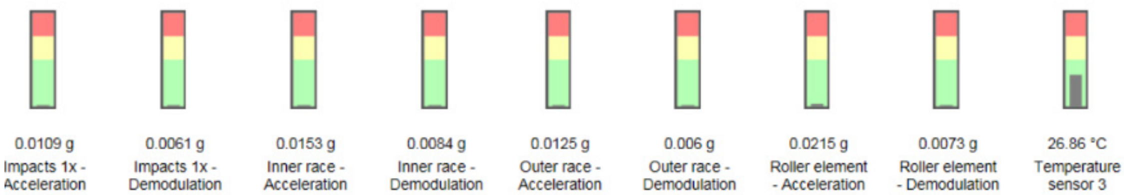


Figure 89: SmartCheck - Status of all elements of a rolling bearing

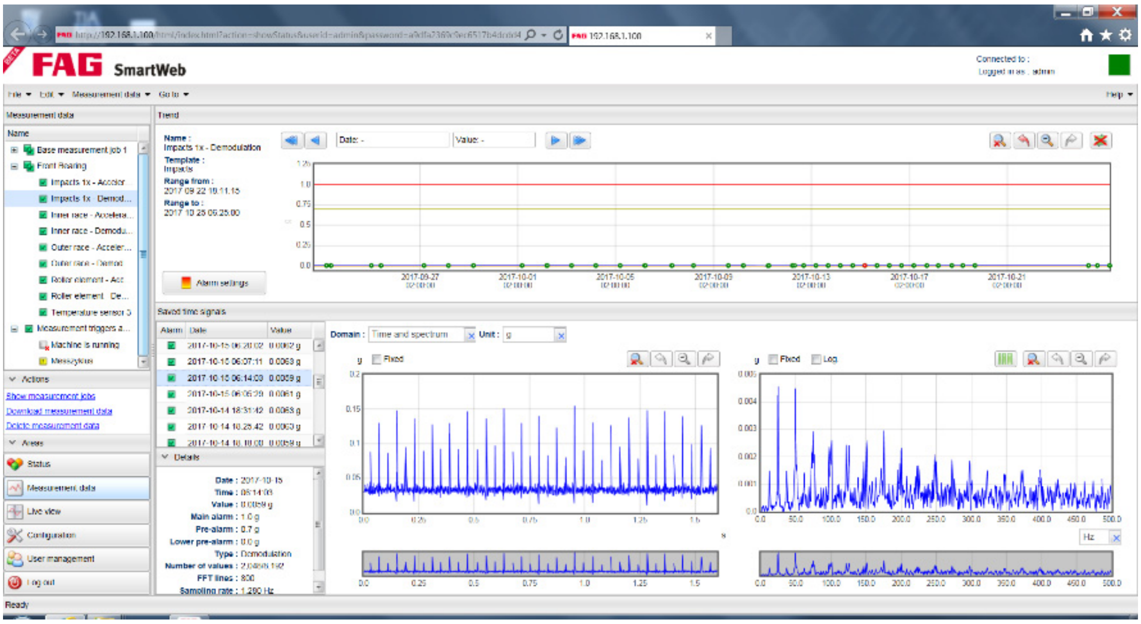


Figure 90:SmartWeb - Measurement data

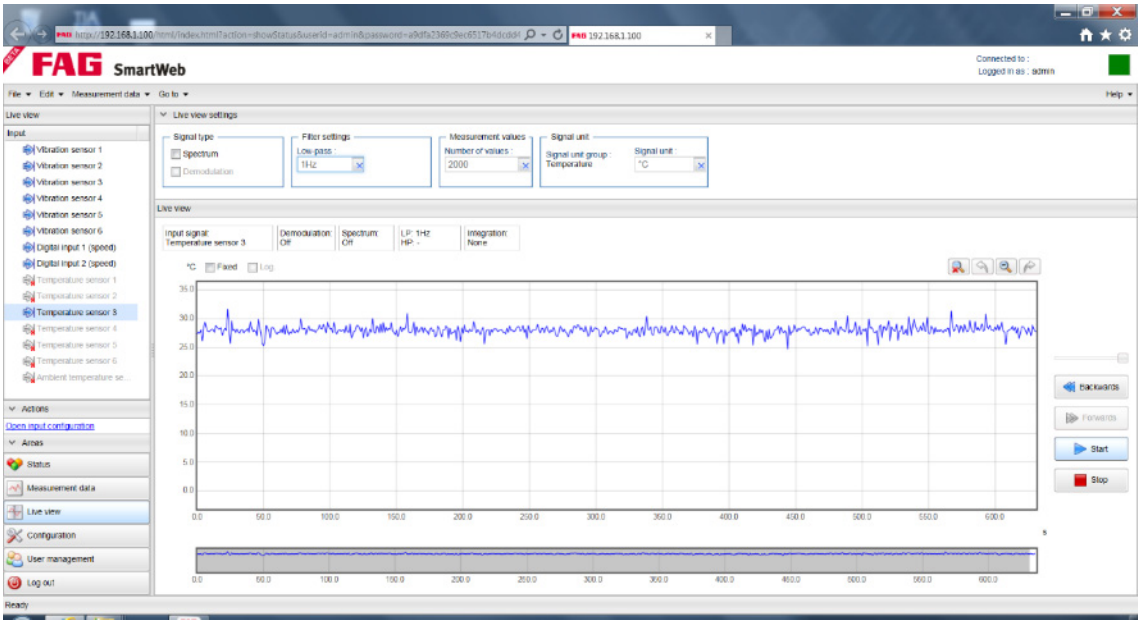


Figure 91:SmartWeb - Live view

As shown in Figure 89, the actual condition of spindle two (monitored with the SmartCheck) is shown. The figure illustrates a very good spindle condition. Furthermore, the chart shows, that it is possible to make a statement about the condition of each bearing component. It is illustrated, that all elements of the front rolling bearing in this spindle are in a very good condition. There are no abnormalities existing.

In the area “Items of selected area” it is possible to choose the component of the bearing which should be investigated more in detail. Caused by the short period of measurements, no change in the trend was detected. Only some small changes in the temperature could be measured. However, these changes are all in the area of normal temperature and lead to the result that the spindle is in very good condition. The change in temperature is shown in Figure 92

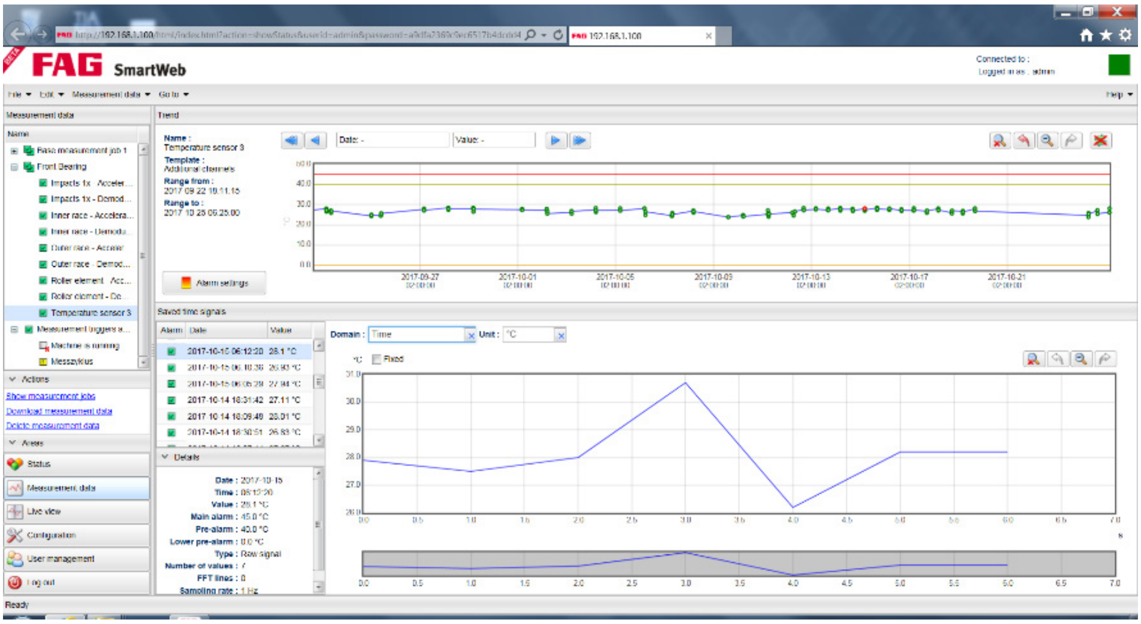


Figure 92: SmartCheck - Temperature trend over a month

In the area of “detailed information” the trend is visualized regarding to the triggered measurement procedure. Under the trend curve, the user has the possibility to choose single measurement points and to illustrate the measurement at this point of time more in detail. Using the visualization of vibration data brings more analyses opportunities than analyzing the temperature. (Figure 92 and Figure 93). Using the visualizing for vibration data brings the opportunity to select single measuring points and to illustrate the raw data and the spectra of this data.

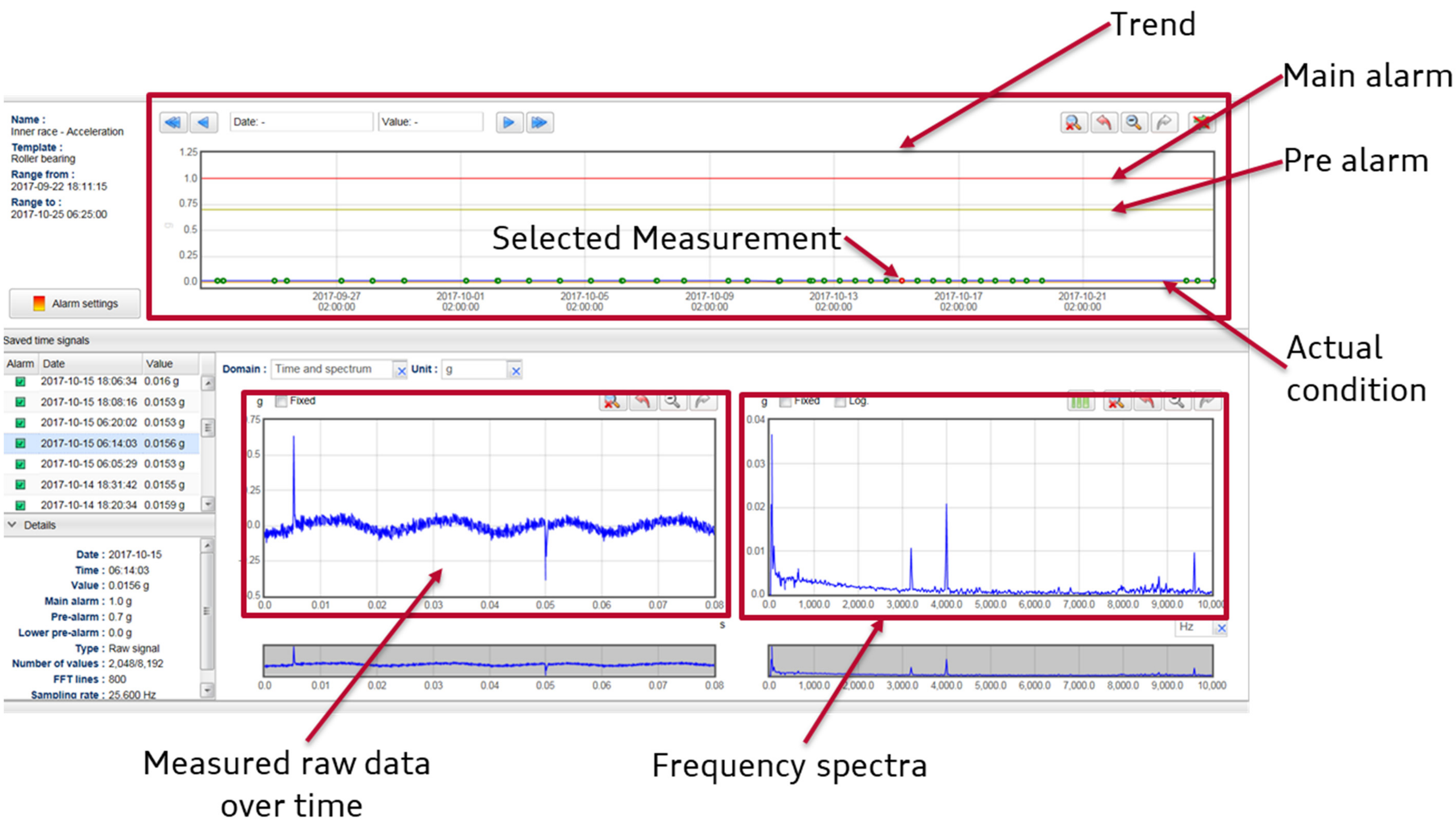


Figure 93: SmartCheck - Vibration trend over one month

In Figure 93 the measured data for the inner race of the bearing is visualized. The chart illustrates the measurement trends over the measuring period (23/09/2017 – 23/10/2017). In the trend chart, the single measurements are marked with green points. Furthermore, the difference between the actual condition and the pre- and main-alarm is shown. The pre-alarm is indicated with the yellow and the main alarm with the red line. On the bottom left side, the chart illustrates the raw data of the measuring over the time. Regarding to the raw data the spectra of the vibration measurement is illustrated on the bottom right side. The raw data and the spectra refers to the selected measurement point which is marked red in the trend chart. The shown measurement was recorded at the 15/10/2017 at 06:14.

It is shown that there is no significant change in the trend. This is maybe caused by the short time period of measurements (only one month). Due to the need of implementing the system in a production free time, the time range to do measurements was very short. Normally a spindle is used more than six months in a machining center before the spindle gets replaced caused by a too low clamping force, bearing damages or issues in the product quality. The measurement over one month did not visualize a change in the trend and indicates a good spindle condition.

5.3. Discussion

At the beginning of the discussion it should be mentioned, that all experiments are related to the aim to implement a condition monitoring system to a GROB machining center with preliminary space for accelerometers in the spindles.

With the first experiments and evaluation, one can figure out very fast, that there is a high potential to use condition monitoring systems, especially systems which uses temperature and vibration sensors. Further experiments illustrated the low effort to implement vibration sensors into Kessler spindles, the processing unit into the machining center or to use the already existing temperature sensor at the front bearing and connect them to the processing unit.

The tests showed differences in signal quality due to different kinds of mounting (mounted with magnet or with screws) or different sensor positions (vertically or horizontally). Furthermore, the evaluation figured out, that nearly all spindles have already installed temperature sensors at the front bearing. Additional to the temperature sensors, a few number of Corcom spindles already have accelerometers integrated and some Kessler spindles have a preliminary space which allows an easy integration of vibration sensors.

As shown in Figure 73 and Figure 74, there are significant differences in using the IFM system or the FAG or SKF system. The measured data of the IFM system is completely different to the other systems. This is maybe caused by the different setting opportunities regarding to the data measurement or to the integrated sensor. Compared to the data from the experiment under production conditions, there is no connection between using the integrated IBIS sensor and poor data quality. In case of experiments under production conditions, the data quality of the IFM and FAG system is highly comparable.

Also, a very big difference is in the usability of the different software packages. Only the FAG SmartUtility with the SmartWeb application fulfills all requirements and gives the possibility to connect to the processing unit via remote control. The web based platform offers opportunities to see the actual condition of the spindle, to get a deeper view into the recorded data or shows the live signal of the sensor. Furthermore, an additional app can visualize the actual condition or can show alarms on the Smartphone.

Regarding to the aim of this thesis to collect data over a long period of time to draw some conclusions between the typical wear graph of a spindle and the development of a spindle condition over the time, it is not possible to make such a statement. The measured period was too short to draw a meaningful conclusion out of it. It was only possible to measure data over one month. Figure 94 illustrates the estimated spindle condition. The condition of the spindle is near to the date of installation. Due to this a far distance to the wear limit is approximated. As you can see in the wear curve (near to the wear limit), the curve increases very fast. Maybe only in this range it is possible to identify changes in the condition. Further tests will show the real wear curve.

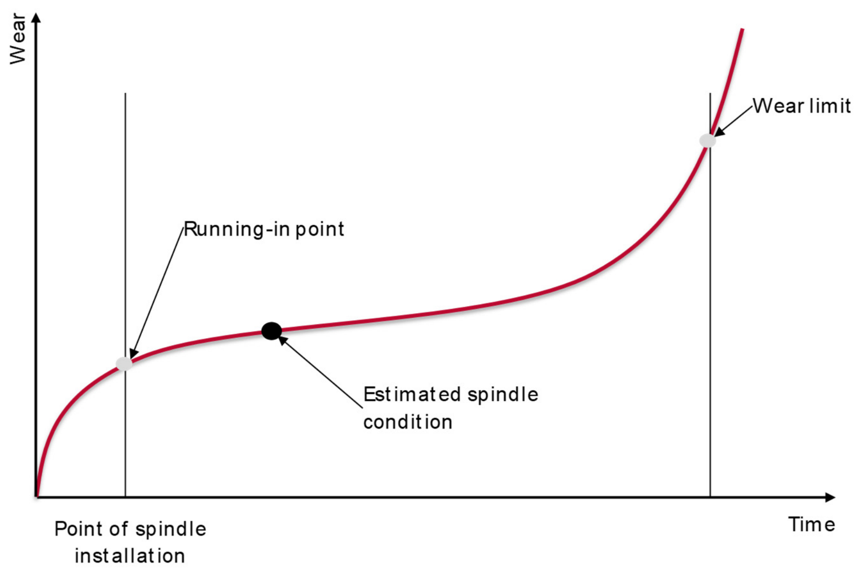


Figure 94: Estimated spindle condition

The experiments showed, that it is possible to implement condition monitoring systems in machining centers to monitor the spindle condition with manageable effort. There are some restrictions due to the possibilities to update machining centers caused by limited opportunities to implement accelerometers in spindles without preliminary spaces. However, the experiments figured out that it is a good method to monitor a spindle condition.

Furthermore, a result of the experiments was that only the FAG system meets all requirements to integrate a monitoring system into the company network. Additionally, the FAG system supports the technician with remote support and gives the opportunity to export the data to a PDA system.

6. Calculation of Overall Downtime Costs

This chapter describes the calculation of the overall downtime costs for machining centers. Furthermore, this chapter will show the break-even point to implement condition monitoring systems into a series production.

At first this chapter gives a short overview about the different types of production lines regarding to the plant from AUDI in Györ. Afterwards, the calculation method and different calculation scenarios are explained. At the end, this chapter illustrates the advantage of implementing condition monitoring systems to the production line.

All data and cost information (machine-hour rate, labor-hour rate etc.) regarding to the model and the scenarios are relating to the thesis from Habich (2017). The calculation model is intended to be a draft for further investigation, which may be applied to other production lines.

6.1. Types of Production

The cost model is based on different existing types of production lines at AH. Caused by the fact that AH is a manufacturer for engines, a lot of mechanical operation steps are done there. It exits a big difference in the arrangement of a production line between a car assembly line and a mechanical production line.

Figure 95 illustrates the different types of production lines at AH regarding to the mechanical engine production. The figure shows different work sequences (AF100 – AF300). These sequences are arranged in a row. The first work sequence (AF100) is a **single machine**. If this single machine has an unplanned breakdown, the complete production will have a breakdown. The next type of production line is shown in work sequence (AF200). This sequence consists of three machines and is called a **redundant system**. All these machines do the same operation step. This could be drilling, milling, turning, etc. The use of this system will increase the cycle time of each machine and will decrease the influence of an unplanned machine breakdown to the complete production line. The last production system is the **transfer line**. Transfer lines consist of many processing stations (turning, drilling, grinding, honing, measuring stations, etc.) arranged in series. Most of the time transfer lines are special machines, which are specially designed for the necessary machining task. Characteristic of a transfer line is furthermore the directional, linear material flow. The workpieces pass through the system with a fixed station sequence. (Weck (2005 p. 415))

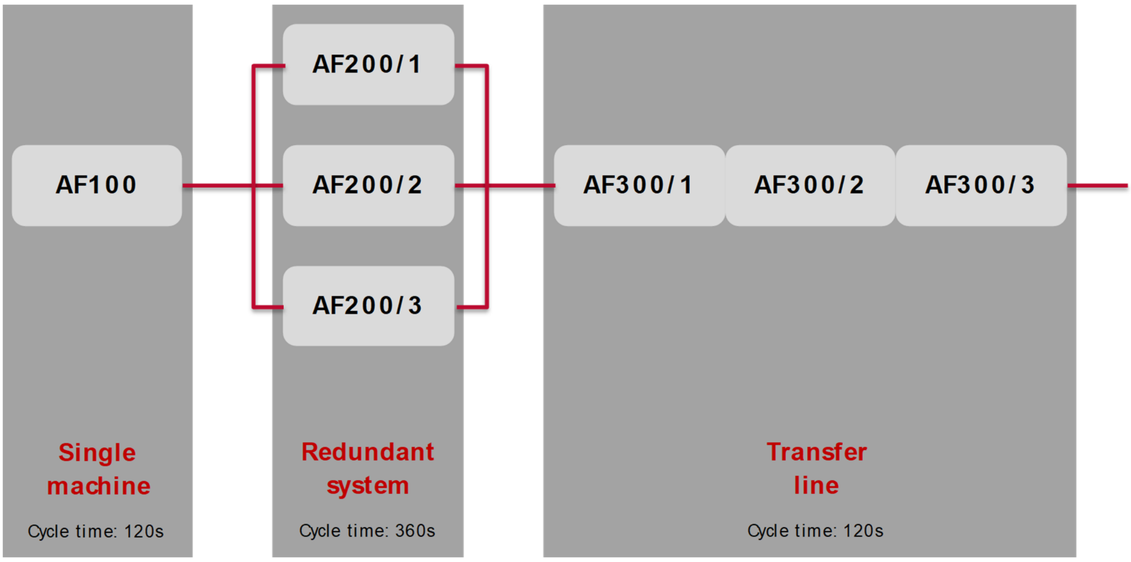


Figure 95: Types of production

Particularly an unplanned breakdown of a single machine or a transfer line has a significant impact to the whole production process. In case of a breakdown of one of these systems the whole production must stop their work. Only the stock of raw material in the existing puffers after the broken machine could be used for further production.

6.2. Overall Downtime Cost Model

This cost model is a rough estimation of costs caused by a machine breakdown in a series production process. At first some general data (like machine-hour rates, labor-hour rates, etc.) were defined and shown in Figure 96.

General Data

Machines in production line	80	#	(1)
Worker in production line	10	#	(2)
Machine-hour rate (exclusive labor costs)	60	€	(3)
Labor-hour rate	16	€	(4)
Cycle time	120	s	(5)

Availability	Effect to prod. Line
0 - 20 %	100 %
21 - 40 %	75 %
41 - 60 %	50 %
61 - 80 %	25 %
81 - 100 %	0 %

Table 1

Figure 96: General data for cost model

Table 1 in Figure 96 illustrates the assumption for effectiveness of machine downtimes to the whole production process. The availability is the number of all machines in a work sequence divided by the number of machines with failures in this work sequence. Regarding to the explanation in the last chapter, it is shown that in case of a breakdown of a single machine the availability would be 0%. The effect to the production line will be 100% and will be considered in the further calculations. Furthermore, it was assumed that no buffers are in the production. Due to this, a dynamic in the production line was not considered.

Also, the values for machines and workers in the production line are assumptions. Further values like the machine-hour rate and the labor-hour rate are depending to the thesis from Habich (2017). The cycle time is depending to the cycle time of the production line P5 ZKG.

To calculate the overall downtime costs a split into three cost categories was done. The overall downtime costs are calculated as shown in Equation 8.

Equation 8: Overall downtime costs

$$\begin{matrix} \text{Overall Downtime} \\ \text{costs} \end{matrix} = \begin{matrix} \text{Downtime} \\ \text{costs} \end{matrix} + \begin{matrix} \text{Catch} - \text{up} \\ \text{costs} \end{matrix} + \begin{matrix} \text{Rework} \\ \text{costs} \end{matrix}$$

The first category is relating to the **downtime costs of the machine** and the impact of this downtime to the whole production line.

To explain the cost model, additional assumptions have to be done. These assumptions are shown in Figure 97.

Cost Model				
Availability rate	75	%	(6)	
Effect to prod. Line	25	%	(7)	=Table 1
Machines in work sequence	4	#	(8)	
Spindles per machine	2	#	(9)	
Cycle time per machine	960	s	(10)	=(5)*(8)*(9)
Machine downtime	500	min	(11)	
Quality issues time	200	min	(12)	

Figure 97: Assumptions for cost model

To calculate the different cost types, it is assumed that the investigated work sequence consists of four machines arranged in a redundant layout. Each machine has two spindles and one machine has a breakdown caused by a broken main spindle. To repair this main spindle the machine has a downtime of 500 minutes. Before the spindle broke down the machine produces parts out of tolerance which will further need a rework. The time for producing workpieces out of tolerance are 200 minutes.

The downtime costs are calculated as shown in Equation 9.

Equation 9: Downtime costs

$$\text{Downtime costs} = \underbrace{\text{Machine downtime} * \left(\text{Machine-hour rate} + \frac{1}{2}\,\text{Labor-hour rate}\right)}_{\text{Machine downtime costs}} + \underbrace{\text{Effect to prod.line} * \left[\left(\text{Number of machines in prod.line} * \text{Machine-hour rate}\right) + \left(\text{Number of worker in prod.line} * \text{Labor-hour rate}\right)\right] * \text{Machine downtime}}_{\text{Effect to prod. Line costs}}$$

Figure 98 shows the downtime costs regarding to the chosen sample.

Downtime costs				
Machine	567	€	(13)	=(11)*[(3)+0,5*(4)]
Production line	10333	€	(14)	=(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**10900**	**€**	**(15)**	**=(13)+(14)**

Figure 98: Downtime costs

This cost classification contains the downtime costs of the machine itself and the impact to the complete production line as shown in Equation 9. A further assumption is done regarding to the labor costs. Only 50% of the labor costs are considered in the calculation, due to the fact, that one worker is able to operate more machines at the same time. The effect costs to the production line refers to Table 1 in Figure 96. In the assumed case (25% effect to the production line) the breakdown causes downtime costs for machines of 10.900€.

The second defined cost classification are costs for catching up **(catch-up costs)** the not produced workpieces during the downtime. To calculate the pieces to catch up, the machine downtime was divided by the cycle time per machine and multiplied with the number of spindles per machine. The cycle time per machine depends on the number of machines in a work sequence and is calculated as shown Figure 97.

Equation 10: Catch-up costs

$$\frac{\textbf{Catch} - \textbf{up}}{\textbf{costs}} = \frac{Pieces\ to}{catch - up} * \frac{\frac{cycle\ time}{per\ machine}}{\frac{spindles}{per\ machine}} * \left(\frac{Machine - hour}{rate} + 2 * \frac{Labor - hour}{rate}\right)$$

Afterwards the catch-up costs are calculated as shown in Equation 10. Therefore, a further assumption relating to the labor costs is done. In case of a catch up most of the worked time is done in additional shifts or in overtime. Due to this, the labor-hour rate is multiplied with a factor two.

Catch-up costs				
Pieces to catch up	63	#	(16)	=(11)/(10)*(9)
Catch-up costs:	**1533**	**€**	**(17)**	**=(16)*(10)/(9)*[(3)+2*(4)]**

Figure 99: Catch-up costs

The last cost category are the costs for rework **(rework costs)**. In case of quality issues goods out of the tolerance are produced. In the chosen example, the machine produced 200 minutes goods out of tolerance, which needs a rework after the production. How to calculate the rework costs is shown in Equation 11.

Equation 11: Rework costs

$$\frac{\textbf{Rework}}{\textbf{costs}} = \frac{Pieces\ to}{rework} * \frac{rework}{cycle\ time} * \left(\frac{Machine - hour}{rate} + \frac{Labor - hour}{rate}\right) * 1{,}2$$

At first it is necessary to determine the pieces to rework. Therefore, the time with quality issues is divided by the machine cycle time and multiplied with the number of spindles per machine. In the chosen example 25 workpieces needs a rework. In case of calculating the rework costs it is necessary to assume two values. At first the rework cycle time is not the same than the machine cycle time. The rework cycle time is 20% higher than the cycle time per machine. This is caused by additional tasks to measure, transport or handle the workpieces, because rework is not done at the area of the production line. Rework is done in separate areas. The second assumption is higher costs for machines and labors or additional costs for renting areas to do the rework. Due to this the costs are multiplied with a factor of 1,2.

Rework costs				
Cycle time per machine	960	s	(10)	
20% Additional time (measuring, transport, handling)	192	s	(18)	=20%*(10)
Rework cycle time	1152	s	(19)	=(10)+(18)
Pieces to rework	25	#	(20)	=(12)/(10)*(9)
Rework costs:	**730**	**€**	**(21)**	**=(20)*(19)*[(3)+(4)]*1,2**

Figure 100: Rework costs

Regarding to Equation 8 the overall downtime costs could be calculated for the chosen example:

Overall Downtime costs:	**13163**	**€**	**(22)**	**=(15)+(17)+(21)**

Figure 101: Overall downtime costs

Figure 101 points out that in the chosen example a downtime of 500 minutes and a production of 25 parts out of tolerance causes overall downtime costs of 13.000€.

Further information and the complete cost model for the chosen example can be found in Appendix 2.

6.2.1. Cost Model Scenarios

To evaluate the differences between the number of machines in a work sequence and the effect to the complete production line three scenarios were created. Each scenario consists out of three sub scenarios. The scenarios are different in the time of machine downtime and the period for producing parts with quality issues (Table 23). The sub scenarios are different in the rate of availability and the effect to production line (Table 24). Scenario one describes a work sequence with six redundant machining centers, scenario two describes a work sequence with three machining centers and scenario three a single machine. In all scenarios, the machining centers have two spindles. Furthermore, the general assumptions as shown to Figure 96 are done (machine-hour rates, labor-hour rates, cycle time, etc.). At all scenarios one machine has an error.

Table 23: Overview about the cost scenarios

	Machine downimte	Quality issues time	Spindles per machine
Scenario 1	420 min	0 min	2
Scenario 2	420 min	180 min	2
Scenario 3	0 min	420 min	2

Table 24: Overview about the sub scenarios

	Machines in work sequence	Down machines	Availability rate	Effect to prod. Line
Sub Scenario 1	6	1	83,30%	0%
Sub Scenario 2	3	1	66,70%	25%
Sub Scenario 3	1	1	0%	100%

Table 25: Scenario 2.2

Scenario 2.2				
Availability rate	66,7	%	(6)	
Effect to prod. Line	25	%	(7)	=Table 1
Machines in work sequence	3	#	(8)	
Spindles per machine	2	#	(9)	
Cycle time per machine	720	s	(10)	=(5)*(8)*(9)
Machine downtime	**420**	**min**	**(11)**	
Quality issues time	**180**	**min**	**(12)**	
Downtime costs				
Machine	476	€	(13)	=(11)*[(3)+0,5*(4)]
Production line	8680	€	(14)	=(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**9156**	**€**	**(15)**	**=(13)+(14)**
Catch-up costs				
Pieces to catch up	70	#	(16)	=(11)/(10)*(9)
Catch-up costs:	**644**	**€**	**(17)**	**=(16)*(10)/(9)*[(3)+2*(4)]**
Rework costs				
Cycle time per machine	720	s	(10)	
20% Additional time (measuring, transport, handling)	144	s	(18)	=(10)+20%*(10)
Rework cycle time	864	s	(19)	=(10)+(18)
Pieces to rework	30	#	(20)	=(12)/(10)*(9)
Rework costs:	**657**	**€**	**(21)**	**=(20)*(19)*[(3)+(4)]*1,2**
Overall Downtime costs:	**10457**	**€**	**(22)**	**=(15)+(17)+(21)**

The values for these scenarios are chosen regarding to typical changing times for main spindles at AH. A typical change of a spindle lasts approximately seven hours (420 minutes). Furthermore, the investigated production line (P5 ZKG) consist of work sequences with three and six machines.

Table 25 illustrates the calculation of scenario 2.2. Scenario two is a combination of 420 minutes machine downtime and 180 minutes production of bad parts. One of three machines have a failure which causes the downtime and the quality issues. Due to the influence rate of 25% (because of low availability) high costs for the complete production line occur. The overall downtime costs (calculated regarding to Equation 8) are 10.457€

The calculation of all other scenario is shown in Appendix 3, Appendix 4 and Appendix 5.

To determine the costs for one breakdown a mix between all scenarios was calculated. Not all scenarios occur with the same probability. Therefore, the following assumption were done:

Table 26: Probability assumptions

	Probability
Scenario 1	70%
Scenario 2	25%
Scenario 3	5%

	Probability
Sub Scenario 1	70%
Sub Scenario 2	25%
Sub Scenario 3	5%

These assumptions lead to an average cost for one breakdown and an average breakdown cost per hour assumed that a breakdown lasts seven hours to repair. The average costs per hour downtime are 716,5€.

Table 27: Average overall downtime costs

		Probability
Scenario 1	€ 5 026,00	70%
Scenario 2	€ 5 682,64	25%
Scenario 3	€ 1 532,16	5%

€ 5 015,47	Average overall downtime costs

Table 28: Average overall downtime costs per hour

		Probability
Scenario 1	€ 718,00	70%
Scenario 2	€ 811,81	25%
Scenario 3	€ 218,88	5%

€ 716,50	Average overall downtime costs per hour

Table 29: Comparison between all scenarios

Scenario 1	Sub Scenario 1	Sub Scenario 2	Sub Scenario 3
Downtime costs:	€ 476,00	€ 9 156,00	€ 35 196,00
Catch-up costs:	€ 644,00	€ 644,00	€ 644,00
Rework costs:	€ 0,00	€ 0,00	€ 0,00
Overall Downtime costs:	€ 1 120,00	€ 9 800,00	€ 35 840,00

Scenario 2			
Downtime costs:	€ 476,00	€ 9 156,00	€ 35 196,00
Catch-up costs:	€ 644,00	€ 644,00	€ 644,00
Rework costs:	€ 656,64	€ 656,64	€ 656,64
Overall Downtime costs:	€ 1 776,64	€ 10 456,64	€ 36 496,64

Scenario 3			
Downtime costs:	€ 0,00	€ 0,00	€ 0,00
Catch-up costs:	€ 0,00	€ 0,00	€ 0,00
Rework costs:	€ 1 532,16	€ 1 532,16	€ 1 532,16
Overall Downtime costs:	€ 1 532,16	€ 1 532,16	€ 1 532,16

Table 29 illustrates the comparison between all scenarios and sub scenarios.

6.3. Discussion

The costs for implementing a condition monitoring system like the FAG SmartCheck to a machining center are approximately 2000€. Scenario 2.2 figures out that only one breakdown with these parameters (downtime, influence on the complete production line, quality issues) costs five times more than the implementation of a monitoring system. Furthermore, the calculation for the average overall downtime costs per hour figured out that the costs for a breakdown are 716€ per hour.

Figure 102 shows that the breakeven point of implementing 80 condition monitoring systems into a production line will be at the point of 32 breakdowns. Assumed that a breakdown lasts seven hours and one CMS costs 2000€. Regarding to the evaluation (done at the production line P5 ZKG in the year 2015 and 2016) 40 breakdowns occurs per year with an average duration of 7 hours (Table 30).

Table 30: Average time per breakdown

	Breakdowns	Time [min]	Time per breakdown [min]
2015	35	16624	475
2016	45	16489	366
average	**40**		**421**

With that evaluation, it is shown that even implementing CMS to all machines at the production line P5 ZKG will be profitable within one year.

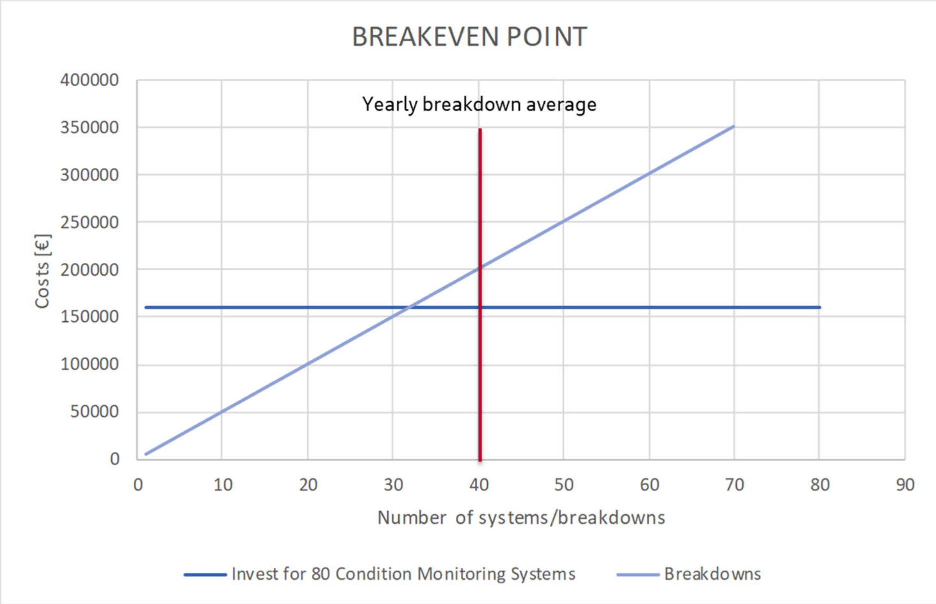


Figure 102: Breakeven point

All calculations and scenarios assume that there are **no buffers** at the production line. As shown in Table 29 the impact of downtime costs related to the complete production line is very high. Caused by this high impact it is necessary to do further analysis. The dynamic of production line caused by buffers, short breakdowns or repairs must be evaluated to draw conclusion about the real impact of machine breakdowns to the complete production line. If the real values will differ a lot to the assumed values the amortization time will change significantly.

7. Conclusion

Already the first potential evaluations figured out that a big difference in the emitted vibrations between used and overhauled spindles is existing. These results lead to the knowledge that using vibration sensors is a good opportunity to identify bearing conditions in main spindles.

Furthermore, the analysis carried out that a lot of different spindle types are used at AH. These different spindle types offer different opportunities to implement sensors for condition monitoring. But quite few types offer even no possibility to integrate vibration sensors into the spindles. Several studies have demonstrated that sensors (vibration and temperature), to monitor the spindle condition, are already installed but not in use. Although, preliminary spaces to implement vibration sensors to the spindle were found.

This thesis is focused on implementing condition monitoring in series production. The selected line (P5 ZKG) for the experiments consists mainly of GROB machining centers equipped with Kessler spindles. These Kessler spindles are very often used at AH and offers the possibility to additionally implement vibration sensors. Therefore, the effort to implement sensors into the spindle and into the machining centers were evaluated. The implementation tests figured out that the effort to implement CM sensors and systems to a machining center is not very high and manageable.

To identify the best systems for use a market analysis was done. Regarding to this analysis the opportunity came up to work and test with a complete new system. This new system is a prototype and not available yet on the market. The prototype combines all advantages of the different products in one system and is based on the very innovative product from FAG. Using the prototype (FAG SmartCheck) gains the possibility to:

- implement the monitoring systems to machining center,
- visualize the actual spindle conditions in a smartphone APP,
- connect several different sensors (temperature, vibration) to one processing unit,
- use external trigger signals for starting and stopping a measurement procedure,
- analyze the measured signals and find the root failure cause,
- use a big database of several bearings with their specific failure frequencies,
- talk with experts and exchange the measured data to get further help,
- manually export the raw data, no automatically export possible,
- visualize trends for the measured signals and
- implement the monitoring systems to plant network.

Several tests figured out that there are differences in signal quality regarding to the sensor position and sensor mounting. The best signals were measured with implemented vibration sensors, fixed with screws to the spindle and arranged in vertical position. Furthermore, the tests showed that there is no influence between the front and the back bearing of main spindles. This lead to the conclusion that two sensors are necessary to monitor the front and the back bearing condition.

Using different systems carried out, that there is big difference in usability and offered software functions. Most of the systems have their primary scope on monitoring the process and not the condition of a component. Therefore, these systems are only further developments and have severe restrictions in the range of functionally. The systems from FAG (SmartCheck Prototype & SmartCheck) are systems developed for component condition monitoring and offers specific measurement tools for this purpose.

Unfortunately, it was not possible to draw conclusions between the typical wear graph of a spindle and the development of a spindle condition over the time. The investigated period (one month) was too short to identify differences in spindle condition. The short measurement period was caused by different factors like additional waiting times for systems or management difficulties. It was planned to collect data over a period from four months. Caused by the waiting times and management difficulties it was only possible to collect data over one month.

The set-up of a cost model to determine the overall downtime costs per hour and the breakeven calculation illustrated the economic sense to use condition monitoring systems. Creating different scenarios and calculating a mean value out of these leads to the finding that even implementing condition monitoring systems to the complete production line will have an amortization period within one year. This calculation is based on several assumptions like a production without buffers or a repair of machines only in production free times.

This thesis figured out that it is possible to monitor a spindle condition using temperature and vibration monitoring systems. Measured differences between used and overhauled spindles confirm this hypothesis. Furthermore, it was shown that the effort to implement such systems to machining centers is manageable.

8. Perspective

It was shown that using condition monitoring systems is a good opportunity to determine the main spindle condition of a machining center. The findings regarding to the existing restrictions in sensor integration ability and the missing connection between the change of condition over the time and the typical wear graph of a spindle leads to the need of further researches and long-term experiments.

A normal spindle life-time at AH is about six months. Actually, the measured values indicate a very good spindle condition. Performing further tests will show the real wear graph of a spindle and will draw further conclusions to determine the optimal predetermined time point for replacing the spindle. Furthermore, more knowledge about the real change of condition will bring possibilities to come up with new prognosis/ scheduling models and will avoid unplanned breakdowns and minimize the downtimes.

Further market studies should be done to find a solution for implementing a sensor to every spindle type. Not only spindles with preliminary space should have the capability to be monitored. Also, further improvements to the prototype system like the correction of the wrong input wiring or the possibility to use digital input signals should be done. To make the prototype ready for the market additional collaboration should be done between Audi and Schaeffler.

The cost analysis was done without considering buffers in the production line. Existing buffers creates specific dynamics in the production process. It is hard to simulate this production dynamic in usual programs. To get a deeper understanding and to determine the exact effect of machine downtimes to the complete production process, further evaluations must be done. Caused by the high cost impact of the downtime costs related to the production line to the overall downtime costs it is absolutely necessary to determine the real effect.

Furthermore, regarding to the short time period of measurements (only one month) it is definitely necessary to do further long-term experiments.

The field of maintenance is still at the beginning of the road in terms of Industry 4.0. However, first steps have already been taken here to prepare a successful realization. Good projects to name would be the TPM4.0 project in cooperation with the TU Graz and AH, or the approach of Audi to implement artificial intelligence connected to condition monitoring systems. Also, Reichel (2009) considered in his book a new way of condition monitoring. So-called “stress-wave-analyzing methods” are possible new ways for monitoring conditions. This method is based on a ultrasonic wave analysis and will give far more information about the component condition.

Still different companies like Schaeffler doing a lot of R&D to find new possibilities for determining the actual machine and component condition. A complete new concept is shown in Figure 103. This system offers opportunities to operate with different sensors, has an integrated software intelligence and cloud connection. Furthermore, this system has a web-based interface for easy handling and operating. (FAG (2017))

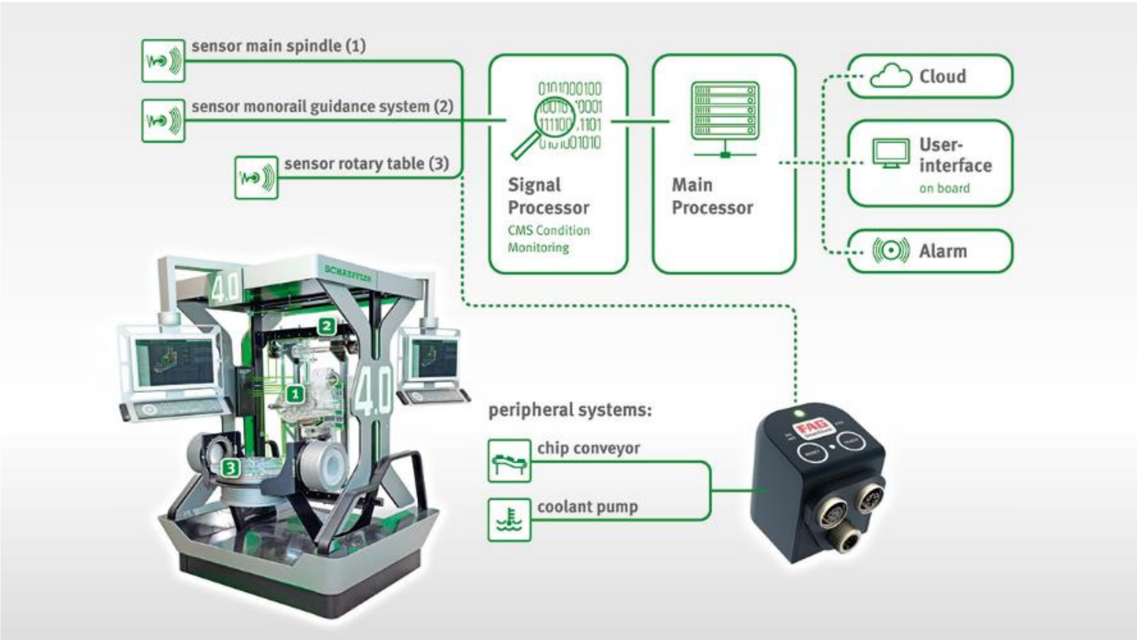


Figure 103: Schaeffler prototype for a 4.0-concept machine by FAG (2017)

9. List of Illustrations

10. List of Tables

11. References

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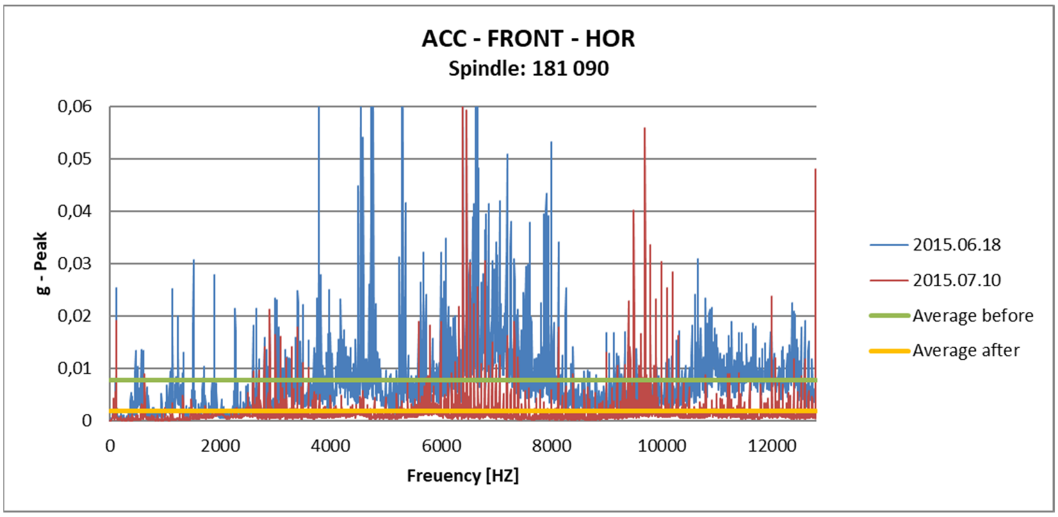
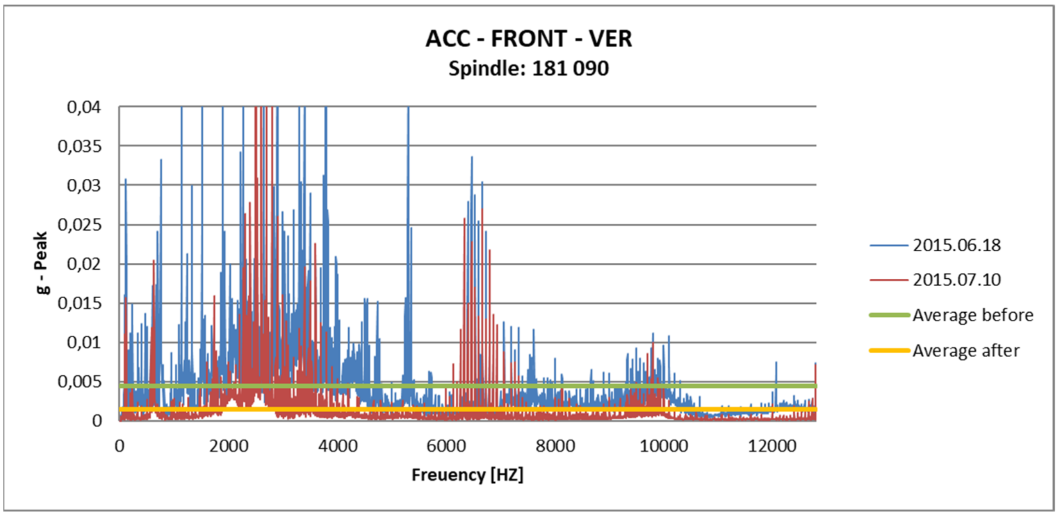
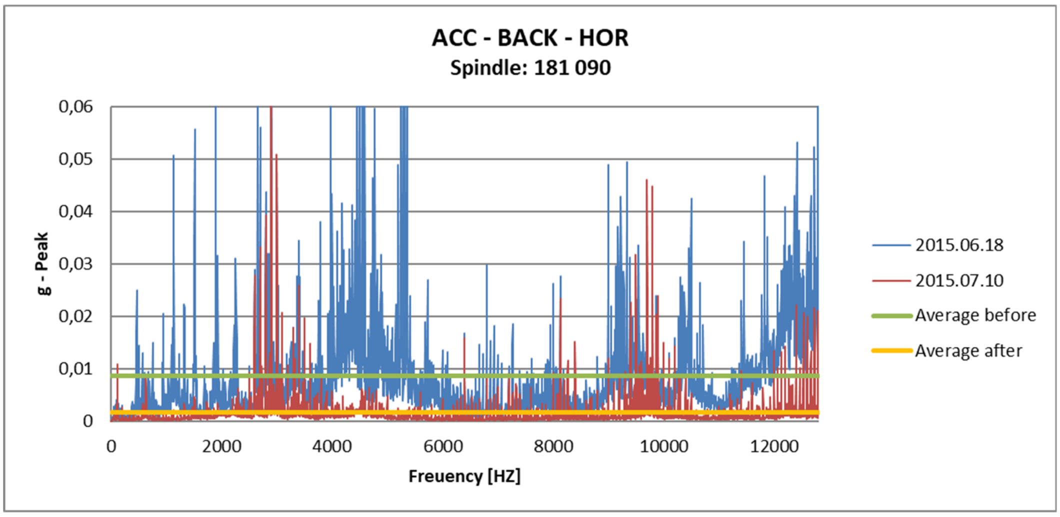
12. Appendix







Appendix 1: Measurement results potential evaluation spindle 181 090

General Data

Machines in production line	80	#	(1)
Worker in production line	10	#	(2)
Machine-hour rate (exclusive labor costs)	60	€	(3)
Labor-hour rate	16	€	(4)
Cycle time	120	s	(5)

Availability		Effect to prod. Line	
0 - 20	%	100	%
21 - 40	%	75	%
41 - 60	%	50	%
61 - 80	%	25	%
81 - 100	%	0	%

Table 1

Cost Model

Availability rate	75	%	(6)	
Effect to prod. Line	25	%	(7)	=Table 1
Machines in work sequence	4	#	(8)	
Spindles per machine	2	#	(9)	
Cycle time per machine	960	s	(10)	=(5)*(8)*(9)
Machine downtime	500	min	(11)	
Quality issues time	200	min	(12)	

Downtime costs

Machine	567	€	(13)	=(11)*[(3)+0,5*(4)]
Production line	10333	€	(14)	=(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**10900**	**€**	**(15)**	**=(13)+(14)**

Catch-up costs

Pieces to catch up	63	#	(16)	=(11)/(10)*(9)
Catch-up costs:	**1533**	**€**	**(17)**	**=(16)*(10)/(9)*[(3)+2*(4)]**

Rework costs

Cycle time per machine	960	s	(10)	
20% Additional time (measuring, transport, handling)	192	s	(18)	=20%*(10)
Rework cycle time	1152	s	(19)	=(10)+(18)
Pieces to rework	25	#	(20)	=(12)/(10)*(9)
Rework costs:	**730**	**€**	**(21)**	**=(20)*(19)*[(3)+(4)]*1,2**

Overall Downtime costs:	**13163**	**€**	**(22)**	**=(15)+(17)+(21)**

Appendix 2: Example cost model

Scenario 1

Scenario 1.1

Availability rate	83,3	%	(6)
Effect to prod. Line	0	%	(7) =Table 1
Machines in work sequence	6	#	(8)
Spindles per machine	2	#	(9)
Cycle time per machine	1440	s	(10) =(5)*(8)*(9)
Machine downtime	**420**	**min**	**(11)**
Quality issues time	**0**	**min**	**(12)**
Downtime costs			
Machine	476	€	(13) =(11)*[(3)+0,5*(4)]
Production line	0	€	(14) =(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**476**	**€**	**(15) =(13)+(14)**
Catch-up costs			
Pieces to catch up	35	#	(16) =(11)/(10)*(9)
Catch-up costs:	**644**	**€**	**(17) =(16)*(10)/(9)*[(3)+2*(4)]**
Rework costs			
Cycle time per machine	1440	s	(10)
20% Additional time (measuring, transport, handling)	288	s	(18) =(10)+20%*(10)
Rework cycle time	1728	s	(19) =(10)+(18)
Pieces to rework	0	#	(20) =(12)/(10)*(9)
Rework costs:	**0**	**€**	**(21) =(20)*(19)*[(3)+(4)]*1,2**
Overall Downtime costs:	**1120**	**€**	**(22) =(15)+(17)+(21)**

Scenario 1.2

Availability rate	66,7	%	(6)
Effect to prod. Line	25	%	(7) =Table 1
Machines in work sequence	3	#	(8)
Spindles per machine	2	#	(9)
Cycle time per machine	720	s	(10) =(5)*(8)*(9)
Machine downtime	**420**	**min**	**(11)**
Quality issues time	**0**	**min**	**(12)**
Downtime costs			
Machine	476	€	(13) =(11)*[(3)+0,5*(4)]
Production line	8680	€	(14) =(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**9156**	**€**	**(15) =(13)+(14)**
Catch-up costs			
Pieces to catch up	70	#	(16) =(11)/(10)*(9)
Catch-up costs:	**644**	**€**	**(17) =(16)*(10)/(9)*[(3)+2*(4)]**
Rework costs			
Cycle time per machine	720	s	(10)
20% Additional time (measuring, transport, handling)	144	s	(18) =(10)+20%*(10)
Rework cycle time	864	s	(19) =(10)+(18)
Pieces to rework	0	#	(20) =(12)/(10)*(9)
Rework costs:	**0**	**€**	**(21) =(20)*(19)*[(3)+(4)]*1,2**
Overall Downtime costs:	**9800**	**€**	**(22) =(15)+(17)+(21)**

Scenario 1.3

Availability rate	0	%	(6)
Effect to prod. Line	100	%	(7) =Table 1
Machines in work sequence	1	#	(8)
Spindles per machine	2	#	(9)
Cycle time per machine	240	s	(10) =(5)*(8)*(9)
Machine downtime	**420**	**min**	**(11)**
Quality issues time	**0**	**min**	**(12)**
Downtime costs			
Machine	476	€	(13) =(11)*[(3)+0,5*(4)]
Production line	34720	€	(14) =(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**35196**	**€**	**(15) =(13)+(14)**
Catch-up costs			
Pieces to catch up	210	#	(16) =(11)/(10)*(9)
Catch-up costs:	**644**	**€**	**(17) =(16)*(10)/(9)*[(3)+2*(4)]**
Rework costs			
Cycle time per machine	240	s	(10)
20% Additional time (measuring, transport, handling)	48	s	(18) =(10)+20%*(10)
Rework cycle time	288	s	(19) =(10)+(18)
Pieces to rework	0	#	(20) =(12)/(10)*(9)
Rework costs:	**0**	**€**	**(21) =(20)*(19)*[(3)+(4)]*1,2**
Overall Downtime costs:	**35840**	**€**	**(22) =(15)+(17)+(21)**

Appendix 3: Scenario 1

Scenario 2

Scenario 2.1

Availability rate	83,3	%	(6)	
Effect to prod. Line	0	%	(7)	=Table 1
Machines in work sequence	6	#	(8)	
Spindles per machine	2	#	(9)	
Cycle time per machine	1440	s	(10)	=(5)*(8)*(9)
Machine downtime	**420**	**min**	**(11)**	
Quality issues time	**180**	**min**	**(12)**	
Downtime costs				
Machine	476	€	(13)	=(11)*[(3)+0,5*(4)]
Production line	0	€	(14)	=(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**476**	**€**	**(15)**	**=(13)+(14)**
Catch-up costs				
Pieces to catch up	35	#	(16)	=(11)/(10)*(9)
Catch-up costs:	**644**	**€**	**(17)**	**=(16)*(10)/(9)*[(3)+2*(4)]**
Rework costs				
Cycle time per machine	1440	s	(10)	
20% Additional time (measuring, transport, handling)	288	s	(18)	=(10)+20%*(10)
Rework cycle time	1728	s	(19)	=(10)+(18)
Pieces to rework	15	#	(20)	=(12)/(10)*(9)
Rework costs:	**657**	**€**	**(21)**	**=(20)*(19)*[(3)+(4)]*1,2**
Overall Downtime costs:	**1777**	**€**	**(22)**	**=(15)+(17)+(21)**

Scenario 2.2

Availability rate	66,7	%	(6)	
Effect to prod. Line	25	%	(7)	=Table 1
Machines in work sequence	3	#	(8)	
Spindles per machine	2	#	(9)	
Cycle time per machine	720	s	(10)	=(5)*(8)*(9)
Machine downtime	**420**	**min**	**(11)**	
Quality issues time	**180**	**min**	**(12)**	
Downtime costs				
Machine	476	€	(13)	=(11)*[(3)+0,5*(4)]
Production line	8680	€	(14)	=(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**9156**	**€**	**(15)**	**=(13)+(14)**
Catch-up costs				
Pieces to catch up	70	#	(16)	=(11)/(10)*(9)
Catch-up costs:	**644**	**€**	**(17)**	**=(16)*(10)/(9)*[(3)+2*(4)]**
Rework costs				
Cycle time per machine	720	s	(10)	
20% Additional time (measuring, transport, handling)	144	s	(18)	=(10)+20%*(10)
Rework cycle time	864	s	(19)	=(10)+(18)
Pieces to rework	30	#	(20)	=(12)/(10)*(9)
Rework costs:	**657**	**€**	**(21)**	**=(20)*(19)*[(3)+(4)]*1,2**
Overall Downtime costs:	**10457**	**€**	**(22)**	**=(15)+(17)+(21)**

Scenario 2.3

Availability rate	0	%	(6)	
Effect to prod. Line	100	%	(7)	=Table 1
Machines in work sequence	1	#	(8)	
Spindles per machine	2	#	(9)	
Cycle time per machine	240	s	(10)	=(5)*(8)*(9)
Machine downtime	**420**	**min**	**(11)**	
Quality issues time	**180**	**min**	**(12)**	
Downtime costs				
Machine	476	€	(13)	=(11)*[(3)+0,5*(4)]
Production line	34720	€	(14)	=(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**35196**	**€**	**(15)**	**=(13)+(14)**
Catch-up costs				
Pieces to catch up	210	#	(16)	=(11)/(10)*(9)
Catch-up costs:	**644**	**€**	**(17)**	**=(16)*(10)/(9)*[(3)+2*(4)]**
Rework costs				
Cycle time per machine	240	s	(10)	
20% Additional time (measuring, transport, handling)	48	s	(18)	=(10)+20%*(10)
Rework cycle time	288	s	(19)	=(10)+(18)
Pieces to rework	90	#	(20)	=(12)/(10)*(9)
Rework costs:	**657**	**€**	**(21)**	**=(20)*(19)*[(3)+(4)]*1,2**
Overall Downtime costs:	**36497**	**€**	**(22)**	**=(15)+(17)+(21)**

Appendix 4: Scenario 2

Scenario 3

Scenario 3.1

Availability rate	83,3	%	(6)	
Effect to prod. Line	0	%	(7)	=Table 1
Machines in work sequence	6	#	(8)	
Spindles per machine	2	#	(9)	
Cycle time per machine	1440	s	(10)	=(5)*(8)*(9)
Machine downtime	**0**	**min**	**(11)**	
Quality issues time	**420**	**min**	**(12)**	
Downtime costs				
Machine	0	€	(13)	=(11)*[(3)+0,5*(4)]
Production line	0	€	(14)	=(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**0**	**€**	**(15)**	**=(13)+(14)**
Catch-up costs				
Pieces to catch up	0	#	(16)	=(11)/(10)*(9)
Catch-up costs:	**0**	**€**	**(17)**	**=(16)*(10)/(9)*[(3)+2*(4)]**
Rework costs				
Cycle time per machine	1440	s	(10)	
20% Additional time (measuring, transport, handling)	288	s	(18)	=(10)+20%*(10)
Rework cycle time	1728	s	(19)	=(10)+(18)
Pieces to rework	35	#	(20)	=(12)/(10)*(9)
Rework costs:	**1532**	**€**	**(21)**	**=(20)*(19)*[(3)+(4)]*1,2**
Overall Downtime costs:	**1532**	**€**	**(22)**	**=(15)+(17)+(21)**

Scenario 3.2

Availability rate	66,7	%	(6)	
Effect to prod. Line	25	%	(7)	=Table 1
Machines in work sequence	3	#	(8)	
Spindles per machine	2	#	(9)	
Cycle time per machine	720	s	(10)	=(5)*(8)*(9)
Machine downtime	**0**	**min**	**(11)**	
Quality issues time	**420**	**min**	**(12)**	
Downtime costs				
Machine	0	€	(13)	=(11)*[(3)+0,5*(4)]
Production line	0	€	(14)	=(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**0**	**€**	**(15)**	**=(13)+(14)**
Catch-up costs				
Pieces to catch up	0	#	(16)	=(11)/(10)*(9)
Catch-up costs:	**0**	**€**	**(17)**	**=(16)*(10)/(9)*[(3)+2*(4)]**
Rework costs				
Cycle time per machine	720	s	(10)	
20% Additional time (measuring, transport, handling)	144	s	(18)	=(10)+20%*(10)
Rework cycle time	864	s	(19)	=(10)+(18)
Pieces to rework	70	#	(20)	=(12)/(10)*(9)
Rework costs:	**1532**	**€**	**(21)**	**=(20)*(19)*[(3)+(4)]*1,2**
Overall Downtime costs:	**1532**	**€**	**(22)**	**=(15)+(17)+(21)**

Scenario 3.3

Availability rate	0	%	(6)	
Effect to prod. Line	100	%	(7)	=Table 1
Machines in work sequence	1	#	(8)	
Spindles per machine	2	#	(9)	
Cycle time per machine	240	s	(10)	=(5)*(8)*(9)
Machine downtime	**0**	**min**	**(11)**	
Quality issues time	**420**	**min**	**(12)**	
Downtime costs				
Machine	0	€	(13)	=(11)*[(3)+0,5*(4)]
Production line	0	€	(14)	=(7)*[(1)*(3)+(2)*(4)]*(11)
Downtime costs:	**0**	**€**	**(15)**	**=(13)+(14)**
Catch-up costs				
Pieces to catch up	0	#	(16)	=(11)/(10)*(9)
Catch-up costs:	**0**	**€**	**(17)**	**=(16)*(10)/(9)*[(3)+2*(4)]**
Rework costs				
Cycle time per machine	240	s	(10)	
20% Additional time (measuring, transport, handling)	48	s	(18)	=(10)+20%*(10)
Rework cycle time	288	s	(19)	=(10)+(18)
Pieces to rework	210	#	(20)	=(12)/(10)*(9)
Rework costs:	**1532**	**€**	**(21)**	**=(20)*(19)*[(3)+(4)]*1,2**
Overall Downtime costs:	**1532**	**€**	**(22)**	**=(15)+(17)+(21)**

Appendix 5: Scenario 3