1 Research Context

The everyday increasing competition in industry and the compulsion of faster investment paybacks for complex and expensive machinery, in addition to operational safety, health and environmental requirements, take for granted a high availability of the production machinery and a high and stable quality of the products. These targets are reached only if the machinery is kept in proper working condition by utilizing an appropriate maintenance tactic [37], [38]. In this framework, monitoring of machinery systems has become progressively more important in meeting the rapidly changing maintenance requirements of today's manufacturing systems. Besides, as the pressure to reduce workforce in plants increases, so too does the need for additional automation and reduced organizational level maintenance. Augmented automation in manufacturing plants has led to rapid growth in the number of machinery sensors installed. Along with reduced manning, increased operating tempos are requiring maintenance providers to make repairs faster and ensure that equipment operates reliably for longer periods. To deal with these challenges, condition based maintenance (CBM) has been widely and acceptably employed within industry. Different condition monitoring techniques, nondestructive tests and machine diagnostic methods provide significant support for CBM programs as long as they are properly employed. These include all those evaluation methods by which the integrity of different machinery components or assembled pieces of equipment is being examined nonintrusively.

1.1 General Research Motivation

Overall, maintenance has been the point of interest of different scientific and practical efforts for years. Even so, till the end of the 19th century maintenance had been merely consisted of machinery repair and inspection. In other words, there had been failures and people used to run to them in order to fix the problems. Since the beginning of 20th century maintenance has found its key position in different industries and has been shaped in a more professional way involving different strategies and various tactics in-taking different techniques and technologies. Hence, in twentieth century man has learnt how to deal with failures in the best possible way. However, in the 21st century there exists only an ultimate goal for all maintenance activities and that is to have zero failure. This is not a mathematical zero; it denotes lowering the number of failures day by day, month by month and year by year to reach an optimum situation in which the production system does not suffer from any failure. Nevertheless, reaching the mathematical zero failure would not be a dream in a few decades [325].

Therefore, in a few decades maintenance would have only a preventive role; an essential commitment in which all activities would have either predictive or proactive forms. Such activities entail predicting and anticipating the potential failures before occurrence and working proactively in order to optimize the maintenance activities. This can be the most intelligent and feasible way to prevent failures and the path to the ultimate goal of zero failure. However, converting this frame of thought into a frame of work requires devotion of further conceptual and practical research, outcomes of which will definitely facilitate the industry with valuable knowledge necessary to walk on the right path and arrive at the wanted target [347]. A first step towards enabling such a conversion is to make use of condition-based maintenance, a preventive maintenance tactic which strives to identify incipient faults before they become critical which enables more accurate planning of the preventive maintenance. CBM can be realized by utilizing complex technical systems or by manual monitoring of the machinery condition that is provided by human senses and experience. Although CBM holds a lot of benefits compared to other maintenance tactics it is not still effectively utilized and efficiently used in many companies, a reason of which is employing of CBM without actually being acquainted with it [325].

Condition based maintenance has different aspects and therefore different systems, each of which involves many sub-systems and related issues that can be taken into account for research and development. A CBM process starts with acquiring data from equipment and machinery via transducers and ended with control and command which is based on rich and high-quality information that has been developed through distinct phases of diagnostics, condition monitoring and assessment, and prognostics, see figure 1. The data and information pass through a communication system that feed different sections. Each and every of the CBM system components boasts its weight and importance and can be a taken as a research focus. This decision is to be made based on requirements of a specific case (e.g. characteristics of a particular industry, plant or machinery) or necessities outlined by the stakeholders like a system's weak points identified by an engineer or a technician.

Overview of a CBM System

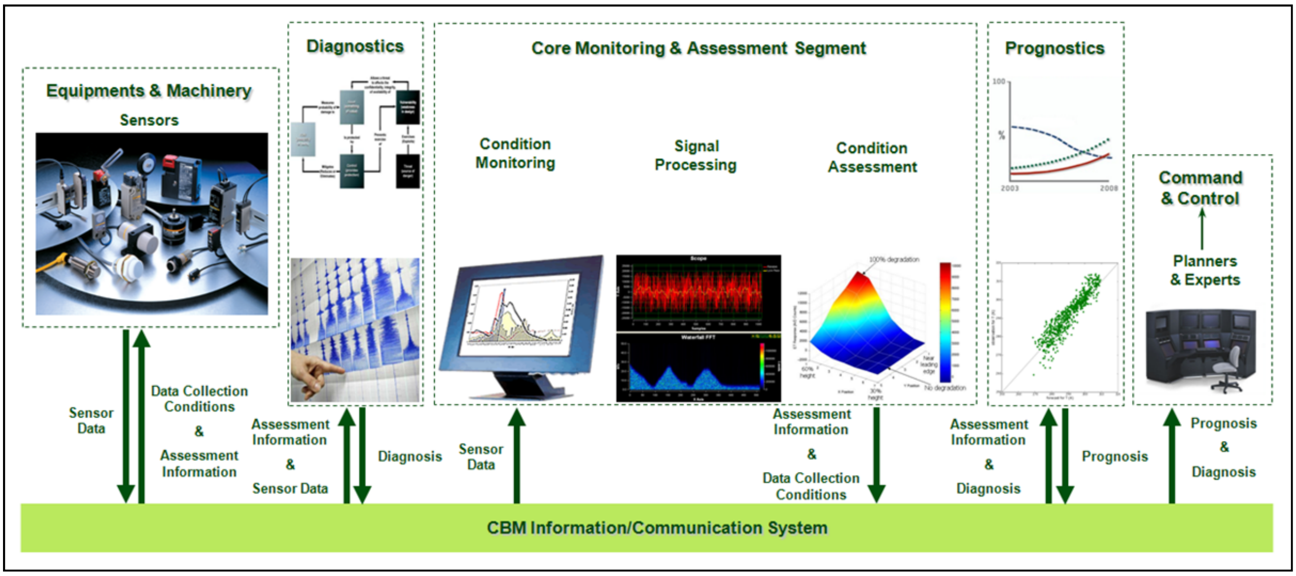

Figure 1 Different components and aspects of a CBM System

Research on any CBM segment will be definitely beneficial for more and better development and improvement of the overall system; eventually, different academic institutes and industrial companies can gain profit from the research results distinctively. However, based on the investigation undertaken by the author and the expert knowledge provided by colleagues and practitioners particularly in the automotive supply industry, it has been reckoned that the dominant barrier against the effective use of a CBM system is not the availability of proper technologies but the readiness of thorough know-what and know-why of various condition monitoring techniques (CMT) and nondestructive tests (NDT) used for CBM. This challenge is then considered to be a major predicament which needs to be dissolved and handled in the most effective and feasible way.

1.2 The Problem and a Potential Solution

Equipment is broken down if it fails to perform its regular function, which is to say there is disruption of normal equipment operation. This expresses that not only when there is function loss but also even if there is a function diminution, it is regarded as equipment failure or breakdown. Equipment stoppage is usually regarded as a major breakdown and not just a disturbance. In the case of function diminution, i.e. function or quality deterioration, continued equipment operation results in production of defective components, reduced output, frequent stoppages, noisy operation, reduced speed, unsafe conditions, and so on. Superior manufacturing companies have for a long time recognized the high costs associated with plant and machinery breakdowns [61]. These costs include inspection, repair, and equipment downtime that are usually measured in terms of reduced productivity, poor quality and increased delivery time [404], [525]. As mentioned above, health and safety is another liability factor and it has to be considered that machinery breakdown must not cause injury [75]. However, as Bengtsson et al. declare, productivity in general is the key factor among all [60].

Generally, a large number of breakdowns occur during startups and shutdowns. However, equipment failure of recently overhauled machine could also be due to poor maintenance. Causes that evade the notice are termed as hidden defects. Thus, the key to reduce breakdowns is to uncover and rectify these hidden defects before breakdown actually occurs. Breakdowns are only a tip of the iceberg. Hidden defects such as sticking, abrasion, looseness, leakage, corrosion, erosion, deformation, scratches, cracks, vibrations, noise, etc., are the irregularities that lie beneath. Even when there are such irregularities, they are neglected because of their minor nature or the perception that such defects are relatively unimportant in comparison with breakdowns. The tendency to overlook such minor defects soon results in minor defects becoming major defects. If these minor defects are not recognized and eliminated as soon as they occur, the initial failure damage may be obscured by subsequent damage and root cause not be known and rectified. Consecutively, this may lead to repetitive or chronic failures. It is, therefore, essential for different companies to employ a reliable CBM program, in which the condition assessment of machinery and equipment is effectively undertaken.

With this incentive, numerous condition monitoring techniques and nondestructive tests have undergone significant advances in recent years. These advances have been manifested by development of new methods or improvement of the available ones. As Dos Reis correctly declares, the driving force behind these activities has been, and continues to be, the need to nonintrusively evaluate and characterize machinery condition as well as to accurately predict fitness for service and remaining useful life of its components or structural system [164]. Like the employment of any new technical concept or technology, its proper application is of critical importance. This need is particularly factual in the field of condition based maintenance that has become increasingly refined and technology-driven. By matching the right CMT/NDT to the proper application, CBM does not need to be extremely complicated, nor does it have to require a large investment of capital.

However, this knowledge does not completely exist in many companies round the globe. Usually, there is trend in the business field based on which companies decide to employ particular CMTs/NDTs, for which they purchase sophisticated instruments and train technicians for proper technical use of them. But then, the missing link is the joint know-what and know-why in application of these tests and techniques. Therefore, there is an essential need to have an extensive overview of all the existing condition monitoring techniques and nondestructive tests, their fitness of use for particular materials and objects (i.e. machinery components), the problems and discontinuity types that can be identified by these CMTs/NDTs, and the advantages and disadvantages of each. With all these information in hand, maintenance managers can reasonably decide what tests are the most appropriate ones for definite applications or certain cases, and thus, establish an effective CBM program.

1.3 Research Proposition, Goal and Stakeholders

Productivity is the armament for manufacturers to keep their competitiveness in today's turbulent but emergent global market. One of the ways to boost productivity is to increase availability, which can be realized by enhancing maintainability [79]. Maintenance in different superior manufacturing industries like automotive has an exceptional economic significance through the increasing automation and complexity of the manufacturing processes. In view of the extent of the capital bound in equipment and spare parts and the demand for maximum availability there is an urgent need for action. Augmented availability through efficient maintenance can be attained in the course of less corrective and more preventive maintenance efforts. CBM strives to identify incipient faults before they become critical through machinery condition assessment derived from condition monitoring and noninvasive tests. To effectively realize an efficient CBM program, it is necessary to recognize failures at an early stage and to predict the progression of a failure as accurately as possible [107]. Despite modern condition monitoring technologies, the achievement of this goal is still difficult and expensive.

Accordingly, the main objective of the dissertation project is to design and develop a methods pool and an application systematics for different CBM tools that facilitate maintenance department of an automotive supplier with the competency to run its CBM program effectively. This research is based on: analysis of available condition monitoring techniques and nondestructive tests and their associated measured variables, pointing out their fitness for use for specific cases of application and of recommendable methods combinations, evaluation of various CMTs and NDTs regarding to their practical and cost-fair application, the resulting information benefit, and their contribution to the diagnosis and maintenance needs of machinery and equipment. The research work focuses on appropriate use of a blend of suitable analyses which are considered as tools of a toolbox. They provide precious information that can be used to improve the overall maintenance aptitude in a plant and to employ different techniques of condition based maintenance in the most effective way.

It is essential to emphasize that the research approach in building of such a new CBM methods pool is strategically planned to be general. This involves an innovative blend of a variety of CBM related tools and techniques being used in different industries worldwide in addition to the ones under research and development. The methods pool is structured as a novel toolbox that facilitates preventive maintenance efforts not only in the automotive supply industry but also in any other manufacturing or production industry. Its ultimate goal is to enhance CBM management with higher accuracy, reasonability, effectiveness, and efficiency in all decision making processes related to CBM activities. The use and benefit of each individual tool is explained in the corresponding chapters. It is notable that the CBM toolbox can be easily upgraded whenever a tool is remodeled or required to be added.

Stakeholders of this doctoral dissertation are the author of the work, Technische Universität Dortmund, Fraunhofer Institute for Material Flow and Logistics - IML, and TRW Automotive Systems (Schalke, Germany). The research project is structured and authorized by Graduate School of Logistics (former Graduate School of Production Engineering and Logistics) at Technische Universität Dortmund. It is partially supervised by Fraunhofer IML, which provides innovative research, development, engineering and consulting services and tailor-made solutions for companies of all industries. The research project is also partially supervised, and technically and financially supported by TRW Automotive Systems, which is part of TRW's European Steering Operations and manufactures different steering systems for numerous automobile companies such as Audi, BMW, Daimler-Chrysler, Porsche and Volkswagen. Nevertheless, the research content has been intentionally worked out as broad as possible not only to be useful in the automotive supply industry but also in any production and processing industry. This doctoral dissertation also benefits all scholars who carry out research in the field of machinery maintenance and technology management as it covers various scientific issues and provides a concrete foundation for further research and development.

1.4 Dissertation Structure

This dissertation addresses various tools that are gathered and integrated to create the CBM toolbox. After a brief introduction to the research context, Chapter 1 continues with expressing the general research motivation in the field of condition based maintenance, the current major problem and a potential solution, the research proposition, goal and stakeholders. Chapter 2 highlights the concepts of systems thinking, and system analysis and synthesis and explains the background behind the undertaken research methodology. Chapter 3 provides an introduction to the concept of condition based maintenance by reviewing important issues about machinery failure and maintenance and describing the roles and benefits of condition monitoring techniques and nondestructive tests in CBM.

The overture and structure of the developed CBM toolbox are explained in Chapter 4. The information flows into, out of and between different tools are also briefly mentioned in this chapter. Besides, the utilization procedure of the CBM toolbox is precisely put in plain words. Chapter 5 commences the content of the series of statistical failure analyses which all together form the first major tool of the CBM toolbox. These include: time based failure analysis, station based failure analysis, object based failure analysis, problem based failure analysis, cause based failure analysis, statistical problem cause analysis, and time based maintenance analysis.

In Chapter 6, the content of the CMT/NDT knowledgebase, the second major tool of the CBM toolbox, is introduced. The knowledgebase contains expert knowledge about the concept, applicability, detectability, advantages and disadvantages of 14 key condition monitoring techniques and nondestructive tests which are employed in different manufacturing and processing industries for the purpose of condition based maintenance. These are namely: acoustic emission testing, electrical inspection, electromagnetic testing, laser inspection, leak testing, magnetic particle testing, penetrant testing, radiographic testing, stress wave analysis, thermal inspection, tribological testing, ultrasonic testing, vibration analysis, and visual/optical inspection.

A financial analysis tool and a CMT/NDT selection matrix are presented in Chapter 7. These auxiliary tools of the CBM toolbox standardize and ease the decision making process in choosing the most appropriate CMT/NDT among all possible alternatives. Chapter 8 renders the concept of object based problem and cause analysis which is considered as the third major tool of the CBM toolbox. This chapter provides the OBPCA undertaken for bearings, compressors, control valves, conveyors, fans, gear systems, and pumps to illustrate the methodic used in such an analysis. Chapter 9 provides a sample application of the CBM toolbox to illustrate how it can be used in practice. Eventually, Chapter 10 concludes the undertaken dissertation project underlining some remarks, contributions and future research potentials of the developed CBM toolbox.