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Empirically Based Asset Management Decision Support for Reliable and Cost Effective Asset Operation

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SUMMARY

This article describes a method that supports asset management decision making so that complex technical assets are operated reliably and cost effectively. It focuses on improving the foundations of planning applied to formulate condition-based maintenance strategies. To this end, it presents a novel empirically based method for determining wear allowances in technical assets. The parameter of wear allowance is referenced to quantify current condition and anticipated changes of condition as a function of asset utilization.

Journal of Economic Literature (JEL) code: M41, G12

INTRODUCTION

Asset management is an integrative task within a company. In collaboration with numerous external partners, it is responsible for effective and efficient interaction of resources and processes in every phase of a technical asset's life cycle (Schenk et al., 2003). This generates a broad and interdisciplinary range of tasks, which extends from the planning of a complex technical asset to its procurement, construction, commissioning, operation and maintenance through decommissioning and dismantling/disposal. The fundamental tasks and objectives of asset management include (Biedermann, 2002):

- ➢ High operational reliability:
  ensuring reliable and stable asset operation without negative effects on humans, the environment and the process
- ➢ High availability:
  assuring all of an industrial asset's functions necessary and desired to perform manufacturing and logistics tasks (Moubray, 1997)
- ➢ High efficiency:
  continuously monitoring the consumption of raw materials and energy and of cost effectiveness

High complexity and flexibility with short product cycles and constantly changing requirements during operation are especially characteristic of the life cycle of modern, adaptable assets (Schenk-Wirth, 2004). This inevitably leads to shorter planning cycles and diminishing planning certainty for maintenance processes, thus generating great need for practical methods and tools that assure asset operation is reliable and cost effective.

The solution to the commercial aspect of this problem is extensively supported by effective methods and tools for life cycle costing (LCC). Their use renders all expenditures transparent, which are necessary throughout the entire product and asset life cycle in a company, and relates them to commercial revenue. In addition to expenditures for investments, raw materials and operating supplies, primarily expenditures for routine and long-term maintenance actions are recorded and corresponding forecasts of economic life are calculated. Then, they are compared with the respective corporate objectives.

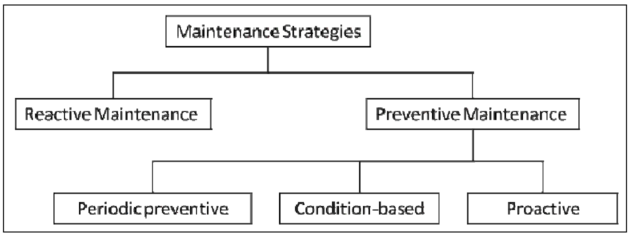
The performance of LCC analyses often reveals the fundamental problem with information on the current and expected condition of technical assets. This information is difficult to obtain in the real setting of asset operation with present solutions, e.g. by applying statistical or analytical methods, specifying physical and chemical properties of materials, performing fault tree analyses or determining load spectra.

A practicable method of quantifying and evaluating the physical property of an asset's "technical condition" over the course of time was developed and tested at the Fraunhofer IFF together with partners from industry.

The method incorporates the irregular wear of an asset's components resulting from its different stresses. This also produces a requirement for intense use-based maintenance. Wear allowance as defined by DIN 31051 is employed as a characteristic that quantifies condition. It is defined as the allowance of potential functional performance under defined conditions, which possesses a unit of analysis based on manufacture, repair or upgrade (DIN 31051). This static analysis allows determining a unit of analysis's potential functional performance characteristic at a particular time as its probability of survival. The time curve of diminishing wear allowances is potted to describe the dynamic of asset utilization and the effects of alternating stresses on wear in order to initiate condition-based maintenance actions.

ORGANIZING CONDITION-BASED MAINTENANCE

Applying the right maintenance strategy (Figure 1) decisively determines technical assets' reliability and maintenance costs. Since the effects of modifications of the maintenance strategy normally only appear in the medium and long term and are often affected by other influencing factors (e.g. product changes and workloads), a concrete demonstration of cost reductions in maintenance proves to be difficult. A correlation between the maintenance strategy and the utilization of the wear allowance of technical assets' components and the downtime caused by failures is demonstrable (Maennel, 1988).



Source: Matyas, 2002

Figure 1. Maintenance strategies according to Matyas

Applying a condition-based maintenance strategy, frequently also called an inspection strategy or proactive maintenance, promises the briefest downtime while utilizing the wear allowance excellently. The two strategies differ in the time when a maintenance unit takes actions to detect potential failures or delay the occurrence of a failure. A condition-based strategy is applied when a potential failure is detected. A proactive strategy already starts earlier. Attempts are made in operation and by preventive maintenance actions to eliminate potential sources of failure, to forecast them before they become evident and to take actions that sustain condition. Thus, even more time is ultimately gained to plan and implement maintenance actions and lower the risk of asset failures.

A significant feature of a condition-based strategy is that time or utilization cycles (e.g. hours of operation, number of starts and landing) no longer serve as the controlled variable that triggers maintenance actions as they do in classic periodic preventive maintenance. Instead condition dictates the initiation of actions.

Figures 2 and 3 illustrate the differences among the controlled variables for maintenance actions. Clearly evident are the better utilization of wear allowances when a condition-based maintenance strategy is applied and thus cost cutting potentials through lower replacement part consumption and a reduced number of actions as a function of the useful life.

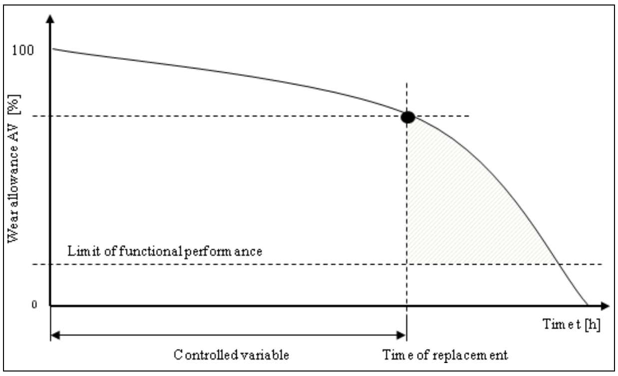


Figure 2. Periodic preventive maintenance with the controlled variable of time

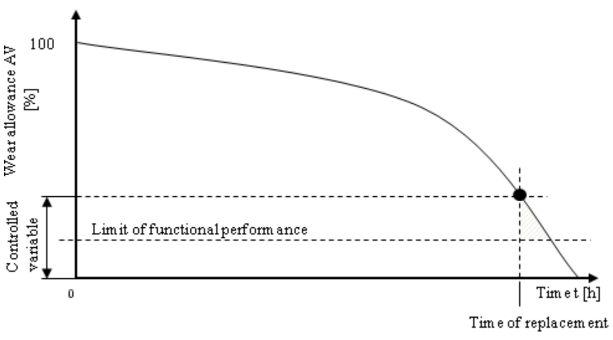


Figure 3. Condition-based maintenance with the controlled variable of wear allowance

Two conditions must be met for condition-based maintenance to be applicable. First, the change of wear allowance must be measureable, i.e. technically feasible (e.g. reduced thickness of a brake disk and increased effective oscillation). Second, the metrological capture of parameters that determined condition must also be economically justifiable.

Effective methods and tools of technical diagnostics are available for condition monitoring. In its simplest form, a person performs monitoring during routine inspections that includes measuring and evaluating parameters relevant to condition. The person may be supported by technical equipment such as vibrometers, endoscopes and thermographic cameras. Continuous monitoring by means of condition monitoring systems (CMS) substantially reduces the time and labor manual inspections require. This has a positive effect on maintenance costs. Current studies reveal a growing tendency to establish condition-based maintenance in companies (Schuh et al., 2005; Müller-Jungjohann, 2007). In one survey (Schuh et al., 2005), 65% of the respondent industrial companies surveyed have employed condition-based maintenance for approximately seven years. The companies primarily cite the reduction of revenue losses by downtimes and the reduction of maintenance costs as advantages, the first point being crucial for decisions about implementation. The benefits of implementing condition-based maintenance include (Schuh et al., 2005):

- better planning of downtimes,
- fewer unnecessary repairs and less disassembly,
- enhanced efficiency in maintenance,
- longer maintenance-free machine running time,
- less time spent troubleshooting,
- lower production losses because of unplanned equipment downtimes and
- lower maintenance costs.

In general, many potentials of condition-based maintenance are still not exploited. Many methods are not applied universally. One reason is often the high cost of investing in the equipment needed for technical diagnosis. For many companies, condition monitoring is either technically too complex or too expensive. Moreover, the organization of condition-based maintenance necessitates applying methods to obtain and interpret condition information in order to ascertain service lives, economic lives and replacement intervals. Present solutions are frequently based on the application of statistical or analytical methods, which are based on statistical evaluations of the failure mode, equivalent loads, load spectra or a description of material changes. These may include:

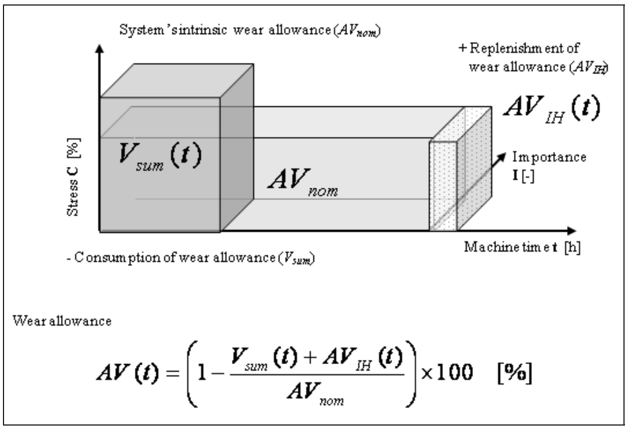
- analytical models based on known or empirical distribution functions of the times between failures,
- failure mode and effects analyses (FMEA),
- risk analyses, fault tolerance analyses and creation of redundancies (e.g. RCM),
- cost-utility analyses, life cycle costing and total cost of ownership,
- business management models (e.g. investment theoretical approach)
- event-oriented simulation models,
- methods of artificial intelligence (e.g. artificial neural networks for fault detection) and
- special diagnostic methods directly related to the physical and chemical factors that influence an asset's condition.

The input variables required to apply the methods mentioned are frequently in the possession of the asset manufacturers and are among their best kept secrets. Thus, they are not passed on to the operating phase for use. This is problematic for users. Moreover, a concrete technical asset, i.e. its performance rather than the performance of a statistical population, is always of interest to maintenance. This also requires considerable effort to perform the analyses and sound knowledge in the field of mathematical statistics and probability theory from the individual involved. Again and again, uncertainties always present in statistical methods because of the multitude of necessary input variables and calculation with probability cause problems with acceptance among users.

One solution relies on the asset operator's and many maintenance service providers' own considerable sound experience with their concrete assets' operating and failure modes. However, such experience is frequently not available as a priori knowledge. Instead, it is implicitly contained in the operating and maintenance staff's minds and notes. The method described below provides asset management support to acquire such knowledge and render it usable for maintenance decisions.

EMPIRICAL DETERMINATION OF WEAR ALLOWANCES BY MEANS OF FUZZY LOGIC

The model employed for empirically based determination of wear allowances in technical assets covers three integral elements (Ryll, 2008; Schenk, 2010).



$$AV(t) = \left(1 - \frac{V_{sum}(t) + AV_{IH}(t)}{AV_{nom}}\right) \times 100 \quad [\%]$$

Figure 4. Base model of empirically based determination of wear allowances

The engineering of every technical asset with its necessary features during the design process so that it may be used as intended constitutes the starting point of the analyses. This also includes the probability of its performance of the stipulated functions under defined nominal stresses over a specified period. This originally extant functional performance characteristic is defined as a system's intrinsic wear allowance (AVnom) and can be described with the following dimensions:

- Probable expected service life (e.g. manufacturer information on mean time between failures and internal service life calculations)

- Nominal stress (=100%)
- Importance of the component for the overall asset.

A system's intrinsic wear allowance constitutes the reference variable in the evaluation model, i.e. it represents the rated life under nominal operating conditions, which is theoretically available during asset operation. The importance of components is dependent on the target function of the evaluation of an asset's condition. From a commercial perspective (target function: monetary asset value), the importance is frequently determined by a component's repurchase or replacement price. From a technical perspective (target function: functional performance or operational reliability), the importance is determined by the consequences expected when components fail. These are quantifiable, for instance, by ascertaining a risk priority number, which incorporates the probability of failure, probability of detection and consequences of failure.

The system's intrinsic wear allowance AV_{nom} is continually consumed during machine time. This consumption of wear allowance (V_{sum}) is a function of the acting stress and its exposure time. When the time is identical, higher stresses accelerate and lower stresses delay the consumption of wear allowance. The amount of stress and the duration of its action on the component is determined in regular time intervals. The consumption of wear allowance is ascertained for every time interval and is subtracted from the system's intrinsic wear allowance. The end of a component's service life is reached when the system's intrinsic wear allowance has been consumed. A maximum bearable stress is additionally determined. When it is exceeded, the wear allowance abruptly drops to the value of zero. In practice, this is manifested when safety systems respond to excessive stress or components malfunction in short time.

A complete or proportional replenishment of wear allowance (AV_{IH}) factors in maintenance actions. The effect is 100 % when a component is replaced. The effect of maintenance actions or reconditioning must be evaluated proportionate to system's intrinsic wear allowance.

The quantification of the consumption of wear allowance V_{sum} necessitates determining a component's instantaneous stress. First, parameters are defined, which relate to the stress. These are predominantly process, operating and diagnostic data (e.g. workpiece dimensions, speeds, pressures and oscillations), as well as data from the asset's environment (e.g. operation temperature and dust concentration) and maintenance data (e.g. time interval since the last lubrication). Only input data is purposely selected, which relate to the component's stresses and condition changes according to the opinions of various experts or experience with operation. Since such data are normally already on hand in a company, their acquisition does not generate any additional labor. They tend to be used to obtain additional information from them and to combine them with knowledge about the asset.

Figure 5 presents a typical set of input parameters with its sources of data, which determine the stress of an electric motor mount.

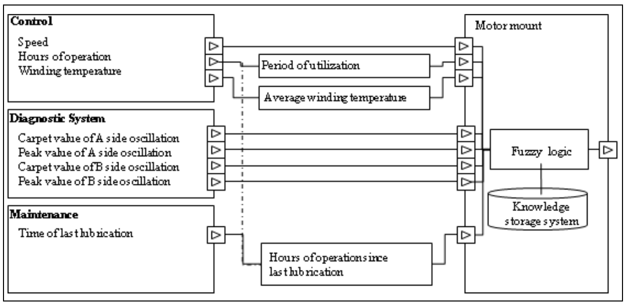


Figure 5. Set of input parameters to determine the stress of a motor mount

Input data are processed by processing logic, which is designed as a fuzzy controller in the applications. Fuzzy logic reasons on the basis of rules generated from colloquial contents by the cause and effect relationships of a technical asset's operating and failure mode (Stoecker, 1999). First, every input parameter must be fuzzified, i.e. linguistic variables must be defined with terms (e.g. characteristics such as low, medium, high) and membership functions. Figure 6 illustrates this transformation process with the parameter of average winding temperature as an example.

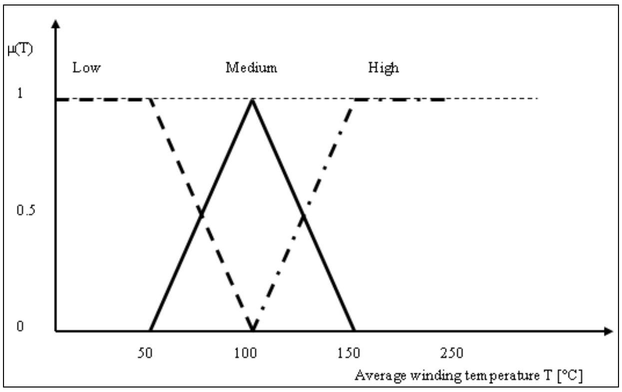


Figure 6. Fuzzy variable of average winding temperature with membership functions

Afterward, a set of linguistic rules is used to process the fuzzy variables into an evaluation of the stress. This constitutes a knowledge storage system that stores the cause and effect relationships between the defined input variables and the stress as IF-THEN relationships. The chief advantage of this type of knowledge storage is the capability to map, amend and correct even complex relationships. Initially, the a priori knowledge from asset operators, manufacturers, maintenance service providers and other experts is collected in interviews and utilized. The logic automatically incorporates identical as well as contradictory opinions from experts (Lutz-Wendt, 2000). The knowledge storage system can be modified and upgraded at any time. Three processing rules that describe the influence of the parameter "average winding temperature" on a motor mount's stress serve as an example here:

- Rule 1: IF (winding temperature is low) THEN (stress is low)
- Rule 2: IF (winding temperature is high) THEN (stress is very high)
- Rule 3: IF (winding temperature is medium) THEN (stress is nominal)

The incremental sequence of actual processing entails the fuzzification, inference and composition of rules followed by defuzzification (Stöcker 1999).

Several fuzzy terms and rules are linked by logical operators (e.g. minimum and maximum method). The center of gravity method and the definitions formulated for the positions and shapes of the fuzzy terms are applied to produce the instantaneous stress as a weighted center of gravity between defined stress classes, subsequently given the shape of a scale. Figure 7 presents an example of the fuzzy processing of two input parameters with two rules and the calculation of a motor mount's stress according to a weighted center of gravity method.

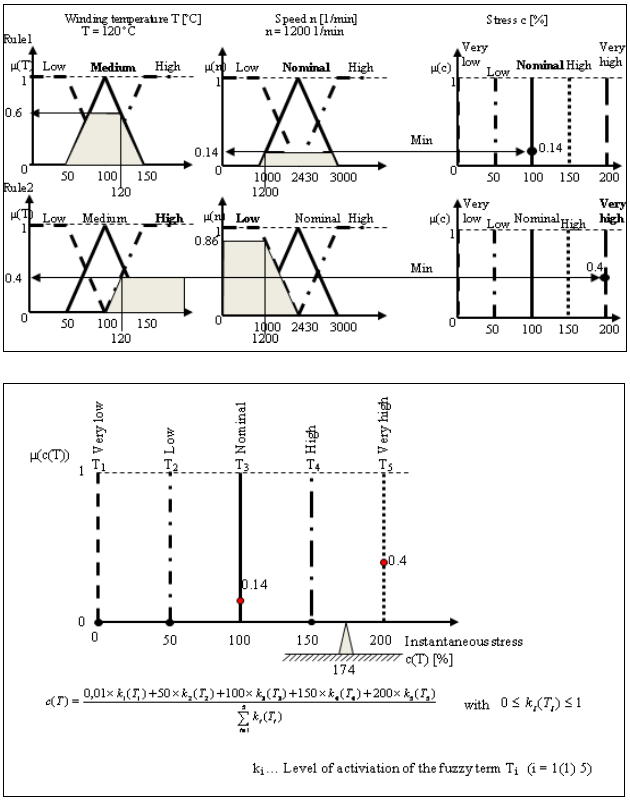


Figure 7. Steps of fuzzy processing to determine stress

A thusly ascertained stress acts on the component until it is recalculated on the basis of a new set of input parameters. Thus, the variability and currency of the result are a direct function of the input data's temporal resolution. Once the current stress has been ascertained, the consumption of a component's wear allowance it causes and, thus, the still extant wear allowance are determined.

Maintenance actions generate positive influences, i.e. they improve technical assets' condition. Therefore, their influence on the replenishment of wear allowances must be allowed for when developing the method. In principle, the replenishment can be represented so that a component is resupplied an additional time allowance, which, in turn, can be consumed in order to reach the planned useful life of the component or start a new life cycle after its replacement. Several characteristics must be considered when describing the effect of maintenance actions. When the action is a replacement of components, the effect is clearly evident. The component abruptly returns to its original condition with 100% of the system's intrinsic wear allowance. The wear allowance currently available at the time of replacement does not play any role.

Assessing the effect of other preventive maintenance actions, e.g. lubrication, adjustment and cleaning, proves to be more difficult. If at all, the visible manifestations of the effect following such actions appear only after a longer period after such work has been performed or not performed. However, diverse interactions with the effects of actions and the influences from asset utilization appear until that time, i.e. the manifestations can no longer be related to past actions.

One feasible method relies on the empirical values from asset manufacturers' maintenance engineers and service technicians and involves compiling catalogs with effects of maintenance actions in percentages.

A complex technical asset's wear allowance is derived from the wear allowances of its individual components. This necessitates incrementally aggregating the component up to the asset level. The evaluation's target function must be borne in mind when forming the aggregation.

A summation is expedient when a monetary asset value has to be determined for a commercial evaluation of condition. This yields the value of the asset as a sum of the components' individual values. The aggregation must be performed differently when an evaluation of an asset's probable functional reliability has to be delivered. The asset structure must be incorporated from the functional perspective. Since the probability of survival and reliability of a unit of analysis is ultimately inferable from the wear allowance, the simplified method of determining concatenated systems' probability of survival is applied. When they are serially concatenated, it multiplies the individual probabilities of survival (Beichelt, 1993).

APPLICATION AND BENEFITS

The method described augments typical monitoring systems by interpreting the effects of different factor that influence asset condition. In the first stage, current and compressed information on stresses and the available wear allowance of components and assets is made available to the operator and maintenance unit as a traffic light with a control function (Figure 8).

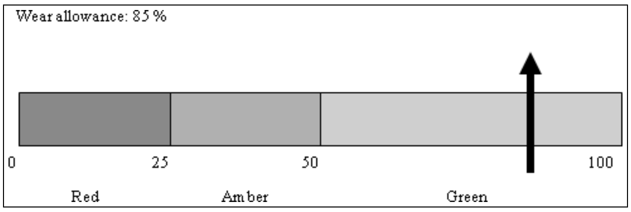


Figure 8. Traffic light display of the current wear allowance

A change in the traffic light's color triggers recommendations for the execution of maintenance actions and changes needed in the operating regime to reduce stresses. The history and forecast of asset utilization as well as the physical and financial resources are incorporated.

The traffic light's amber color indicates that half of the wear allowance has been consumed and an onsite inspection is advisable. Then, maintenance logistics processes are initiated as a function of the result of inspection in order to procure replacement parts in good time, for instance. The traffic light's red color indicates an acute need for action since the wear allowance has largely been consumed and thus a high risk of asset downtime exists. A maintenance asset's ability to now independently signal maintenance requirements and control the subsequent processes ought to be considered as a new approach.

Another visualization option entails plotting the temporal characteristic of the consumption of wear allowance (Figure 9). Influences from stresses during asset operation are revealed in the drop of the consumption curve. Effects from maintenance actions ought to be evident by sudden improvements of the wear allowance. This representation provides an aid to review the planning and effects of maintenance actions as a function of variance analyses and to adjust them to the current requirements. In addition, a series of other applications are produced, ranging from monitoring of external maintenance service providers' adherence to schedules through the design of business models with stipulated condition indicators.

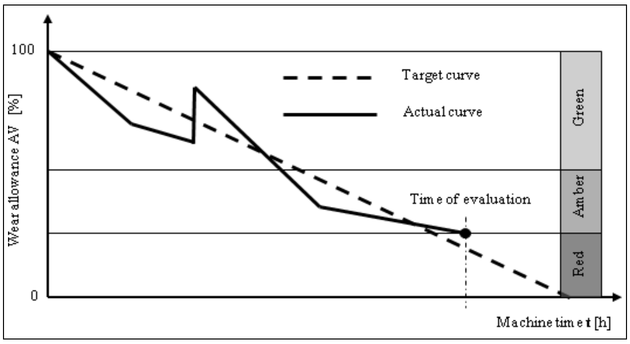


Figure 9. Graph of the history of the consumption of wear allowance

The method described may additionally be used to prepare forecasts of the future characteristic of the depletion of wear allowances. The anticipated input parameters are supplied to the fuzzy controllers and the calculation is updated into the future. During a forecast, every maintenance job is generated, which is necessary based on the expiration of time intervals or undershot wear allowance thresholds. Forecasts effectively support resource planning and budgeting, the description of scenarios for particularly reliable and cost effective asset operation and maintenance and the determination of times for removal from operation.

One significant advantage of evaluations based on the method described here is the availability of current and objective information on asset condition to infer decisions. All partners accept the decisions since they all have the same level of objectified information. The knowledge base and evaluation logic are constantly being perfected by new actors, experiences and discussion of the results of the evaluation. Finally, the results of this learning process are collected in a valuable knowledge base. Thus, asset know-how is generated and lastingly preserved even when generations of maintenance staffs come and go.

The high transparency of the decisions supports a paradigm change in asset management, i.e. a shift from simply following defined rules to actively solving problems. In order to derive sustainable improvements for asset operation and maintenance, it is essential to integrate the ongoing evaluations in a maintenance unit in a continuous process to provide decision support and learn asset performance. Direct coupling to other processes to continuously improve maintenance (e.g. Kaizen and TPM) is often an expedient means to provide support.

CONCLUSION

The formulation of a condition-based maintenance strategy holds great potentials to ensure that technical assets are operated reliably and cost effectively. Their implementation necessitates a quantification of the abstract variables of a technical asset's condition with methods that appropriately describe operating and failure modes.

Using condition indicators to obtain knowledge of condition directly from the process by means of methods of technical diagnostics is often technically unfeasible and expensive. An interpretation often proves difficult because of the complexity of the influences.

Applying the method of empirically based determination of wear allowances described here significantly reduces the complexity of the task. It makes it possible to describe effects of utilization, stresses, and maintenance actions on assets' condition sufficiently precisely and to derive recommendations for action. The evaluation methodology developed is based on the theory of fuzzy logic, which has proven itself in control engineering even in complicated processes. Its advantage is the capability to formulate and continuously modify complex cause and effect relationships by means of simple verbal descriptions as if-then relationships even without knowledge of the underlying physical or mathematical relationships. This makes empirical knowledge available to the many actors in maintenance.

The Fraunhofer IFF developed Statelogger®, a modular software system supported by a database, to apply the evaluation methods and has implemented it in various assets (air compressors, handling systems, wind energy converters and vehicles). The system may be used stand-alone or integrated in already existing operating data acquisition, diagnostic and maintenance planning and control systems. By providing the requisite input information, the evaluations and forecasts deliver a supporting basis for the implementation of concepts of life cycle costing (LCC) and total cost of ownership (TCO).

A holistic analysis can be expected to reduce medium-term cost in maintenance while simultaneously lowering the risk of failure.

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