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From Volatile Maintenance Data Forecasting to Reliable Capacity Planning

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Abstract— **Maintenance, repair and overhaul processes (MRO processes) are elaborate and complex. Rising demands on these after sales services require reliable production planning and control methods particularly for maintaining valuable capital goods. Downtimes lead to high costs and an inability to meet delivery due dates results in severe contract penalties. Predicting the required capacities for maintenance orders in advance is often difficult due to unknown part conditions unless the goods are actually inspected. This planning uncertainty results in extensive capital tie-up by rising stock levels within the whole MRO network.**

This paper outlines an approach to planning capacities when maintenance data forecasting is volatile. It focuses on the development of prerequisites for a reliable capacity planning method. This is achieved by deriving order probabilities from Bayesian networks. In addition the residual wear margin is used to determine an appropriate part-dependent work content.

Index Terms— **Capacity Planning, Capital, Forecasting, Maintenance Logistics, Production and Operation Management.**

I. Introduction

Valuable capital goods are increasingly complex and distinguish themselves from other goods due to their high initial costs. Avoiding downtime due to breakdowns and maximizing availability is thus particularly important. As a result the role of maintenance – whose job is to maintain the function and performance of the valuable capital goods – has clearly gained significance in the last years [1] - [3]. Maintenance is associated with extensive usage of personnel and materials as well as the costs evolving from both. While the maintenance of machines and facilities have been the centre of great attention in the last years and the planning processes vastly optimized, the technical services and organizational aspects for maintenance, repair and overhaul processes (MRO processes) of valuable capital goods have only been minimally examined or improved [4], [5].

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Therefore, MRO service providers in particular, experience serious difficulties planning capacities in order to meet demands [6]. Moreover, the required spare parts are not easily estimated. As a result, large stores are maintained tying up significant amounts of capital in often expensive spare parts. Predicting the requirements for MRO resources is rarely systematically analyzed and there is tremendous need of suitable methods for doing so. To make the situation worse, the forecast for the upcoming orders and their work content fluctuates depending on the constantly updated – and therefore changing – information regarding the condition of the various parts [7]. For this reason, the measures required for maintaining the capital good are usually only clear after it has been completely disassembled. By that point in time though, it is too late to schedule capacities in advance. The MRO resources thus needs to be plannable before the disassembly takes place in order to be able to plan capacities over the long term.

II. Maintenance, Repair and Overhaul Processes

In order to plan the maintenance resources, it is essential to distinguish the maintenance processes from one another. Based on DIN 31051 [8] Fig. 1 illustrates this differentiation. In addition to the main processes Maintenance, Repair und Overhaul (MRO), the replacement of a defective part is defined as P [9].

Whereas planned maintenance tasks and measures for maintaining the target state are referred to in general as 'maintenance', the term 'repair' includes the unplanned processes and measures used to re-establish the target state such as overhauling a component. Replacement is necessary when MRO is not economical, no longer possible or would take to long.

Distinguishing the measures makes a huge difference when determining the work content. Precise knowledge about the work content is in turn required for planning capacities.

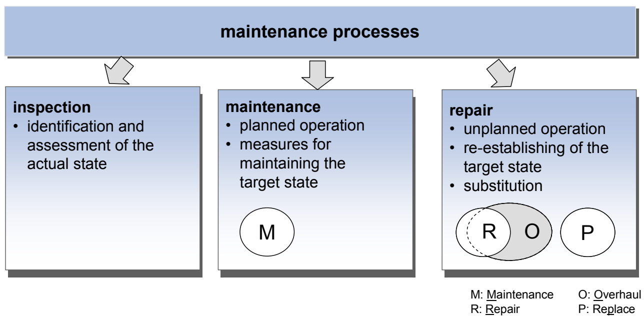

Fig. 1: Allocation of MRO-P in Maintenance Processes

Replacing a specific part usually generates the same work content each time. This value is known from the empirical data found in its service history and can be clearly and easily planned. Since the time required to recondition a part strongly varies depending on how advanced the wear is, determining the work content related to reconditioning is generally much more problematic.

III. Forecasting of Order Probabilities by Means of Bayesian Networks

One method for developing a highly reactionary MRO order processing centered on probabilities is discussed in [7]. Standard machine data as well as data concerning the machine's workload and other influential, external factors serve as a basis for this. Since this data is not always sufficiently available, it is difficult to precisely plan orders.

Calculating a specific order probability for each individual part, from which the maintenance orders can then be generated is therefore useful for planning the required maintenance resources. This is also known as an MRO probability (p(O)).

In order to do this the structure of a valuable capital good is represented using a Bayesian network. According to its product structure – which is based on the parts list [10] – the aggregate is organized into components and individual parts. How these are arranged is visible in the Bayesian network. Every part is provided with a specific value, indicating its current condition and the resulting probability of a maintenance order (Fig. 2).

The Bayesian network ensures that the interactions between all the individual parts are considered for each individual part by interlinking them [11]. Furthermore, external influences such as the demands placed upon them and their point of use can be mapped. Through the use of Bayesian networks, it can be determined how a changing MRO probability of one part impacts the MRO probabilities of the other parts in the network. The knowledge gained about the condition of the parts during the disassembly are fed back directly into the network. As a result, the precision of the forecasted MRO probabilities steadily increases during the disassembly. These probabilities only refer to the necessary likelihood that an individual part will generally

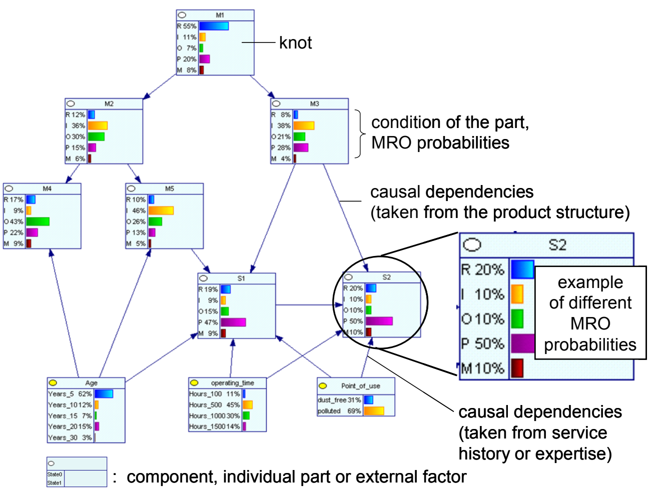

Fig. 2: MRO Probabilities in the Bayesian Network

need to be processed; no information regarding the expected work content is provided at this stage. Nevertheless, the calculated probabilities form a good basis for deriving a probability sensitive order planning (see Sect. V).

IV. Probability Sensitive Forecasting of the Work Content

A. *Importance of the Remaining Part Quality*

Determining the work content serves as a basis for planning capacities, but its forecast is volatile over time. The established work content has to be as precise as possible, otherwise the advanced capacity planning will either be excessive or insufficient. An excessive supply costs employee time and wages which often cannot be utilized in another way and are thus wasted. On the other hand an insufficient supply makes it necessary to temporarily apply expensive capacity control measures. Failing to implement them could cause existing orders not to be fulfilled on time, which especially in the MRO area leads to intolerable delivery delays.

Since the need for maintenance resources can differ depending on the part's condition, the part quality should be taken into account in order to estimate a realistic work content. The part quality serves as a key value for the actual condition of the part and thus indicates how worn the individual part already is. The work content for the necessary MRO measures results from this value.

For this purpose, the wear progress curve of the individual parts is utilized. The goal here is to determine exactly how each part wears as well as to objectively establish their current operating state on the wear progress curve. Based upon this MRO measures are derived from the residual wear margin.

B. *Deriving the Residual Wear Margin from the Wear Progress Curve*

The wear is a material surface's loss of mass (wearing away of surface) due to grinding, striking, scratching, chemical or thermal demands [12]. A typical wear progress curve is depicted in Fig. 3.

The wear progress curve can be broken down into three phases. Phase one, referred to as "degressive wear" (I) initially indicates a strong deterioration. This can be attributed to the smoothing of the roughness created during production. Since this coarseness is gradually reduced, the wear progresses increasingly slower. At the end of this phase,

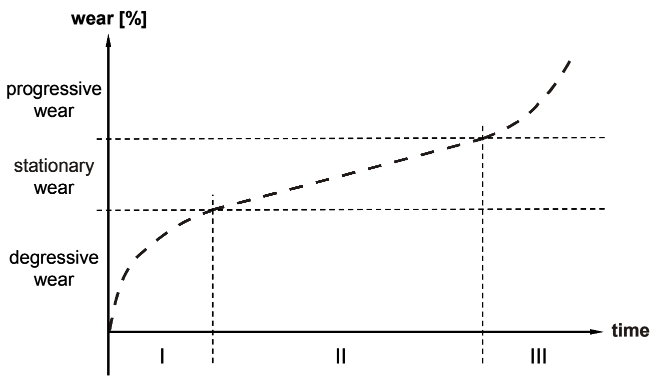

Fig. 3: Three Wear Phases of the Wear Progress Curve

optimal operating conditions prevail and the second phase "stationary wear" (II) begins. Phase three, the "progressive wear" stage (III), is the phase during which damage occurs. Because the damage progressively impacts operations, the component continues to be worn down until it fails [13].

Since the wear progress curve is different for each part, a specific wear curve has to be developed for each component. These result from external factors which influence the wear, for example, the age, load or operating conditions. A large quantity of operating and service data has to be available in order to effectively derive the curves. In the case where there is insufficient data, the typical curve mentioned above can initially be used for further considerations.

In the next step, the residual wear margin is referred to in order to determine the work content of a maintenance order (Fig. 4). The wear margin can be derived from the previously defined wear progress curve. Here, the following correlation (1) is applicable:

$$WM = 100 - W \tag{1}$$

where
WM: residual wear margin [%], and
W: wear [%].

C. Deriving an Appropriate Wear Dependent Work Content

Fig. 4 depicts an example of a residual wear margin curve. The level at which the wear margin is so small that the parts ability to function is inadmissibly impaired is referred to as the damage threshold. Up until the point in time in which the curve crosses the damage threshold (Fig. 4, point C), the component is fully functional. If the wear margin falls below the damage threshold, its function is influenced to an impermissible degree and can no longer be fulfilled [13].

In order to improve the work content planning, the exact point B on the residual wear margin curve has to be determined for each and every part. This point is generated from empirical data and indicates up to which wear margin value it is efficient to recondition the part and after which value it is only sensible to replace it.

Even within the zone between the points B and C the component's functionality is still technically ensured. However, since the probability of failure during the next

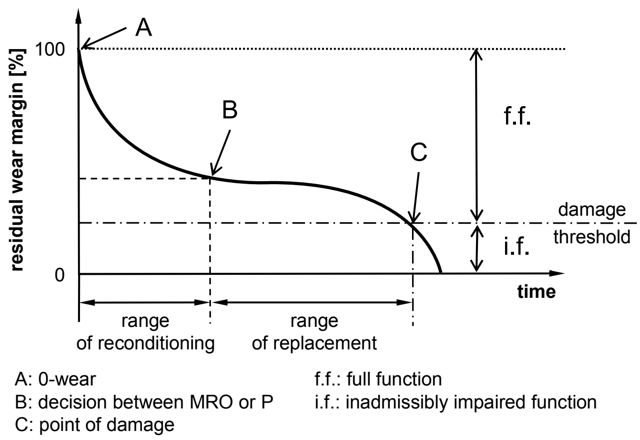

Fig. 4: Residual Wear Margin Curve

operational period is so high, the part is replaced as a preventative measure.

When the current point for a part on the residual wear margin curve is still in the reconditionable range, generating the work content time is more difficult than when the part is to be replaced. The range, in which it is still efficient to recondition it runs between point A, when the wear margin is 100 % (= zero wear) and point B at which reconditioning is no longer economical. That is, when a replacement is necessary. For every point within this range i.e., for every possible state of the part, a different work content applies.

Where there is no documented service history but only mean values, a curve for the reconditioning interval is determined according to (2). It takes into account that the lost wear margin is linear over time.

$$WC_{plan}(WM) = -\frac{WC_{\max} - WC_{\min}}{WM_A - WM_B} \cdot WM + \ldots$$
$$\ldots + WM_B \frac{WC_{\max} - WC_{\min}}{WM_A - WM_B} + WC_{\max} \tag{2}$$

where
WC_{plan} : planned work contend [hrs],
WC_{max} : maximum work contend [hrs],
WC_{min} : initial, minimum work contend [hrs],
WM_A : residual wear margin at point A [%] (not necessarily 100 %), and
WM_B : residual wear margin at point B [%].

Using this curve the required work content WC_{plan} can be calculated from the current wear margin. Where service data exists, the corresponding wear margin is assigned a work content (WC_{plan}) using a statistical software tool developed at the Institute of Production Systems and Logistics (IFA).

V. Dealing with Volatile Data for Order Planning

While developing a maintenance plan the order probabilities dynamically change. In order to deal with this a probability sensitive work content of an order $WC_p(O)$ can be calculated using the following formula (3):

$$WC_p(O) = p(O) \cdot WC_{plan}(O) \tag{3}$$

where
$WC_p(O)$: probability sensitive work content [hrs],
$p(O)$: MRO probability of an order, derived from the Bayesian network (see Sect. III),
$WC_{plan}(O)$: planned work content of an order [hrs], and
O : order.

An identical selection of orders can thus impact a workstation's load account variously at different times during the forecast periods n-1 and n-2. An example of this is illustrated in Fig. 5. Different load situations can develop at the workstation during the periods. Finally, by the time the planned period n arrives, the diagnosis is completed, and the status of each order has been determined: The orders that now appear to be released can be regarded with their complete work content (100 % probability). Other orders which previously seemed to require processing with a certain probability are cancelled because they are ultimately no longer necessary. The workstation's load accounts however, then need to be considered. There are generally three cases to differentiate between:

Case 1: Full Utilization

The load limitation of the load account is determined in the sense of the Load Oriented Order Release (LOOR) according to the available capacity of a workstation. If it is achieved all of the existing orders are released and can be processed [14], [15].

Case 2: Overload

Here, there are still orders which exist beyond the load limitations. These were scheduled to be released, but in accordance with LOOR have to be initially deferred. However, since a set back in the maintenance of valuable capital goods is not possible or undesired, measurements for regulating the capacity have to be put in place.

Case 3: Underload

In this case, the capacities account is not exhausted by the actual orders that are to be processed. Therefore, measures for controlling the capacities in order to temporarily decrease it should also be considered here.

In order to avoid overload or underload of workstations a capacity control needs to be set up. It should be able to plan in the medium-term and react in the short-term taking the dynamically changing probabilities into account. The handling of different load situations in the forecast periods is still subject to ongoing research at the Institute of Production Systems and Logistics.

VI. Capacity Planning with Part Quality Aligned Work Content

The sum of the orders (4) which are debited to a capacity account corresponds to the required capacity of a workstation C_{WS}:

$$C_{ws} = \sum_{i=1}^{n} WC_{p,i}(O_i) \quad (4)$$

where

C_{WS} : required capacity of a workstation,
$WC_p(O)$: probability sensitive work content [hrs], and
O : order.

The capacity requirement index determines the type of the capacity planning or control measure depending on the available reaction time. Graduations in this index have to be determined specific to each enterprise.

Fig. 6 illustrates medium-term measures for planning capacities, which the MRO service provider can take in order to shore up necessary capacities (index 3 and 4) when there is a preparation time of seven to ten days. These controls include for example outsourcing and weekend shifts. In the short-term range though, measures for controlling the capacity which have a preparation time of a few days have to be implemented, e.g. scheduling night shifts or overtime (index 1 and 2).

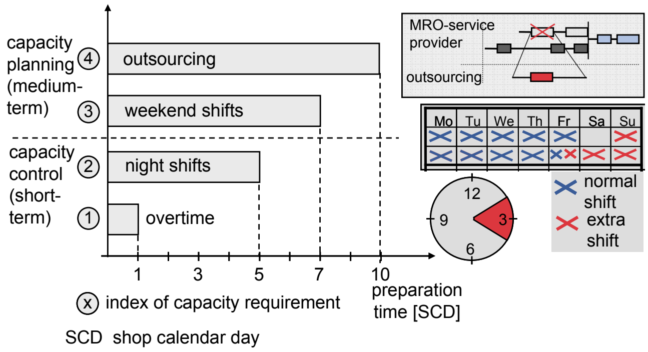

Fig. 6: Measures of Probability Sensitive Capacity Planning and Control

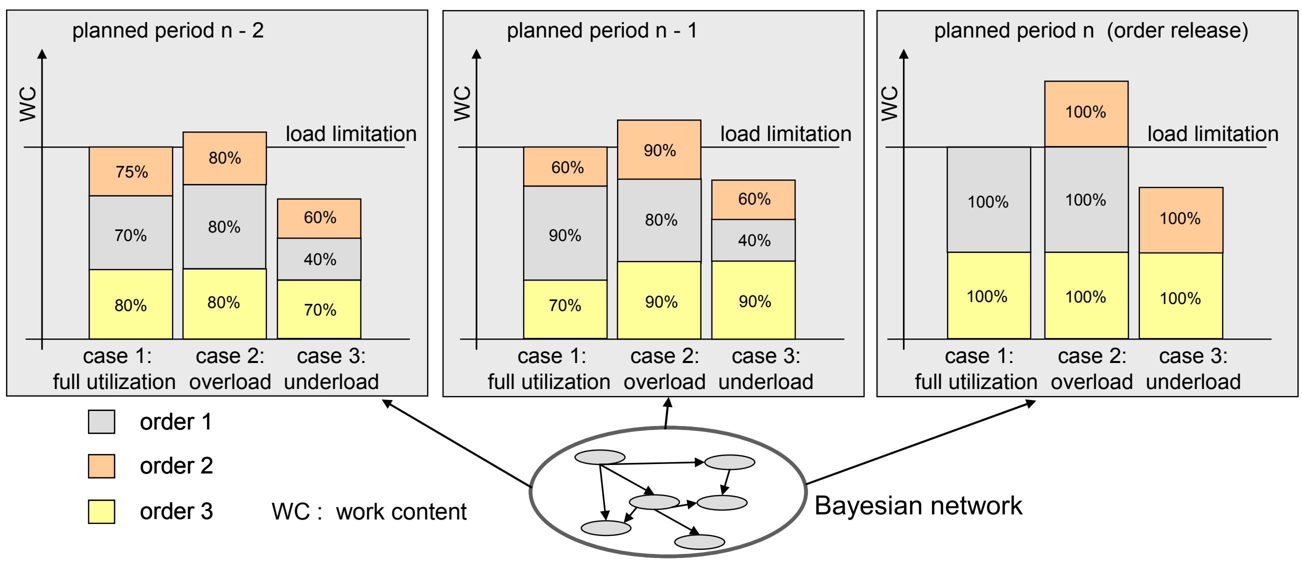

Fig. 5: Probability Sensitive Workload Estimation

VII. Conclusions

Based on current research this paper has outlined an approach to planning capacities when maintenance data forecasting is volatile. In order to deal with the changing demands for the required capacities it is necessary to know the work contents of the aggregate which is to be maintained. Therefore, a work content is calculated which depends on part quality and wear progress.

The more precisely the work contents are determined, the more realistic the predictions regarding the required capacities of a workstation will be. A method suitable for this is introduced here. In order to do so, the corresponding wear progress and residual wear margin curves are utilized to determine the current part quality. Probability sensitive workload estimation differentiates various load cases which, according to the capacity requirement index, are met by adequate measures for controlling the necessary capacities. The improved planning reliability can support MRO service providers in shortening delivery times and reducing stock levels. This enables a quick response to MRO orders and helps enterprises to enhance the performance of their maintenance logistics.

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