Predictive Maintenance for Synchronizing Maintenance Planning with Production

Harald Rødseth, Per Schjølberg, Markus Wabner and Uwe Frieß

Abstract With the immense pressure to sustain competitive in European manufacturing, the strategy of digitalizing in this industry sector is indeed necessary. With the onset of new ICT technology and big data capabilities, the physical asset and data computation is integrated in manufacturing through Cyber Physical Systems (CPS). This strategy also denoted as Industry 4.0 will also improve the maintenance function significantly in manufacturing. In particular, maintenance planning will be more synchronized in production scheduling. The aim of this article is to develop an integrated planning (IPL) approach that synchronizes production and maintenance planning with predictive maintenance capability. The result in this article is based on a case study and simulation of manufacturing equipment. In particular, application of key performance indicators (KPIs) is shown to be essential when running the synchronizing mechanism in IPL. The scientific application of the case study is alignment of the IPL theory and new approach in maintenance planning. Furthermore, the application to practice is improved maintenance planning in IPL that increases a reliable plant capacity. It is concluded that the IPL approach should be considered to be a generic platform for manufacturing industry that should be demonstrated further in other manufacturing branches in Europe.

Keywords Predictive maintenance · Integrated planning · Industry 4.0
Key performance indicators

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1 Introduction

It is an important need in European manufacturing to sustain competitive supported by information and communication technology [8]. With the internet age, the industry is now offered a new concept to process information and control the manufacturing equipment with Internet of Things (IoT) and big data analytics. In sum, this concept is denoted as Industry 4.0 [9].

With the possibilities offered in Industry 4.0, maintenance planning in predictive maintenance can benefit of being more synchronized with other disciplines such as production. This is also supported by the European Commission where methods that schedule maintenance activities together with production activities are developed and demonstrated [5]. These methods are also known to be a part of the integrated planning (IPL) approach [14]. In particular, a structured approach for data driven predictive maintenance has been proposed [16]. It remains to investigate how predictive maintenance algorithms can support IPL.

The aim in this article is to develop and demonstrate a novel IPL approach that synchronizes production and maintenance planning with predictive maintenance capability.

The further structure of this article is as follows: Sect. 2 presents the state of the art within digitalization of maintenance, IPL and predictive maintenance. The IPL approach is presented in Sect. 3 based on a case study. Finally, concluding remarks are given in Sect. 4.

2 Literature

2.1 Digitalizing Maintenance

Based on Industry 4.0, many future trends are related to maintenance. In Norway, two important technology driven trends have been pointed out to be relevant for maintenance [13]:

- *Digitalizing the Industry*: Smart application of sensor technology can both reduce the down time for machines and improve the efficiency of maintenance.
- *Virtual Reality*: Application of augmented reality as projections on glasses can support maintenance engineers in visualizing the effect of conducting maintenance.

Also, the German standardization roadmap for Industry 4.0 endorses maintenance and presents *smart maintenance* to be an enabler of Industry 4.0 [4]. It is even stated that without systematic development of maintenance into smart maintenance, the successful implementation of Industry 4.0 will be put at risk.

In particular, predictive maintenance has been pointed out to be an important element in digitalizing maintenance with different application within remote maintenance [11]. It has also been estimated that predictive maintenance can reduce the machine downtime by 30–50% and extend the lifetime of the machine by 20–40% [12].

2.2 *Remaining Useful Life Algorithm in Predictive Maintenance*

Model based approaches in general try to reproduce certain aspects of real-life physical assets like machine tools. In case of condition monitoring the wear-causing mechanism has to be reproduced by the underlying model. This inherently leads to a prediction functionality of model based approaches [2, 3, 6, 7]. Therefore model-based approaches are not only usable for in-service monitoring and RUL prediction, but also as estimation of the life expectancy of components [3]. Figure 1 shows characteristics of model-based approaches.

However the challenge of model-based approaches comes from the indirect linkage of wear-causing measuring values, e.g. loads over time, to the life-expectancy of components. The failure modes are typically stochastically determined and influenced by various parameters up until tolerances of ball elements or the actual state of the lubricants. This inherently reduces the accuracy of empirical models [2, 7].

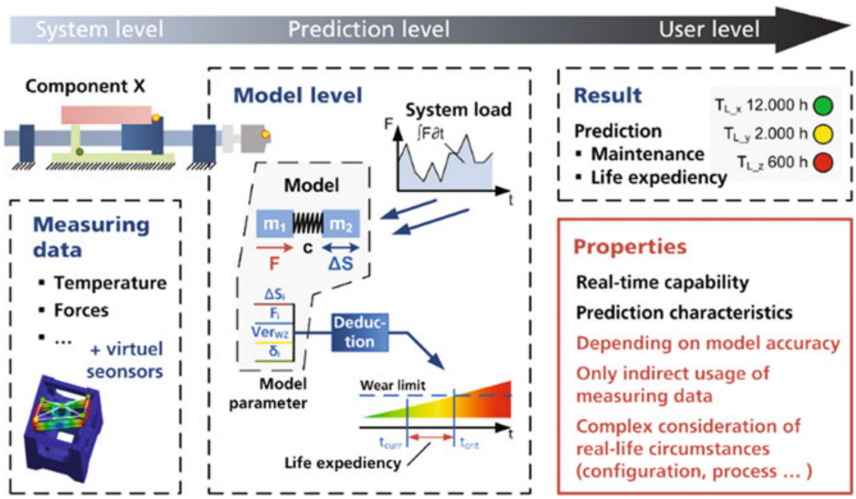

Fig. 1 Characteristics of model-based RUL methods

2.3 Predictive Maintenance and Maintenance Planning

The European standard EN 13306 [1] defines predictive maintenance as "*Condition based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item*." This standard also classifies condition based maintenance as preventive maintenance where maintenance is carried out at predetermined intervals or other criteria intended to reduce the probability of failure. In IPL a reliability based approach for maintenance optimization has been proposed that establish the maintenance intervals [15]. The heuristic for indirect maintenance grouping has been presented in [15]. By following this heuristic, maintenance activities are scheduled with specific maintenance intervals where maintenance costs and reliability data are considered. For the reliability data, Weibull distribution is assumed to model degradation of the system. Maintenance costs comprise preventive maintenance costs, corrective maintenance costs, and set-up costs. Further research for this model is to include predictions of remaining useful life (RUL). This estimation will improve the decision support e.g. during the production planning. In particular it will be of interest to study how model based approaches will build up a work order system in maintenance planning where estimation of RUL will provide digital support in maintenance notifications. This will then require more investigation developing a digitalized predictive maintenance architecture. Currently, the 5C architecture for implementation of Cyber-Physical System proposed by Lee [10] is of highly relevance and has been tested in different industry branches such as the aluminum production [17].

3 IPL Approach

The proposed IPL approach is outlined in Fig. 2. Further in this chapter each step is elaborated. Also, the model of RUL is based on a case study from wear of bearings.

3.1 Step 1: Initial Maintenance Plan

Maintenance planning is essential in preventive maintenance where a detailed maintenance plan is created. The maintenance plan is defined by EN 13306 [1] as

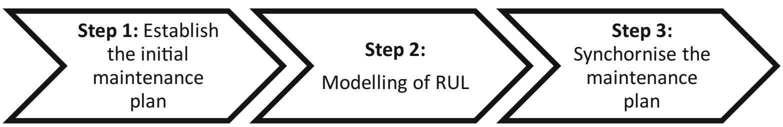

Fig. 2 IPL approach of maintenance synchronisation

"*Structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance*." To establish an initial maintenance plan for IPL, indirect grouping is proposed in this phase, see Fig. 3. For indirect grouping there are only opportunities for preventive maintenance each *T* time units. For each component *i*, it is possible to perform preventive maintenance every k_iT time unit. k_i is an integer.

3.2 Step 2: Modelling of RUL

The empirical formula regarding balls screws and linear guideways with rolling ball elements is well-established [6]:

$$L_{10}^{0} = \left(\left[\left(\frac{C_a \times T_{0.1}}{\int_{T=0}^{T_{0.1}} F \partial t \times k_{1 \ldots n}} \right)^3 \times 10^6 \right]^{-1} + \left[\left(\frac{C_a \times [T_{0.2} - T_{0.1}]}{\int_{T_{0.1}}^{T_{0.2}} F \partial t \times k_{1 \ldots n}} \right)^3 \times 10^6 \right]^{-1} + \cdots + \left[\left(\frac{C_a \times [T_1 - T_{i-1}]}{\int_{T_{i-1}}^{T_1} F \partial t \times k_{1 \ldots n}} \right)^3 \times 10^6 \right]^{-1} \times i \right) \quad (1)$$

where

L_{10}^{0} Overall life expectancy with 10% failure probability [distance, e.g. km/rotations]
I sector i
C_a Dynamic parameter (supplier value based on experimental test)
$T_{0.i}$ Period 0, subsector i
T_1 Overall first period
F Load in sector i
k_n Correction parameters

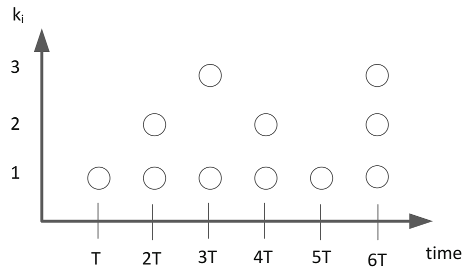

Fig. 3 Initial maintenance plan, based on [15]

It directly predicts the lifetime of a component based on wear-causing load over time. By using real-life data about historical loads and speeds it offers the possibility to directly calculate the already used percentage of the "wear stock" and calculate RUL. Furthermore, RUL can be evaluated virtually before performing certain manufacturing processes on a machine tool.

Based on the empirical formula an algorithm, a data acquisition methodology and a graphic user interface were developed to directly interact and calculate the RUL based on real-life data, see Fig. 4.

Historic load data of components are stored and can be used to calculate RUL. In addition, any artificial load-cycle or combination of several load-cycles can be used as well. Also an average lifetime of a given component can be estimated for a given process—translated to a concrete load on the component level—and/or compare how fast a given process will eat up the wear stock of different machines available for production.

3.3 Step 3: Synchronizing Maintenance Plan

When RUL has been modelled, this can be applied for synchronizing the maintenance and production plan. Figure 5 illustrates an example of how the maintenance synchronization is conducted.

At 4T there is an overlap between the maintenance and production plan, and it is of interest to evaluate the possibilities of restructuring the maintenance plan. When considering the analysis of the component at t_0, two possible scenarios can be identified; RUL1 and RUL2. If RUL1 is the most likely scenario, it is not possible

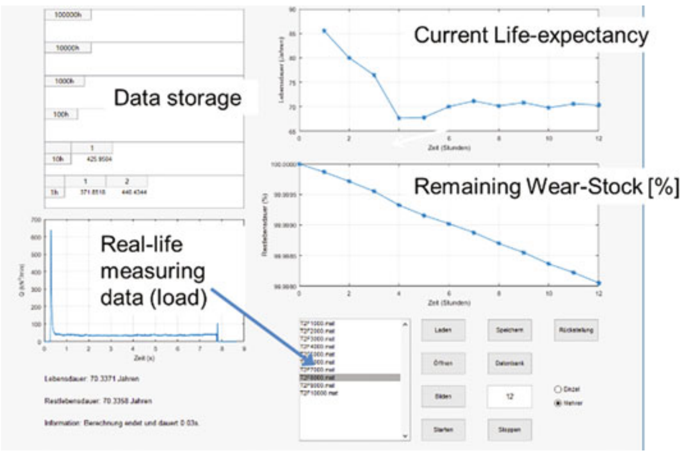

Fig. 4 Graphic user interface (GUI)

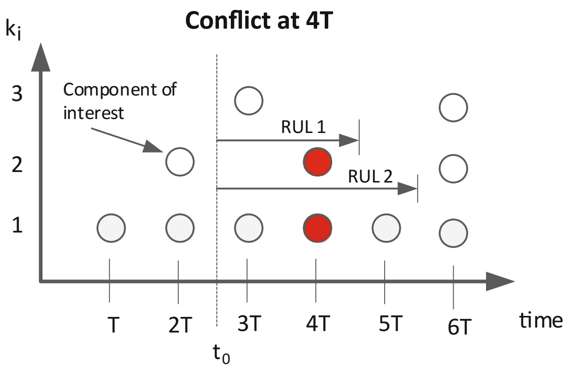

Fig. 5 Maintenance-production synchronization

to postpone the maintenance activity to 5T and it should instead be conducted at 3T. For RUL2 it is possible to postpone the maintenance activity to 5T.

4 Concluding Remarks

The aim in this article was to develop and demonstrate an IPL approach. With methodology from maintenance grouping and predictive maintenance, and IPL approach with three steps was proposed.

It is concluded that this IPL approach is a novel predictive maintenance concept combining maintenance grouping with a model based prediction of RUL.

Further research will require more detailed and integrated modelling of maintenance scheduling and prediction of RUL. For example, based on historical estimation of RUL it can be possible to re-adjust the initial maintenance plan.

Another topic that is important to consider in future research is the balance between accuracy in estimating RUL and the future time window in maintenance planning. For the maintenance planner it is important to have a future time window in order to reschedule when there is an overlap between the maintenance and production plan. This will enable the maintenance planner to reschedule the maintenance activity either earlier or later than originally planned. However, when a larger maintenance window is required it can be more difficult to predict the RUL since the future load characteristics of the bearing can fluctuate.

Finally, it is expected that more testing in industry is needed for the proposed IPL approach including several industry branches.

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