Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia CIRP 3 (2012) 61 – 66

www.elsevier.com/locate/procedia

45th CIRP Conference on Manufacturing Systems 2012

Operational Planning of Maintenance Measures by Means of Event-driven Simulation

B. Denkena[a], S. Kröninga[a,]*, K. Doreth[a]

[a]*Institute of Production Engineering and Machine Tools, An der Universität 2, 30823 Garbsen, Germany*

* Corresponding author. Tel.: +49 511 762 18305; fax: +49 511 762 5115. *E-mail address*: kroening@ifw.uni-hannover.de

Abstract

Modern manufacturing systems are characterized by an increasing complexity and high dynamic. This leads to new challenges for the operational planning of maintenance and production. This paper introduces a novel approach to an online simulation which enables a cost-optimized integration of condition-based maintenance measures in the production plan. The dynamic approach is implemented by means of event-driven simulation. It enables to depict the actual state of a complex manufacturing system, to simulate the future development of the production and thereby to evaluate different planning alternatives of maintenance.

Keywords: Manufacturing systems modeling; Operational maintenance planning; Production planning

1. Introduction

Due to an increasing complexity of modern production systems maintenance planning becomes more and more important. Especially in those complex and highly automated production systems an unplanned failure of machines can cause the problem that the total productivity is no longer determined by the original production bottleneck in most cases, but by the resulting maintenance bottleneck. Consequences of the availability reduction are productivity reductions and resulting failure costs.

For real production systems, however, often an isolated production and maintenance planning is carried out [1]. This can be a possible cause for an interrupted production process due to required maintenance measures and a shortly reduced productivity of the production system. The mostly isolated consideration of the two areas results from the insufficient possibility of the past to predict a machine failure. But, with modern monitoring systems it is possible to identify the wear condition for selected components and to show the need of maintenance measures way ahead of abrupt component failures [2, 3]. These technical proceedings enable more and more to replace selected components not just at the failure (reactive maintenance), but they can estimate the remaining lifetime based on the actual wear condition and future loading (condition-based maintenance). The resulting planning lead time can be used in order to coordinate the condition-based maintenance measures and production plan at optimal costs [4].

The main requirement of a least-cost integration of condition-based maintenance measures is to predict direct costs (e.g. material, staff) and implicit costs (e.g. failure costs which occur when the productivity is reduced by carrying out the maintenance measure) for possible planning alternatives. However, frequent changes in variants accompanied by varying stock and buffer sizes lead to a dynamic change of the production information and of the database for production and maintenance costs. An example is the failure cost which can vary significantly depending on the filling quantity of the stock and intermediate buffer.

In the literature, there are several scientific approaches described which focus on integrated

doi:10.1016/j.procir.2012.07.012

production and maintenance planning. But however, for complex and high dynamic manufacturing systems, these approaches are mostly inadequate (short planning horizon). This is due to the fact, that these approaches mainly consider simple production systems including just one single machine (e. g. [5] [6] [7]), or are mostly static (e. g. [8] [9]) and do not regard short-term changes of production information.

This paper presents a novel dynamic approach - developed by the Institute of Production Engineering and Machine Tools (IFW) - that offers an operational and least-cost integration of condition-based maintenance measures in the production plan. The knowledge of the current wear reserve of selected components and their future, various loadings by lots or different variants shall be used within the production planning phase (variation of the lot size and sequence planning) in order to specifically reschedule the time of maintenance measures into production-free periods. This approach is realized as an online simulation.

2. Approach to an online simulation

The IFW developed a planning approach to an online simulation which fulfills simultaneous production and maintenance planning on the one hand and depicts the high dynamic and complexity of real production systems on the other hand. The structure of the planning approach is shown as a summary in Figure 1.

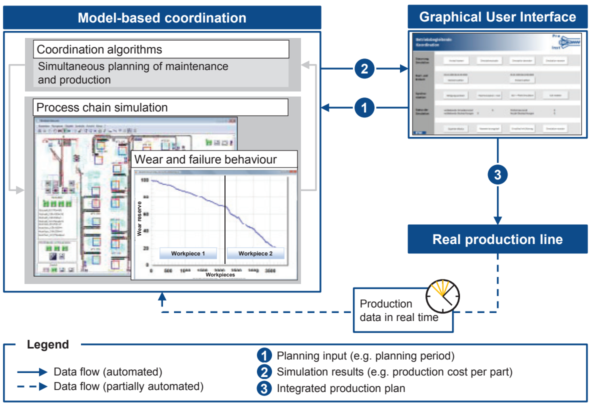


Fig. 1: Approach to an online simulation

[Krö/60894 © IFW]

The user can manage the input data of the simultaneous production and maintenance planning by a Graphical User Interface (see Figure 1, top right). Furthermore, it is possible to control the required simulation experiments and to visualize the output data of the simulation. Significant input data for the planning period are the production quantity of the individual product variants and all relevant information for the condition-based maintenance measures (e.g. wear model, execution time and required staff).

These data are automatically transported to the model-based coordination via interface (see Figure 1, left). The model-based coordination is completely realized with the simulation software Plant Simulation® [10]. It consists of the three main modules process chain simulation, models for describing the wear and failure behavior and the coordination algorithm.

Real production structures and procedures of an application scenario are depicted within the process chain simulation (First module, see Chapter 3).

Against the background to realize a simultaneous production and maintenance planning, it is important to focus on the detailed depiction of the real disturbance reaction of the machines and conveyers. For this purpose, a detailed analysis of the failure and wear behavior of selected components was carried out in the application scenario. The results were transferred to feasible wear models and implemented within the process chain simulation (Second module, see Chapter 3).

Within the third module, algorithms for a simultaneous maintenance and production planning are depicted (see chapter 4). The methodology was developed based on the method Design of Experiments (DoE). It provides a basis of valuation of the current wear reserve of selected components and their future, various loadings by the lots or different variants. The aim is to specifically reschedule the execution time of condition-based maintenance measures into production-free periods by a systematic variation of the production plan (lot size and sequence order adjustment).

The model-based coordination can depict the actual state of the production in the process chain simulation and simulate the relevant, future production information as well. At the same time, it is possible to dynamically evaluate different planning alternatives (different lot sizes and sequences, adjustment of maintenance periods) of the simultaneous production and maintenance planning. The simulation results are displayed within the Graphical User Interface and enable to select a least-cost production plan considering the required condition-based maintenance measures.

So far, the model-based coordination of the approach has been developed as a prototype. The following chapters therefore describe in more detail the three modules of the model-based coordination. The Graphical User Interface and the selection of data for online simulation are subject of future research works.

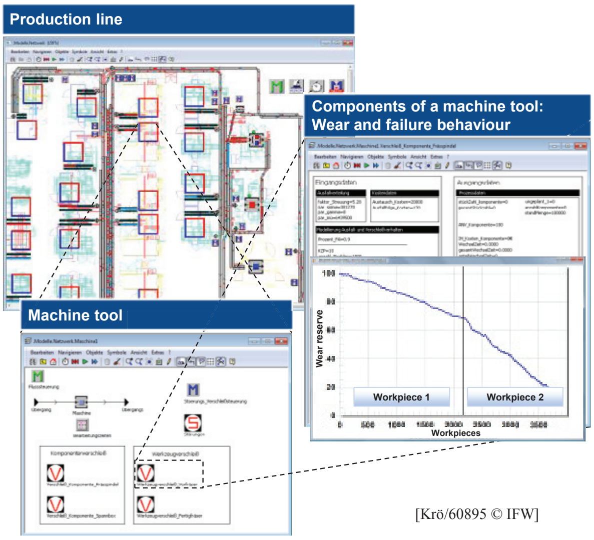
3. Development of an event-driven simulation model

A rigidly linked production line was used for the model-based coordination as an application scenario.

The production organization of the line corresponds to a line of a flow production. In total, four different variants are fabricated in different lot sizes by the week. Thereby, for most of the cutting process steps there are several, redundant machines which are connected by automated conveyers.

The event-driven simulation model of the linked production line has three levels in total (see Figure 2).

On the first level, the production structures (e. g. machines and band conveyers) and procedures in the simulation are shown between the raw part stock (system entrance) and stock for finished parts (system exit). Amongst other things, the single machines include cycle, set-up times and the shift schedule. The conveyers include speeds and capacities as well as algorithms of the material flow control. The stock for finished parts has an outward stock movement to be defined for the four variants.



[Krö/60895 © IFW]

Fig. 2: Levels of the event-driven simulation model

Each cutting machine tool and all relevant components, for which the failure and wear behavior is depicted in detail, are modeled in separate networks (second level). The failure and wear models for selected components of these machine tools are deposited in the third level.

In these models (described in detail in [4]), it is possible to indicate a distribution function of the lifetime for the regarded component depending on the variant to be produced. In addition, a wear mode (linear, exponential) can be implemented. Based on this, an average removal of the wear reserve is calculated by means of the Wiener Processes [11] after the machining of each workpiece. If the wear reserve reaches a determined limit, the component has to be maintained for a defined maintenance period.

In order to parameterize the failure and wear models, an extensive field data analysis was carried out at the application scenario. The failure distribution functions (mainly Weibull distribution) of ten tools in total were determined by means of the tool-life reports according to the single variants. It was possible to deduce the wear mode (linear and exponential) [4, 12] from the measurements of the torsional integrals. Furthermore, failure distribution functions were also determined for other selected components (e.g. milling spindles, engines) based on the history data of the past ten years.

A final validation showed that the simulation model has a high planning quality. By comparing the simulated and real output of the total production line per shift, the maximum difference was below 5%.

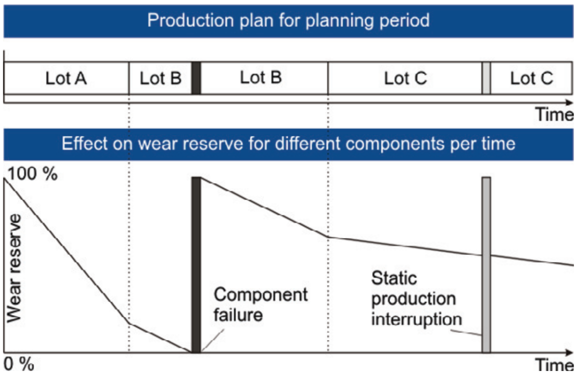
4. Development of an approach to a simultaneous maintenance and production planning

4.1. Approach to a simultaneous maintenance and production planning

In the approach, it is distinguished between static and dynamic interruptions:

- Static interruptions appear independently from production plans (e.g. breaks, weekends)
- Dynamic interruptions appear depending on production plans (e.g. setup times).

Basis for scheduling of condition-based maintenance measures in production-free times (static or dynamic interruptions) is the presence of different variants or lots, which produce alternating loading or wear to machines and machining components. It must be ensured, that the grade of wear growth is known per time unit or per fabricated part in a lot.



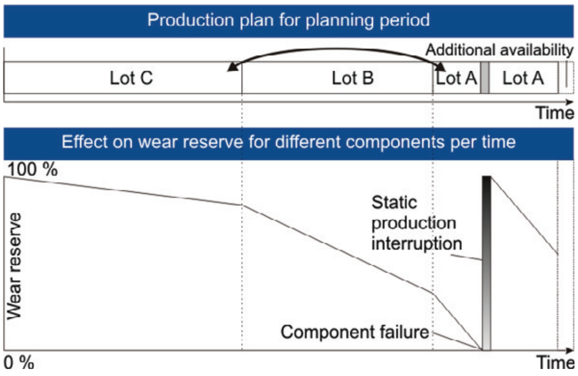
[Krö/60900 © IFW]

Fig. 3: Required wear reserve of a component for different lots

Figure 3 shows this as an example. The upper part of the figure shows a production plan for an upcoming production period. The lower part depicts how many wear reserve must be hold for one components of a production system. Reaching a predefined wear limit (in this case: 0%) the component will fail and as a result a maintenance measure will be necessary. As a consequence, the availability of the regarded machine tool is decreased.

For visualizing purposes this example uses only one component which has a linear and deterministic wear growth (compare field data analysis for tools, chapter 3). Nonetheless this method can also be applied to several components with different wear forms (e.g. exponential). Furthermore, in this case it is assumed, that setting up the machines for new variants takes no time. Consequently, only static production interruptions are displayed.

To move a condition-based maintenance measure into a static or dynamic interruption the components wear condition must be either on or under the wear limit at the same time when the interruption begins. This scenario can be achieved by switching the sequence of lots (Figure 4). Thereby, the availability of the reviewed machine tool is increased. But it also has effects on the time of failure of all regarded components within the manufacturing system. As a conclusion it is necessary to involve every component into this method, which is suited for condition monitoring.



[Krö/68751 © IFW]

Fig. 4: Effect of changing the sequence order on the point of failure

Equivalently to that it is possible to move condition-based maintenance measures into static or dynamic interruptions by resizing one or multiple lots. This is also integrated into the method and implemented in the simulation model.

4.2. Procedure for simultaneous maintenance and production planning

The procedure for simultaneous maintenance and production planning with the help of event-driven simulation is summarized in Figure 5. In the following the individual steps are explained in detail.

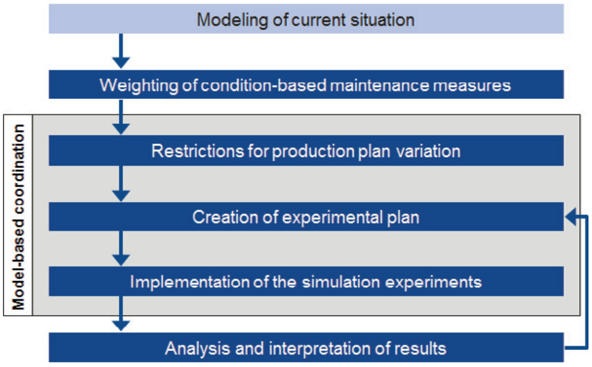


Fig. 5: Procedure for simultaneous planning

Modeling of current situation

At the beginning, the simulation model and models for describing the failure and wear behavior have to be initialized for picturing the actual state of the production at the observation time. Among other things this includes initializing the status of storage and intermediate buffer loads, machining status (ready, failure, etc.) as well as actual wear reserves of condition-based components.

Weighting of condition-based maintenance measures

Basis for lot size and sequence adjustments is the given production quantities of the different variants which have to be produced in the reviewed production period. Starting point is an economically optimal production program generated with isolated maintenance and production planning.

With the help of event-driven simulation model it is analyzed which condition-based maintenance measures must be done in the reviewed period. The influence of each measure on the production is evaluated and weighted by the simulation. Thereby, it is proved if changing the production plan for the future maintenance measures makes sense. For this the planning period is simulated with and without carrying out each maintenance measure in order to determine the productivity change of the whole system.

Restrictions for production plan variation

Depending on the number of fabricated parts in stock and how many parts are presumably requested in the next planning period, it is possible to have a deviation from the calculated (with isolated planning) production lots unless they can be decoupled from customer orders.

To get the value range for adapting the orders, presumed request amounts of different varieties are compared to the actual stock filling. The aim is to identify all possibilities for lot size and sequence variation in the period, which do not cause a delivery interruption for all variants. The result is a value range for every variant for lot size variation and possibilities as well as limits to change lot sequences.

Creation of experimental plan

Based on the scope of variation, an experimental plan for simulation experiments is developed. This includes setting up every valid combination of production lot sizes and sequence orders. The amount of combinations results out of the amount of production lots, the value ranges for variation of the lots (e. g. ± 100 parts), the step size (e. g. 20 parts) as well as the order amount.

Each combination of lot size and sequence order is proofed with a mathematical scheme if a supply disruption in the stock for finished parts is possible. The aim is to significantly reduce the efforts on experiments. Every valid combination is saved in the experimental plan.

Implementation of the simulation experiments

First the experimental plan will be processed by means of statistically verified simulation runs. For that every experiment will be run ten times with the same lot size and sequence order. Entering a static or dynamic production interruption the wear reserves of all regarded components are checked. When the wear reserve of a component is beneath a defined reserve tolerance (e. g. 5 %) the component will be maintained for a given time.

The approach has a major influence on the availability of machines, which affects logistic targets with different degrees of intensity, e. g. the production rate of the entire production system. However there are several minor effects (e. g. wasted wear reserves) which also affect the production efficiency.

In order to evaluate the efficiency of every experiment and for this every lot size and sequence variation (and shifting maintenance measures), the original approach of production cost per part [e. g. 13] has been adapted (Equation 1). With the dynamic production cost per part C_P all cost are considered which change dynamically when adapting the production plan:

$$C_P = \frac{C_{LH} \times T_J + C_{AM} + C_S + C_{St}}{n} \qquad (1)$$

C_{LH}	[€/s]	Cost for line usage per time
C_{AM}	[€]	Additional tool cost for maintenance
C_S	[€]	Setup cost
C_{St}	[€]	Stock cost for planning period
T_J	[s]	Production time for all parts
n	[-]	Number of produced parts

The production cost per part C_P include cost for running the production system C_{LH} per time (machine cost and labour cost) as well as the cost for wasted wear reserves C_{AM} when components are maintained before exceeding the wear limit of 0%. Furthermore, setup cost C_S, stock cost C_{St} and the number of produced parts n are considered in this approach.

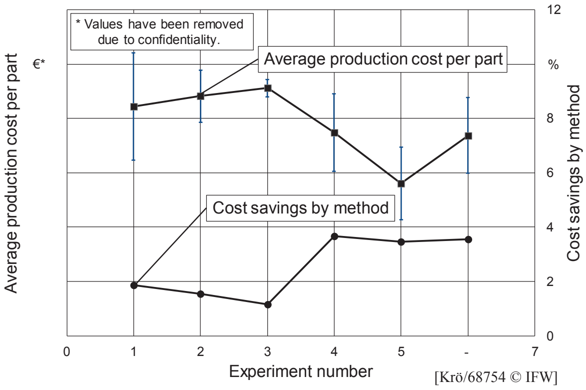
Analysis and interpretation of results

The results are reviewed afterwards in a visualization (Graphical User Interface, see Figure 1). Comparing combinations of lot sizes and sequences lead to a production plan which has the highest probability to provide lowest dynamic production cost per part. This plan provides from the view of production and maintenance a cost minimum.

4.3. Verification of simultaneous planning approach

For a first verification of the simultaneous planning approach, the given production system was considered in the period of one week (with three lots). Furthermore, three fictitious wear components were implemented on every machine (based on the results of field data analysis of tool wear, maintenance times between 5-60 minutes).

All simulation experiments were repeated ten times with isolated respectively conventional (reactive, components are changed at 0% wear reserve) and also with the simultaneous concept (condition-based, components are changed during static and dynamic interruptions with 5% limit alert). Comparing the two planning concepts in the simulation experiments allows identifying the actual influence of the simultaneous planning on the dynamic production cost per part.



[Krö/68754 © IFW]

Fig. 6: Sequence order adjustment

For a testing series with the mechanism of sequence order adjustment the average cost per part is noticeable changing in relation to the sequence order, which is shown above in Figure 6 (with 95% confidence interval).

The lower graph shows the cost savings which result from changing the maintenance strategy (reactive to condition-based strategy) and from moving maintenance measures into the production interruptions. According to the mirrored graphs an influence of the developed concept can be expected. The minimum cost production plan (experiment No. 5) is able to lower the cost compared to the initial program. The reason for that is the higher productivity compared to the original program. However, the minimum costs per part are not achieved at the maximum cost savings by the method. This is because further effects have an impact on the production costs (e. g. experiment No. 5 has less setups than the experiments No. 4 and 6). That is why the production plan from experiment No. 5 would be chosen.

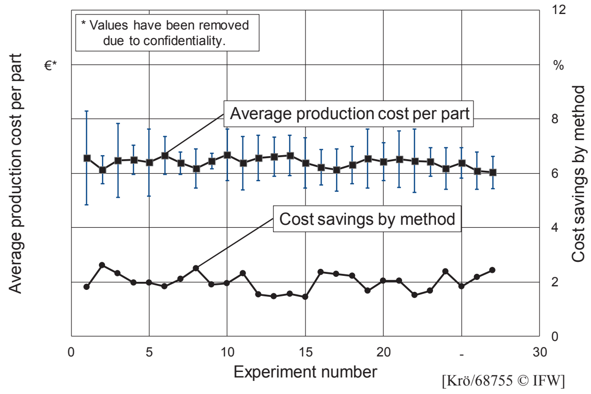


Fig. 7: Lot size variation

Figure 7 displays the results of simultaneous planning with variation of production lot sizes. The cost shift in this case is less significant than in the concept of sequence order adjustment.

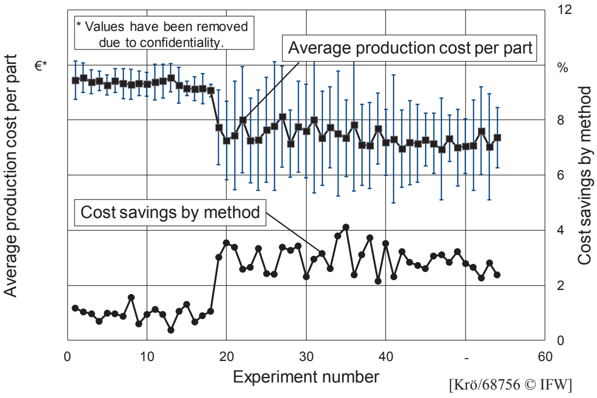


Fig. 8: Combined lot size and sequence order variation

In the third simulation study the lot size and the sequence order were varied simultaneously (Figure 8). Also in this simulation study, the sequence order adjustment has a bigger influence on cost per part. This can be seen in the sudden cost jump (Experiment No. 19).

5. Summary and conclusion

In this paper a dynamic approach to simultaneous maintenance and production planning was presented. The approach integrates the knowledge of the actual wear reserve of chosen components as well as different loading and wear growth in dependence of different variants. Based on that, the method provides a basis for evaluating a systematic scheduling of maintenance measures to production free times by variation of the production plan (lot size and sequence order).

The methods were implemented and verified within an event-driven simulation model of a real production line. The verification pointed out function and potential of this method, but it also showed the challenges like high statistical spreading of the output values. This is due to the stochastic wear prediction.

Acknowledgements

The research work will be continued within the frame of the project “Model-based coordination of the operational maintenance and production planning and control” (project “MK-ProInst”, DE 447/81-1). The authors would like to thank the German Research Foundation for its financial and organizational support.

References

[1] Aghezzaf, E. H., Jamali, M.A., Ait-Kadi, D., 2007, An integrated production and preventive maintenance planning model, European Journal of Operational Research.

[2] Neugebauer, R., Fischer, J., Praedicow, M., 2011, Condition-based preventive maintenance of main spindles, Production Engineering, 5/1, 95-102, Springer.

[3] Brecher, C., Witt, S., Klein, W., 2011, Condition monitoring of monorail guidance systems, Production Engineering, 2/3, 333-337, Springer.

[4] Denkena, B., Kröning, S., Blümel, P., 2011, Integrated planning and control of maintenance and production, The 44th CIRP Conference on Manufacturing Systems, June 1-3, 2011, Madison, Wisconsin, USA, 6 Pages.

[5] Ji, M., He, Y., Cheng, T.C.E., 2006, Scheduling linear deteriorating jobs with an availability constraint on a single machine, Theoretical Computer Science 362 (2006), pp. 115-126.

[6] Cassady, C. R., Kutanoglu, E., 2005, Integrating Preventive Maintenance Planning and Production Scheduling for a Single Machine, IEEE Transactions on Reliability, Vol. 54, No. 2, pp. 304-309.

[7] Pan, E., Liao, W., Xi, L., 2010, Single-Machine-based production scheduling model integrated preventive maintenance planning, International Journal of Advanced Manufacturing Technology (2010) 50, pp. 365-375.

[8] Wang, J.-B., Wei, C.-M., 2011, Parallel machine scheduling with a deteriorating maintenance activity and total absolute differences penalties, Applied Mathematics and Computation, pp. 8093-8099.

[9] Sanlaville, E., Schmidt, G., 1998, Machine scheduling with availability constraints, Acta Informatica, Vol. 35, No. 9, pp. 795-811.

[10] Bangsow, S., 2010, Manufacturing Simulation with Plant Simulation and Simtalk, Springer.

[11] Lefebvre, M., 2007, Applied Stochastic Processes, Springer, New York.

[12] Blümel, P., 2011, Kostenorientierte Instandhaltungsplanung basierend auf Maschinenzustandsdaten, Dissertation, PZH-Verlag.

[13] Tönshoff, H. K., 1995, Werkzeugmaschinen - Grundlagen, Springer, Berlin.