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Integrated production and maintenance planning in cyber-physical production systems

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Abstract

Rising production costs and efficiency requirements are challenges for manufacturing companies. One possibility to cope with these challenges is to improve maintenance efficiency and effectiveness by integrating predictive maintenance tools into cyber-physical production systems. However, the integration of these tool information into production and maintenance planning systems in order to determine necessary maintenance tasks is one of the main challenges for manufacturing companies. Therefore, this paper presents an innovative system for an effective integrated production and maintenance planning in complex cyber-physical production systems using multi-criteria decision-making. A prototypical application is presented to demonstrate the feasibility of the approach.

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Keywords: Maintenance planning, multi-criteria decision making; decision support system

1. Introduction

1.1. Motivation

As a result of globalization, manufacturing companies are facing high competitive and cost pressure. Furthermore, customers require innovative, highly functional products with high quality, which manufacturing companies have to provide [1].

In addition, market volatility increased in recent years due to the raised dynamics of the environment. For manufacturing companies this leads to the requirement of high flexibility [2].

In order to secure and improve their competitiveness manufacturing companies take actions such as the development of complex production networks [3,4], the flexible linking of production systems, and also the improvement of the utilization and efficiency of the production system and individual production lines and machines [5]. Furthermore, companies also integrate investment-intensive, highly automated cyber-physical systems (CPS) into their existing production systems leading to cyber-physical production systems (CPPS) [5,6].

These actions have a significant impact on the production infrastructure and planning processes of manufacturing companies. They lead to an increase in plant and production system complexity [4,7] as well as increased requirements of plant reliability and availability [3,4,5]. The progressing automation of production lines results in an increased amount of equipment and components that need to be monitored and repaired [4,5].

The described impacts directly affect the field of action of maintenance. According to [3], 93 % of the manufacturing companies surveyed stated that the importance of maintenance will be high to very high in the future. As a result, measures to ensure competitiveness of the manufacturing companies lead to an increased importance of maintenance.

1.2. *Problem statement and purpose*

The requirements for maintenance measures are determined on the basis of an object-specific maintenance strategy. According to [8], three main basic strategies are distinguished: the damage-based strategy, the time-based strategy and the condition-based strategy. In recent years the proportion of companies pursuing the condition-based strategy for their

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production lines and machines has increased [3,5]. Within condition-based strategy the actual maintenance requirement based on the current condition is determined and thus times of the requirements can be predicted at an early stage. According to [5] this trend will continue.

Maintenance planning must take into account manifold effects on the production system due to complex network structures, the dynamic boundary conditions caused by market volatility and the resource conflict of a limited number of resources with production planning in the planning process [4,7,9]. Due to the high number of decision variables, a large solution space has to be explored in order to determine a suitable production and maintenance plan. Consequently, the decision-making situation has a highly complex character. To determine a suitable production and maintenance plan the decision-making process must be supported by a decision support system. The objective of the publication is to present a decision support system to support the decision-making process in production and maintenance planning to determine an improved production and maintenance plan, taking into account a multi-criteria target system.

2. Fundamentals

The main objective of production planning is to generate a plan of production orders taking into consideration the available capacities and to achieve the economic and logistic targets of the manufacturing company. These targets are partially competitive. The goal is to reduce logistics costs, which results in minimizing inventory and maximizing machine utilization [10]. On the other hand, consistent adherence to delivery dates and short throughput times should improve the logistics performance perceived by the market [10].

As the accuracy and distribution of predictive maintenance tools emerges, targeted planning and preparation of maintenance measures becomes the key enabler for efficient and effective production [4,5]. The task of maintenance planning includes determining the type and number of maintenance measures to be performed in a planning period [9]. The main objective of maintenance planning is to maintain and increase the technical capability of the production system while keeping maintenance and failure (follow-up) costs low and preserving plant availability [4,11].

Production and maintenance planning overlap in the field of capacity adjustment measures, production program planning and production factor provisioning. In this field, maintenance measures have to be taken into account. Either the capacity of the resource considered is reduced or, on closer inspection, the affected resources for the respective period are assigned maintenance measures [4]. In most cases, production planning and maintenance planning are treated as separate problems [12,13]. However, production and maintenance planning have a high impact on each other. Manufacturing products requires manufacturing resources. This leads to a deterioration of the condition of the manufacturing resources. This phenomenon can be prevented by maintenance measures. During these times, however, production is normally not possible since maintenance tasks must be executed. Therefore, in the short term, maintenance measures lead to a reduction in plant productivity, even though it will be maximized in the long term [4,14].

3. Literature Review

Several approaches have been developed to support the decision-making process during the establishment of the maintenance program. These approaches are presented in the following paragraphs.

[9] presents an approach of optimizing the selection of maintenance measures within program planning and the integrated determination of the necessary maintenance budget. Optimization is carried out with the goal of minimizing the direct and indirect maintenance costs, while maintaining a minimum availability of the production system and considering the economic and technical risks. A mathematical model is presented for this purpose, which consists of the three submodels: decision, evaluation and restriction model. The model is solved by a genetic algorithm.

[15] present a model for planning maintenance measures in a multi-line production system considering possible failures of production resources. The objective function takes production, set-up and storage costs into account. The optimum interval for maintenance measures is determined for each production line. To solve the nonlinear mixed integer optimization problem, a heuristic based on the Lagrangean relaxation is presented.

The assessment approach of [16] supports the decision of awarding maintenance measures to internal or external service providers. Different maintenance measures, delivery options and service providers are evaluated under monetary and technical criteria within the multiphase approach. These quantitative and qualitative criteria are weighted using a pairwise comparison and converted into a cost-equity function. In order to solve the optimization problem, a linking algorithm is used to rank the alternatives and a sensitivity analysis is carried out.

[7] presents a method for determining cost-optimized maintenance times based on the residual life prediction. The procedure is divided into four steps. The first step integrates the data from machine condition monitoring with residual life forecasting. In the second step alternative maintenance times are determined and evaluated. Evaluation is based on the criteria of costs and potential malfunction costs. In the third step the planned measures are assigned to maintenance groups and action alternatives are selected using cost-criteria.

[17] introduces an approach for cost-effective specification of maintenance measures to improve reliability and availability. The planning horizon is divided into discrete time periods in which three possible maintenance measures (repair, replacement, no action) can be carried out. The objective functions are the total cost of ownership and the reliability and availability of the entire system. For this purpose, a nonlinear multi-objective optimization model is presented and a Pareto optimal repair and exchange plan is determined.

An approach to integrated production and maintenance planning and control by means of simulation technology is presented by [4]. The focus is a short- to medium-term schedule and capacity planning. Dynamic maintenance costs are considered as target criteria. The plan of maintenance measures is determined by means of simulation. Inputs to the simulation model are the requirements for maintenance measures and production orders. A feasible plan is developed by adapting the input information. Two approaches are presented for this purpose. In the first procedure, the times of the maintenance measures are first varied and integrated into the production plan. In the second procedure, the times of the maintenance measures are fixed and there is an adaptation of the production plan by shifting the production orders.

[18] present an approach to planning maintenance measures in a multi-line manufacturing system, with the goals of minimizing costs and maximizing reliability. Malfunction costs, adjustment and replacement costs and malfunction follow up costs are considered within the cost-function. This approach considers limited availability of personnel and spare parts for carrying out maintenance measures. Maintenance measures are differentiated into repair and replacement. A mixed-integer nonlinear optimization model (MINLP) is formulated and the objective functions are merged using the weighted sum method. The model determines the optimal times for maintenance measures and decides whether a repair or an exchange should be carried out.

The model of [19] determines maintenance times and batch sizes of the products to be manufactured while optimizing costs. A Proportional Lot-Sizing and Scheduling Problem with Setup Classes and Maintenance (PLSP-SC-M) optimization model is presented. The model takes into account different setup classes, the wear of components in the production system, the demand for a product as well as its current inventory. The decision variables considered are time of a setup process, the setup state and the execution of a maintenance measure within the planning horizon. To solve the optimization problem, a heuristic approach on the basis of the Fix & Optimize heuristic, is adopted.

[20] present an approach to optimize machining time and overall maintenance costs. The time interval between two maintenance measures can be set freely within a time window. Two types of maintenance measures are differentiated: reinstating "as good as new", and due to the progressive wear a complete replacement. For each production order the presented NSGA-II algorithm determines on which machine it is produced and whether a maintenance measures is performed before an order.

The state of research shows the deficits described below. The planning of maintenance measures is often based on a single target criteria. Often, only costs are taken into account. Furthermore, there is insufficient consideration of influencing the output of the production system by performing maintenance measures. The separate consideration of production and maintenance planning creates unrealistic forecasting in production planning, which negatively impacts the achievement of logistical goals [4]. In addition, there is low reliability and safety of production and maintenance planning and insufficient consideration of the complexity of the multi-criteria decision-making situation and resources [4]. This leads to reduced efficiency and waste in maintenance [3,5].

4. Approach

The following paragraphs present a new approach for integrated production and maintenance for cyber-physical production systems. The goal of this approach is to support the multi-criteria decision-making process in production and maintenance planning in order to determine an improved sequence of maintenance measures in production systems.

4.1. *Overview of the system for an integrated production and maintenance planning*

A comprehensive decision support system that is oriented towards the decision-making approach is needed for an integrated production and maintenance planning. The prescriptive decision theory provides universal operational sequence descriptions of decision processes. These sequence descriptions can be applied context-independent and consist of several operational sequences, beginning with the determination of a gap between the current and the targeted state. Action alternatives are determined in the decision process, evaluated and completed with the selection of an alternative or realization of an alternative. Therefore, the decision theory is the basis of a procedure for integrated production and maintenance planning.

The decision support system is divided into two parts: *system configuration* and *procedure*.

Within the first part, *system configuration,* the model of the production system with resources and processes relevant to production and maintenance planning is created. It ensures that the dynamic dependencies and the complex processes within the production system are mapped correctly and the target criteria for the planning process are set.

In the second part, *procedure,* the processes for production and maintenance planning are carried out and consist of six process steps. The order of the process steps is oriented to towards the decision-making process and results in an integrated maintenance and production plan for the considered planning period.

4.1. System configuration

The *system configuration* part is divided into the three sub-parts data model, target system and production system model and to be seen in Fig. 1.

In the production system model part, modeling of the considered production system with the resources relevant for the integrated planning process takes place. Furthermore, necessary and available input information is identified and integrated into the model. Exemplary input information is the general capacity and performance data from production lines and machines in fabrication, assembly and maintenance and logistics data.

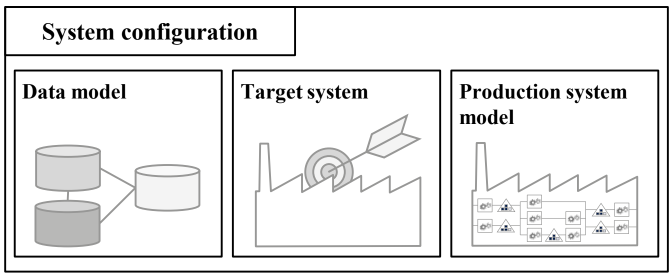

Fig. 1. Overview of system configuration for an integrated production and maintenance planning

The data model provides the essential information for the planning process within the defined planning period. The planning period determines the interval for which the integrated production and maintenance plan is created. For this period, the required input information, such as the production orders, shift schedules and costs must be provided. Furthermore, the warning limits for the waste stock must be specified, below which the planned maintenance measures should be scheduled. When setting the warning limits, attention must be paid to restrictions such as lead times for ordering or making spare parts. Different interactions may occur when carrying out maintenance measures on production lines and machines. Measures can be mutually exclusive, neutral or may need to be carried out jointly. These interactions must be integrated into a measure-relationship matrix by the user. This input information enables the determination of the suitable maintenance times, taking into account the course of the remaining useful life as a result of future load according to the planned production orders.

In the part target system the determination and evaluation of target criteria is carried out. The target criteria must be derived from the long-term corporate goals and take into account the specific key figures of production and maintenance planning. Examples of possible target criteria are: costs, production line/machine availability and delivery reliability. The weighting of the individual target criteria is company-specific and must be specified, taking into account the application case. The selection of the weighting procedure as well as the determination of weighting factors influences the determination of the integrated production and maintenance plan.

4.2. Procedure for an integrated production and maintenance planning

The *procedure* is subdivided into six steps, which are carried out depending on the result of the preceding step. The procedure is to be seen in Fig. 2.

The necessary maintenance measures are determined in the first process step. Based on the current status, the times of maintenance requirements are determined taking into account the curve of the remaining useful life, the future wear by the long term production plan and the maximum total life of a component. Necessary maintenance measures can be determined based on the defined remaining useful life curve, condition monitoring systems, specified intervals, inspections and failures. The determination of the requirements must also take into account the future utilization of production resources based on the planned production orders, the execution of which leads to wear on the machines and production lines.

For the identified maintenance requirements, all possible times for the execution of maintenance measures in the production plan within the planning period are identified in step two. The determination must take into account the long-term production plan as well as the availability of the resources necessary to carry out the required maintenance. In the event that no possible times could be determined for the maintenance requirements in the production plan, step five of the procedure needs to be carried out. Otherwise step three follows.

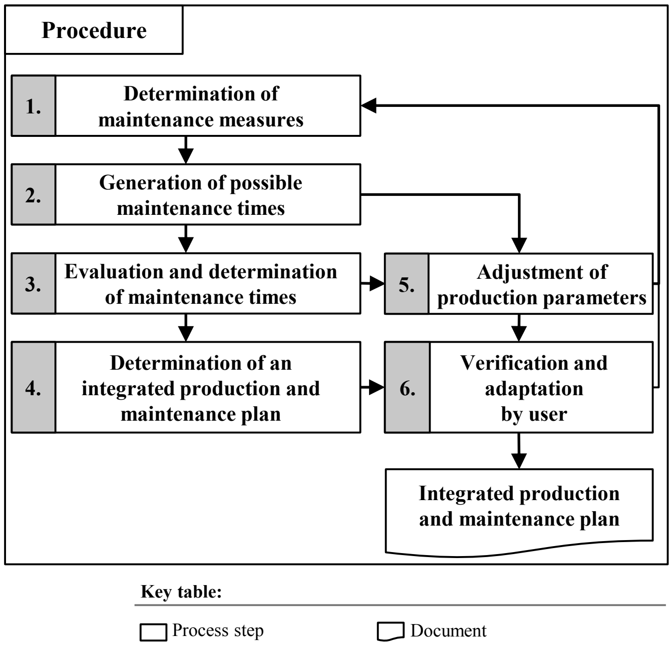

Fig. 2. Overview of the proposed procedure for an integrated production and maintenance planning

The generated maintenance times are evaluated and selected in the third step. This process step uses the multi-objective target system and evaluation procedures defined in the system configuration. For each generated maintenance time, the function values to determine the characteristics of the individual targets are calculated. Subsequently, an evaluation of the results is carried out as to whether the criteria of the evaluation procedure are sufficiently fulfilled. If the target criteria are not sufficiently met in any of the action alternatives identified, Step five follows.

In step four, the best alternative based on the target system of the integrated production and maintenance plan is selected. In addition, all affected allocation and resource plans will be updated.

If no or, according to the target criteria, only unsuitable timings for the maintenance measures could be determined, step five follows the method. A comparison of the current model parameters with the permissible limits of the production parameters is used to check whether an adaptation is acceptable. If the system parameters can be adapted, the process sequence is re-executed to determine an integrated production and maintenance plan.

In the final step of the process the user reviews and publishes the plan for the planning horizon. Based on his expert knowledge, manual adjustments to the integrated production and maintenance plan can be made, if necessary, in order to integrate influences that were not taken into account in the model.

5. Case Study

5.1. *Production system and planning process*

The decision support system is prototypically applied in a production systems which produces household appliances. The plant is subdivided into the fabrication, assembly and maintenance departments. Fabrication consists of different production lines for various components of the products manufactured at the site. Fabrication and assembly are separated from each other by a warehouse. The maintenance department supervises all production lines and carries out technical and administrative processes for inspection, maintenance, repair and improvement of machines and tools. The division has integrated tool making for the manufacture of spare parts, cleaning of tools and maintenance measures.

A broadband press for manufacturing sheet metal parts that are incorporated into each product manufactured at the plant presents a bottleneck in the production system. The availability of the broadband press under consideration is therefore of fundamental importance for ensuring the economic viability of the relevant production area at this site. The maintenance times and cycles of the machine and tools were determined based on experience. By integrating a predictive maintenance tool into the broadband press, maintenance cycles can be determined based on machine data [21].

In the context of production and maintenance planning several deficits in the decision-making process are to be seen. Production orders and maintenance measures are planned separately. In joint planning rounds, the various plans are coordinated by a voting process and are characterized by difficult consensus finding. In addition, coordination is based purely on the experience of production and maintenance planners without a decision support system for the decision-making process.

5.2. Strategies for integrated production and maintenance planning

Two strategies are integrated in the system to plan production orders and maintenance measures. The first strategy represents the current approach of the maintenance department for planning and performing maintenance measures. In every planning period a four hour time slot is used to execute preventive maintenance measures. Due to wear and insufficient condition, monitoring machine malfunctions take place during operation or product quality problems occur, which lead to shutdowns of the broadband press. The machine and tools have to be serviced immediately by a worker from the maintenance department. In the simulation, two of these maintenance measures are considered.

The second strategy implements the integrated production and maintenance planning procedure presented in Chapter 4. In the system configuration part, due to the implemented predictive maintenance tool, the actual condition that the remaining useful life (RUL) of the machine and tool and the maintenance cycles for cleaning and inspection are known.

Availability of a worker, the maintenance measure relationship matrix, the current production plan and maintenance requirements are integrated in the simulation in the implementation of the process flow.

The key figures of the target system are: the RUL of a component, the current output, the minimum lot size of each job and the number of strokes of the press.

Within the evaluation the generated production and maintenance plans are evaluated in regards to the minimization of the loss of RUL, which leads directly to costs, the minimization of downtimes by setup and maintenance measures in order to save time and the compliance with the required lot sizes. For each integrated plan the target function is calculated using the weighted sum method.

5.3. Results

The simulation is executed using different initial states for the RUL of the maintenance measures for strategy one and strategy two. For the tool and the press the RUL varies between 10 % and 50 % as the initial state and 100 experiments for each strategy are carried out.

The results for the produced parts and the machine downtime of the press are shown in Fig. 3. The results show that using the integrated maintenance and production planning the output of produced parts increases in average about 5400 parts for a planning period of seven days. This represents an increase of around 2.5 %.

The integrated production and maintenance planning reduces on average the down-time by about 35 % from 3.68 % to 2.41 %.

The results for the setup and maintenance time under consideration of the maintenance measure relationship matrix are to be seen in Fig. 4. It shows that the setup processes and maintenance measures can be combined and lead to increased production time within the planning period.

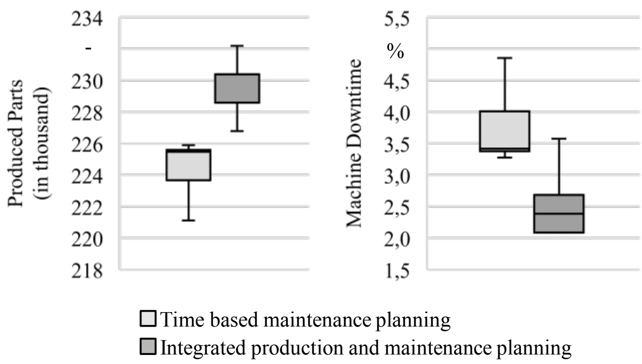

Fig. 3. Simulation results of total number of produced parts and percentage of the downtime of the broadband press of the presented strategies

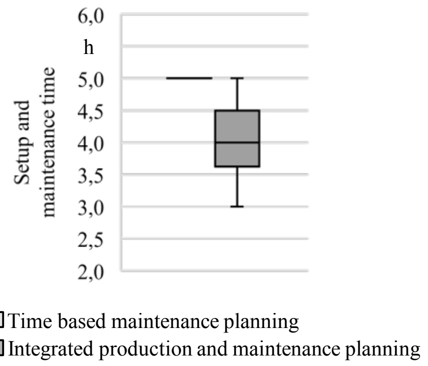

Fig. 4. Simulation results of the setup and maintenance time of the presented strategies

Due to the benefits of merging maintenance measures and job changes on the press, the average setup and maintenance time is reduced by about 18 % from 5 hours to 4.1 hours.

As the multi-criteria target system tries to find an optimum of diverging criteria, the increased number of produced parts and reduced machine downtime lead to a decreased utilization of the RUL of the tool.

Due to the combination of setup processes and maintenance measures in order to save time, the lifecycles of the tools are not used in full and maintenance measures carried out.

The results show as well that the integrated production and maintenance plan leads to a more constant operation of the press. In addition, having an integrated maintenance and production plan increases the predictability of resource planning for the company. Therefore, the decision support system determines under consideration of the target system the best integrated production and maintenance plan for the cyber-physical production system.

6. Summary

High competitive pressure and increasing customer demands pose increasing challenges for manufacturing companies. Maintenance, as a central element in ensuring productivity and, thus, compliance with customer requirements, must be prepared for this. As the accuracy and distribution of predictive maintenance tools emerges, targeted planning and preparation of maintenance measures become the key enablers for efficient and effective production.

A comprehensive overview is presented of a decision support system for an integrated production and maintenance planning, which enables mapping the entire complexity of real-world production systems and supports production and maintenance planners in the decision-making process.

The system has shown its advantages in complex cyber-physical production systems using multi-criteria decision-making. A prototypical application scenario is presented to demonstrate the feasibility of the approach.

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