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A performance measurement system for integrated production and maintenance planning

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Abstract

The increasing amount of production resources to be maintained and efficiency requirements are forcing manufacturing companies to improve production and maintenance effectiveness by a mutual consideration of both functions in an integrated planning process.
However, less attention is paid to monitor the performance of manufacturing systems based on key performance indicators to identify the need for measures and adapting plans. Performance Measurement Systems (PMS) are applied to accomplish this task. Therefore, this paper presents an evaluation of existing PMS's for production and maintenance planning. A new PMS that considers strategic and operational views is presented and validated by an industrial case study.

Keywords: performance measurement system, maintenance planning, multi-criteria decision making

1. Introduction

In recent years manufacturing companies have increased the degree of automation of their manufacturing systems, e.g. by integrating cyber-physical systems (CPS) into their production lines [1]. Automation leads to an enlarged amount of resources, that need to be monitored and maintained and therefore, results in an increased importance of maintenance to secure the availability of manufacturing system resources [2, 3]. However, the importance of maintenance is often neglected. Maintenance and its contribution to the economic success of manufacturing companies is underestimated and therefore, maintenance is occasionally characterized as an auxiliary function [2, 4, 5].

Due to high cost pressure manufacturing companies need to safeguard their competitiveness through a more efficient and effective use of their resources [1]. To optimize the utilization and efficiency of processes in manufacturing systems production and maintenance planning must be considered simultaneously in the planning process [5, 6]. Such an integrated planning process can lead to increased availability and productivity and is therefore economically advantageous for manufacturing companies [7-9]. Integrated production and maintenance planning is a multi-criteria decision-making process, where based on current manufacturing system information action alternatives are developed and selected. However, less attention is paid to the starting point of a planning process: the identification of the need for action. To identify the need for action, a stimulation information is needed, which can be identified by monitoring the performance of the manufacturing system.

Manufacturing companies use performance measurement systems (PMS) for providing current information about manufacturing system resources and processes, monitoring

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performance and identifying planning problems [10]. PMS's enable the comparison of the current with the desired situation by using key performance indicators (KPIs) and allow for the early detection of unwanted deviations. Furthermore, PMS's measure the contribution of a department to the company's success and therefore can make the contribution of maintenance more transparent and comprehensible [5].

This paper is arranged as follows: requirements, design methodologies and existing PMS's in production and maintenance are presented in section two; section three discusses an approach for a PMS for integrated production and maintenance planning based on the identified research gap; in section four, the applicability of the approach is validated by an industrial case study and a summary is given in section five.

2. Literature Review

2.1. Requirements for performance measurement systems

PMS's and KPIs are fundamental instruments for the planning, control and monitoring of companies [10]. A PMS is defined as "a set of metrics used to quantify both the efficiency and effectiveness of actions" [11] and comprises a broad range of performance variables, and combines the functions involved with the objective of forming an overall optimum [12].

Focusing on the formulated and implemented strategy of the company is of particular importance for the realization of a PMS [10, 13]. The KPIs within a PMS should be directly related to the strategy of the company and contain both financial and non-financial KPIs [14]. The system should be adaptable to changes in the manufacturing system, easy to operate, enable the identification of bottlenecks and stimulate continuous improvement [12].

2.2. Design methodologies for performance measurement systems

Design methodologies for PMS are not stand-alone PMS. They are used for the structured development of specific PMS. The design methodologies Balanced Score Card and concept of selective KPIs are presented in the following paragraphs.

Kaplan & Norton [15] develop the Balanced Score Card (BSC) in cooperation with twelve companies. The BSC considers financial and operational aspects and a quick overview of business operations for management is enabled. It consists of four perspectives: customer, internal company, innovation and learning and the financial perspective. For each of the perspective goals, a set of KPIs, target values and measures are to be developed.

Weber et al. [12, 16] introduce the concept of selective KPIs. It is a design methodology for deducting relevant KPIs and supports managers in the decision-making process for the selection of KPIs. Strategic performance attributes (SPAs) are determined based on the company's strategy and can be used within planning to derive a plan. For monitoring strategy implementation and occurrences of unplanned problems in the operational processes, operative performance attributes (OPAs) are derived. The logical combination of the SPAs and OPAs is done in the countercurrent process.

2.3. Performance measurement approaches in production and maintenance

Parida & Chattopadhyay [17] present a hierarchical PMS for maintenance, which consists of 21 KPIs for the organizational levels of strategy, tactics and operations and seven classes of different perspectives of maintenance. The seven classes are costs and finances, maintenance-related indicators, customer satisfaction, learning and growth, health, safety and environment and employee satisfaction. The KPIs are derived from the company's strategic objectives. However, the procedure for the derivation, assignment and adjustment of the KPIs is not explained.

Carnero [18] develops a multi-criteria PMS for maintenance. The system is based on nine classes: quality, environmental and safety standards, organization, costs, outsourcing, control, digitization, training and management. The classes consist of a total of 50 sub-criteria and the fuzzy analytic hierarchy process (AHP) is used for weighting the criteria within the utility function. Production is not considered.

Rodríguez-Padial et al. [19] present a methodology for prioritizing KPIs in maintenance using the BSC and the AHP. Finances, customers, internal business processes and learning/growth are considered as classes and are divided into sub-criteria. Each sub-criterion is represented by an individually selectable KPI. The weightings of each class and sub-criterion are determined using the AHP. However, a method for selecting the KPIs is not presented.

Raza et al. [20] develop a PMS for maintenance. It consists of four classes: reliability, availability, maintainability and safety. Individual KPIs are assigned to the four classes for each level of maintenance management. For the selection of KPIs it is necessary to define a corporate strategy, from which a strategy for production is then derived. In the next step, objectives for maintenance, such as lower costs or higher plant availability, are defined. Critical systems are then identified and the KPIs selected for the management levels. A specific method for selecting KPIs is also not presented.

VDI 2893 [21] is a guideline for creating KPIs and structuring them into a PMS for maintenance. Based on the business processes and maintenance objectives, basic figures are identified and KPIs are formed. These KPIs are subdivided into organizational levels and are assigned to the perspectives of finance, customers, processes, employees and external providers. A list of possible KPIs is presented. The process of assigning KPIs is not described in detail and production planning is not considered.

Muchiri et al. [22] develop a PMS that merges the objectives from company organization, manufacturing system and maintenance. It is stated that maintenance measures should be selected and evaluated within a maintenance loop. KPIs are examined in terms of equipment performance and maintenance costs. A list of possible KPIs based on surveys and benchmarks is provided. However, a method for explicitly selecting the KPIs is not presented.

Medina et al. [23] present a PMS based on a probabilistic relational model (PRM). PRMs are used for performance analysis, decision support and process optimization in production and maintenance. The model is coupled with the manufacturing system model by means of logical relationships and semantic rules. A procedure for the determination of weighting factors for KPIs is not presented.

2.4. Conclusions

Each of the PMS's includes an innovative aspect. The stand-alone PMS's of Parida & Chattopadhyay [17], Carnero [18], Rodríguez-Padial et al. [19] Raza et al. [20] and VDI 2893 [21] provide insight into the relevant performance dimension of either production or maintenance.

However, no PMS jointly considers production and maintenance and no PMS enables to analyze the effects of the current state of resources and processes in the manufacturing system on the objectives of the planning functions. Furthermore, no stand-alone PMS considers strategic and operational perspectives, which are needed to support a target-oriented coordination of the two planning functions. In addition, it is to be seen that a widespread differentiation within PMS, as for example in VDI 2893 [21], leads to less clarity of the PMS.

In conclusion, to the best of the authors' knowledge, there is no PMS that meets all requirements for performance measurement for the integrated production and maintenance planning of manufacturing systems. The integration of production and maintenance in a PMS is necessary to monitor the manufacturing system performance, to identify the need for action to plan measures and to adapt existing plans. Therefore, the development of a PMS for integrated production and maintenance planning is needed.

3. Approach for a PMS for an integrated production and maintenance planning system

3.1. Selection of the basis PMS concept

Lelke [10] developed a criteria catalog of eight dimensions for the evaluation of PMS's. Especially relevant for a PMS for integrated production and maintenance planning are: problem adequacy, consistency, flexibility, operationalizability, economic efficiency and balance.

Lelke [10] evaluates the BSC and concept of selective KPIs against the criteria catalog. The BSC has been transferred to many different industries and is evaluated as problem adequate, balanced and with high flexibility. Due to its focus on strategy, in practice it can be difficult to secure operationalizability and establish valid cause-and-effect relationships. The concept of selective KPIs is characterized by a high consistency and flexibility. It also can be transferred to different applications, e.g. to manufacturing networks [24]. The countercurrent method to select individual KPIs in the PMS ensures consistency and allows for cause-and-effect analysis [10].

Both approaches meet the requirements to a high degree for a PMS for integrated production and maintenance planning. Nevertheless, the combination of strategic and operational KPIs of the concept of selective KPIs is beneficial for manufacturing companies. It allows for the analysis of operational processes, as well as the identification of potential bottlenecks and cause-and-effect relationships. Therefore, in conclusion, the concept of selective KPIs is selected as a basis.

3.2. Strategic performance attributes

Within the concept of selective KPIs strategic performance attributes (SPAs) and operative performance attributes (OPAs) are to be determined. SPAs refer to the competitive advantages of a manufacturing company to create a long-term differentiation from the competition to enable economic success. They thus represent a strategic differentiation factor from the customer's point of view. OPAs are used to identify potential bottlenecks, problems in the strategy realization and to control their potential risk [12]. The SPAs have a long-term validity and focus, while the OPAs are short-term and can thus be adjusted more frequently.

The identification of companies' critical success factors as SPAs is a key research field of empirical success factor research [4]. The results of the research are subsequently analyzed regarding their applicability in integrated production and maintenance planning. Furthermore, the analysis examines the target system of Wiendahl [25] for production planning and control and the formal targets for maintenance by Biedermann [26], which are widely used in literature.

Manufacturing companies pursue the sustainable maximization of profit by selling products to customers. The competitive advantage must relate to a performance characteristic, which is relevant for the customer [4]. Furthermore, it must be actually perceived by the customer and must not be quickly overtaken by competitors [4].

Alcalde Rasch [4] defines, based on a literature review, costs, time, quality and flexibility as strategic success factors. However, costs of a manufacturing company are not directly perceived by the customer, but the price of a product. In today's buyer markets, however, the price of a product is defined by the market and therefore, cannot be significantly influenced by the integrated planning. Nevertheless, costs are an important aspect for manufacturing companies to achieve a competitive advantage [27]. Companies, which produce products with lower costs are able to offer them over the long-term at lower prices. Wiendahl [25] defines that logistics costs are evaluated by process costs and capital commitment costs. Therefore, the company can achieve a competitive advantage from considering set-up, manufacturing, inventory and logistic costs. They are to be considered as productions costs in the integrated planning. Biedermann [26] differentiates for maintenance between direct and indirect maintenance costs. Personnel costs are especially relevant for direct costs. Indirect maintenance cost arise as a result of losses in the production volume due to failures/stoppages of a manufacturing system resource.

Time as a strategic success factor must be distinguished into time regarding the development of new products and technologies and time regarding the customer demand fulfillment for existing products [28]. Only the time demand fulfillment can be significantly influenced by integrated production and maintenance planning. Time regarding the customer demand fulfillment is defined by Wiendahl [25] as logistics performance with (short) delivery times and (high) delivery reliability. Companies have focused on gaining competitive advantages by shortening the throughput and delivery times [28]. However, this time advantage only generates a benefit for the customer, if the products are made available on the desired delivery date. From the customer's point of view, the delivery time and the delivery reliability are perceived decisively [28].

Quality can be distinguished between product quality and the quality of the processes [4]. The quality of a product is mainly determined by product development and not by the manufacturing system. While measures to ensure quality of processes are part of quality management, for an integrated planning the quality of the performance processes needs to be considered implicitly by backlog costs. From the customer's point of view, a delay occurs when an amount of products is not delivered on time. From the perspective of production planning a backlog of products occurs and can cause costs. For maintenance planning, the quality of processes is mapped by carrying out measures on time. Consequently, delay costs must be considered when a deviation from the planned time for a maintenance measure occurs. The backlog costs for production and maintenance also refer directly to the delivery reliability of the SPA time.

Flexibility refers to the adaptation of a manufacturing system to realize different output quantities using the existing resources of the system. Kaluza [29] distinguishes between real and dispositive flexibility. Real flexibility includes qualitative and quantitative adaptability in the areas of personnel, technologies, work organization structure and technical relationships. Dispositive flexibility refers to the ability to adapt planning and control. Integrated production and maintenance planning can ensure allocation of products to resources using existing capabilities and ensure the availability and reliability of the resources of the manufacturing system to enable the adjustment of the output quantities of the products. Measures to increase reliability lead to a reduction in losses due to downtime and speed and consequently to an increase of the availability. Availability of resources leads to the flexibility of accepting short-term customer orders and adapting the output quantities. As a result, integrated planning takes volume flexibility into account.

3.3. Operational performance attributes

The operational implementation of the strategy of a manufacturing company cannot only fail due to the disregard of the targets, but also due to unexpected problems within the manufacturing system [12]. According to Weber [12], KPIs on the operational level serve to identify and effectively manage the monitoring of performance. Therefore, the potential bottleneck areas of the manufacturing system must be identified by the PMS. The potential bottleneck areas of a manufacturing system are: critical efficiency drivers, potentially critical developments and critical performance bottlenecks [12]. This structure can be transferred to the PMS for integrated planning and will be further elaborated in the following paragraphs.

In order to measure the contribution to the economic success of both functions, production and maintenance, as well as to be able to identify and monitor changes within the manufacturing system, KPIs for each function must be integrated. However, the potential bottlenecks of a manufacturing system depend on company-specific conditions and can change continuously due to adaptions in the manufacturing system. Consequently, rather than defined KPIs for the PMS, lists of possible KPIs for production and maintenance planning are provided in table 1 and table 2, respectively. The selection of KPIs as OPAs for each class of potential bottleneck areas is carried out in workshops by a management team of the manufacturing company using AHP. The AHP for KPIs is described in [30]. Note, that the lists are not exhaustive and contain the most widely used KPIs for production and maintenance according to [5, 31, 32]. Therefore, these lists can be extended to company-specific KPIs.

Table 1. List of possible KPIs as OPAs for production

Class of potential bottleneck areas	KPIs for production
critical performance bottlenecks	quality rate, availability, capacity utilization, number of products rejected by quality control
critical efficiency drivers	performance efficiency, production quantity/capacity, inventory, actual/planned production
potentially critical developments	alteration in downtime, downtime costs, alteration in cycle time

Table 2. List of possible KPIs as OPAs for maintenance

Class of potential bottleneck areas	KPIs for maintenance
critical performance bottlenecks	error rate; mean time between failures (MTBF), mean time between repair (MTBR), response time
critical efficiency drivers	mean time to repair (MTTR), number of measures completed/planned/unplanned, cost compliance of measures, period-specific maintenance expenses
potentially critical developments	alteration in downtime, alteration in work backlog, maintenance-related under-performance rate

3.4. PMS for an integrated production and maintenance planning system

Within the final step of the formulation of the PMS for an integrated production and maintenance planning system based on the concept of selective KPIs, the deducted SPAs and OPAs as well as the interdependencies between the attributes need to be analyzed [16]. The OPAs monitor the performance of the manufacturing system and need to be linked to the strategy in order to secure the successful implementation of the SPAs. The link secures the alignment of the processes and achievements with the corporate strategy and enables the usability of the PMS throughout the entire company [33].

The objective of minimizing production and maintenance costs can be achieved operationally by e. g. monitoring performance efficiency and period-specific maintenance expenses. Performance efficiency in production is the comparison of actual performance to the target performance of produced products. Reductions in the performance efficiency result from idle times, downtimes and reduced production speed and therefore, lead to reduced production quantity. As a result, the shortfall must be compensated by additional set-up processes and production shifts, which result in additional production costs. The period-specific maintenance expenses can e. g. serve to monitor long-term maintenance costs, which need to be in compliance with the maintenance budget. High period-specific expenses can therefore be used as an early indicator of high maintenance costs.

Delivery times of products in a manufacturing system are influenced by production and set-up times and can be minimized in the planning process. However, if a resource is down, the production process cannot be carried out. Therefore, an increase in downtime can indicate possible delays of orders at an early stage.

The work backlog for maintenance is a KPI of the needed number of working hours of maintenance in the manufacturing system. An increase in the work backlog indicates an overload of the maintenance resources, which can lead to delayed executions of measures. The alteration in the work-backlog can therefore anticipate long-term negative developments in maintenance reliability.

Delivery reliability can e. g. be monitored by the quality rate. A low quality rate indicates production process errors, which can lead to losses in the production quantity and rework and thus to the late completion of orders. Therefore, alteration in downtime aligns with the objective of low delivery time.

Availability is defined as “the probability that the production resource will be encountered in a functioning condition at a certain point in time [26]”. Malfunctions and downtime reduce the availability and as a result, they stand in the way of volume flexibility to produce short-term orders from customers. General negative effects of high availability on flexibility cannot be identified.

The resulting PMS with the exemplary KPIs for SPA and OPAs is illustrated in figure 1.

4. Industrial case study

The PMS for integrated production and maintenance planning has been prototypically applied in a manufacturing system for household appliances. For reasons of confidentiality, all information presented is anonymized. The plant is subdivided into the departments of manufacturing, assembly, supply chain and maintenance. The manufacturing department consists of different production lines that produce components for assembly. The maintenance planning department plans maintenance measures for all production lines and carries out technical and administrative processes.

For the verification of the PMS structure, the selection of the OPAs and the analysis of the interdependencies between SPAs and OPAs in the plant, workshops were held with the management of production and maintenance.

Within the first step of the proposed concept, the bottlenecks of the manufacturing system were identified. The bottlenecks are two presses that manufacture sheet-metal parts, which are incorporated into each product. Production planning creates the schedule for the presses based on the known demand of the assembly line. The presses and tools are subject to the wear and tear of the production process and need to be maintained. Maintenance measures of the tools are carried out in an area for toolmaking.

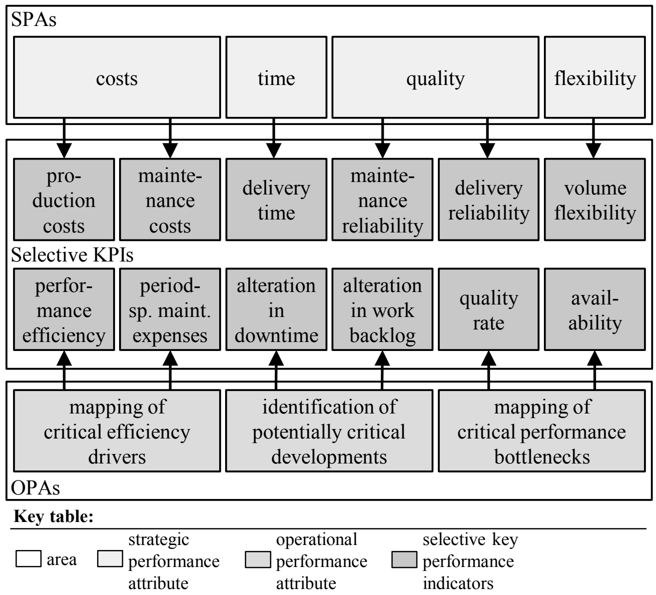

Fig. 1. PMS for integrated production and maintenance planning

The planning process of production and maintenance is currently carried out separately, which leads to efficiency losses, high inventory costs and delayed maintenance measures for the presses and tools.

In the second step, the presented lists of possible KPIs for each class of potential bottleneck areas were discussed and for the efficiency drivers, critical developments and performance bottlenecks KPIs were selected by the management using AHP for the prioritization. The selected KPIs are the KPIs seen in figure 1. It was found that performance efficiency, availability and quality rate, as parts of the overall equipment effectiveness, provide information for production and maintenance planning. Furthermore, as an alternative KPI for critical efficiency drivers to period-specific maintenance expenses, the cost compliance of measures was found useful by management. An alternative to the alteration in work backlog in maintenance can the maintenance-related under-performance rate be, since it is a KPI for the efficiency and effectiveness of maintenance.

Furthermore, the calculation of each KPI for the PMS was defined. For example, as production costs for products p, machines m and equipment e the costs for set-up, manufacturing, logistic, inventory and backlog are to be considered within the PMS for integrated production and maintenance planning (see eq. 1).

$$costP = costSet + costMan + costLog + costInv + costBlog \quad (1)$$

$$costSet = \sum_{p \in P} \sum_{m \in M} \sum_{e \in E} (cSet_{pme} * aSet_{pme}) \quad (2)$$

$$costMan = \sum_{p \in P} \sum_{m \in M} \sum_{e \in E} (cMan_{pme} * aMan_{pme}) \quad (3)$$

$$costLog = \sum_{p \in P} (cLog_p * aLog_p) \quad (4)$$

$$costInv = \sum_{p \in P} (cInv_p * aInv_p) \quad (5)$$

$$costBlog = \sum_{p \in P} (cBlog_p * aBlog_p) \quad (6)$$

In eq. (2) setup costs are calculated as the sum of the cost of a setup and the amount of setups. Manufacturing costs are the sum of the manufacturing amount and the costs for each product (see eq. (3)). In eqs. (4), (5), (6) the costs are calculated as the sum of the amount and costs for each product for logistic, inventory and backlog, respectively.

In addition to the presented PMS and as a result of the workshops, management developed a deeper awareness of the dependencies between production and maintenance as well as the necessity to control the efficiency of the resources of the manufacturing system.

5. Summary

Manufacturing companies are required to improve production and maintenance effectiveness through a mutual consideration of both functions in an integrated planning process. To monitor the performance of manufacturing systems, to quantify the efficiency and effectiveness of actions and to identify the need for measures and adapting plans, a PMS for integrated production and maintenance planning is needed. Therefore, a PMS for integrated production and maintenance planning based on the concept of selective KPIs is developed. The applicability is validated by an industrial case study. The PMS jointly considers production and maintenance and considers strategic performance attributes and monitors potential bottleneck areas of the manufacturing system. Furthermore, the PMS enables to analyze the dependencies and interrelationships between production and maintenance planning in manufacturing systems and supports to make the contribution of maintenance to the economic success of manufacturing companies transparent.

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