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An Approach Towards an Adaptive Quality Assurance

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Abstract

In order to optimize the quality-related costs, the quality assurance within the production must be designed in terms of economical criteria. This design is time-consuming and cost-intensive. However, due to the increasing individualization up to lot size one, the quality assurance must be adapted in increasingly shorter cycles in order to achieve an economical optimal quality assurance at any time. The realization of an adaptive quality assurance within the production enables manufacturing companies to achieve a minimum of quality-related costs at any time despite an increasing individualization up to lot size one. Due to their high degree of swiftness regarding data acquisition, data processing and output of data in real-time, and furthermore, their capability to control physical elements with computer-based algorithms in an intertwined way, cyber-physical systems (CPS) are predestined to perform an adaptive quality assurance within the production. But, no approach towards an adaptive quality assurance, which is performed by a cyber-physical system in order to achieve a minimum of quality-related costs at any time despite an increasing individualization of manufactured products up to lot size one, has been described in literature yet. This paper fills the gap by showing an approach towards an adaptive quality assurance within the production, which is performed by a cyber-physical system.

1. Introduction

Increasing globalization and growing scarcity of resources are leading to a rising cost pressure within manufacturing companies. To face this challenge, measures to reduce costs are essential. The enhancement of resource efficiency within the production represents one possible measure. This enhancement can be achieved through the elimination of wastes. According to the Japanese engineer Taiichi Ōno, the wastes which occur within the production can be subdivided into seven categories: Overproduction, Waiting, Transporting, Over-processing, Inventories, Moving, Making defective parts and products [1]. Faulty actions within the production are leading to the last mentioned category of wastes (“Making defective parts and products”). Typical examples for this category of wastes are scrap, replacement production and rework [2]. The effort of nonconformity represents the assessed consumption of services and goods caused by faulty actions [3]. The monetary effects of the effort of nonconformity are summarized under the term failure costs, which can be subdivided into internal and external failure costs [4,5]. Internal failure costs arise due to the effort caused by failures which are detected within the company, whereas external failure costs incur because products fail to conform to requirements after being delivered to the customer or fail to satisfy the customer [6,7]. According to a previous calculation, internal failure costs had an amount of around 11 Billion Euro in German electrical and mechanical engineering companies in 2014 [8].

The application of quality improvement approaches and methods (e.g. Six Sigma, TPM, 5S, FMEA) is a possible measure to reduce failures within the production. Processes, which are repetitive and automated can be optimized up to zero defects, but within processes performed by workers, faulty actions which are leading to failures can occur at any time. Therefore, failures can only be reduced and cannot be avoided completely.

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Faulty units which are not detected and reach downstream production stages lead to an increasing effort of nonconformity and therefore cause further costs.

On the one hand, quality control steps, which are implemented between two consecutive production stages in order to detect faulty units before they are transferred to downstream production stages, can enable the reduction of the effort of nonconformity and as a consequence lead to decreasing failure costs. On the other hand, these quality control steps are leading to an additional use of resources (e.g., quality personnel, test equipment) which in turn leads to further costs. These costs are termed appraisal costs and arise from the effort caused by quality control steps [7].

In order to achieve an optimal level of quality-related costs, within the inspection planning, production planners have to design the quality assurance within the production in terms of economical criteria by deciding about the implementation of quality control steps between production stages.

The economical savings depending on the arrangement of quality control steps within the production have already been evaluated. This evaluation is based on a sample process sequence including several production stages and different scenarios concerning the error rate of production stages. The maximum possible economical savings of internal failure costs and appraisal costs, compared to the situation that (except of a final inspection and testing step) no quality control steps are implemented, amounts 12.9 percent and in addition, the average of maximum possible economical savings of the different scenarios amounts 7.0 percent [9].

These results highlight the importance of the arrangement of quality control steps within the production from an economical point of view. However, inspection planning within the production in terms of economical criteria proves difficult and causes a high effort due to the high number of influence quantities. In order to face this challenge, a decision-making support methodology to achieve an economical optimal solution concerning whether or not a quality control step should be implemented between two consecutive production stages has already been developed [10]. This methodology can be easily applied, provided that specific parameters (e.g., error rate of different processes, cycle time of different processes) are available and valid for each processed unit.

Commonly, the inspection planning within the production takes place in an iterative way based on empirical values. Hence, this approach is both time-consuming and cost-intensive.

The trend of increasing individual customer demands, which leads to an increasing individualization of manufactured products up to lot size one, impacts the production due to rising product variants significantly, because the higher the number of product variants, the higher the number of process variants is [11]. Furthermore, the rising number of process variants leads to an increasing probability of faulty actions which are leading to failures within the production.

Despite Fords quote “We believe […] that no factory is large enough to make two kinds of products” [12], the amount of product variants and therefore also the amount of process variants is growing continuously. As an example, for the BMW 5 series, 18 different variants of painting, 17 different variants of fabric resp. leather upholstery and 17 different variants of engines are selectable in each combination [13].

As a result of rising process variants, the economical optimal design of the quality assurance differs from product variant to product variant. Moreover, the quality assurance must be adapted in increasingly shorter cycles in order to achieve a minimum of quality-related costs at any time. The realization of an adaptive quality assurance within the production enables manufacturing companies to achieve this at any time despite an increasing individualization.

Due to their high degree of swiftness regarding data acquisition, data processing and output of data in real-time, and furthermore, their capability to control physical elements with computer-based algorithms in an intertwined way, cyber-physical systems (CPS) are predestined to perform an adaptive quality assurance within the production.

According to a definition of Lee, cyber-physical systems are integrations of physical processes and computation, whereby the physical processes are monitored and controlled by embedded computers as well as networks. Characteristically, physical processes affect computation and vice versa with the usage of feedback loops. [14]

Cyber-physical systems can be found in a wide spectrum of domains such as critical infrastructure control like electric power, traffic management, environmental control, smart buildings, etc. [15]

Based on the research of Drath, Siepmann developed a general structure for cyber-physical systems which consists of three levels [16,17]:

- Level 1: Physical Objects (e.g. tooling machines, 3D-printers)
- Level 2: Data Storages (e.g. documents, 3D-models)
- Level 3: Service Systems (e.g. algorithms, evaluations)

Within level 1 (Physical Objects), the data acquisition takes place. Level 2 (Data Storages) acts as an interface and transfers data between level 1 and level 3 (Service Systems), in which the data are processed. The processed data is transferred via level 2 as control data to level 1. [17]

The cyber part is represented by level 2 and level 3. [16]

Compared to common automation systems, cyber-physical systems enable the connectivity globally via the internet [18].

This is very important when it comes to the quality assurance because in many manufacturing companies the production and therefore also the quality assurance within the production takes place at different facilities around the globe.

There are several challenges which have to be considered when it comes to the testing of adaptive systems. These challenges have been already discussed by Siqueira et al. [19] and Eberhardinger et al. [20].

2. Need for Action

Various approaches for the optimization of the inspection planning have already been well described in literature. Overviews are given by Zhao [21] and Shevtan [22]. Further studies are dealing with quality issues in mass customization [23,24]. Moreover, Fogliatto et al., highlight, that the adaption
of “traditional quality control schemes to single-unit production lots” is an important issue in research [25].

However, there is still a lack of knowledge when it comes to the inspection planning within a production up to lot size one in terms of economical criteria. More specifically, there is no approach towards an adaptive quality assurance, which is performed by a cyber-physical system in order to achieve a minimum of quality-related costs at any time despite an increasing individualization of manufactured products up to lot size one, described yet.

In order to deal with this issue, scientists from Bayreuth developed such an approach.

3. Requirements

In this section, the three major requirements, which have to be considered within the development of the approach, are shown and discussed in detail. The first major requirement represents the achievement of minimum quality-related costs, which is purposed by the approach because it is an overall goal of the quality management in manufacturing companies.

The second and the third major requirement ensure the novelty of the approach. As mentioned below, there is a trend to an increasing individualization of manufactured products up to lot size one which leads to the challenge, that it is mandatory to designed the inspection plans in even shorter times.

The applicability for multi-stage productions which are distributed around the globe represents the third major requirement for the approach. These requirements are explained in more detail in the following which leads to sub-requirements.

3.1. Achieving the minimum quality-related costs

First of all, the requirement, that a minimum of quality-related costs is achieved at any time, must be considered within the development of the approach towards an adaptive quality assurance. For quality-related costs, hereinafter also referred to as quality costs, various quality cost models are described in literature. A common quality cost model is Feigenbaum’s PAF (Prevention – Appraisal – Failure) model [26]. Within this model, the quality costs are subdivided into prevention costs, appraisal costs and failure costs [27,28]. Prevention costs are the costs which arise from the effort to prevent failures from being made (e.g. costs for quality-related trainings, costs to perform a Failure Mode and Effect Analysis) [29]. As already mentioned in the introduction, failure costs can be subdivided into internal failure costs and external failure costs [4,5]. The amount of the aforementioned categories of quality costs per unit depends on the quality level. Within the PAF model, the economical optimal quality level represents the quality level with the lowest total quality costs, which are equal to the sum of the prevention costs, the appraisal costs, the internal failure costs and the external failure costs.

As mentioned before, within processes performed by workers, faulty actions which lead to failures can occur at any time and furthermore, the rising number of process variants lead to an increasing probability of faulty actions which are leading to failures. Therefore, the economical optimal quality level is somewhere between 0 percent and 100 percent.

In the course of time, further quality cost models were developed. Crosby subdivides quality costs into costs of conformance and costs of nonconformance [30,31,32,33]. Costs (or price) of nonconformance arise when processes fail to conform to requirements (e.g. correction, rework, scrapping) [31].

Compared to the costs of conformance, the costs of nonconformance are avoidable as well as unpredictable and thus, can only be estimated [34].

Examples for further quality cost models are opportunity or intangible cost models and activity-based costing [31,33].

According to results of a survey which was carried out by Schiffauerova and Thomson, the PAF model is most commonly deployed in enterprises [31].

Consequently, the approach must aim at achieving minimum quality-related costs and due to the various quality cost models described in literature and also deployed in different enterprises, the approach must be developed in order to ensure the applicability for different quality cost models.

3.2. Applicability for production with a high amount of process variants up to lot size one

An additional requirement, which must be considered within the development of the approach towards an adaptive quality assurance, is the applicability of the approach for productions with a high amount of process variants up to lot size one. As already mentioned in the introduction, the trend of increasing individual customer demands leads to and increasing individualization of manufactured products which impacts significantly the production, due to rising product variants and therefore due to rising process variants [11].

Because of this high and still increasing amount of variants, the approach must be applicable for the manufacturing of several product variants but especially for the manufacturing of unique, custom-made products.

Moreover, because a product variant can be a combination of different features, it must be taken into consideration, that these features may occur repeatedly despite different product variants. Summarizing, a high degree of flexibility is necessary. This can be fulfilled by the deployment of cyber-physical system due to its swiftness.

3.3. Applicability for multi-stage productions which are distributed around the globe

Furthermore, the applicability of the approach for multi-stage productions which are distributed around the globe must be ensured. Based on the number of production stages, productions can be subdivided into single-stage productions and multi-stage productions [35]. The approach towards an adaptive quality assurance, which is performed by a cyber-physical system, has to aim at achieving minimum quality-related costs at any time by deciding about between which
production stages an implemented quality control step is economical useful.

Furthermore, production systems can extend over various facilities located around the globe. Therefore, it is crucial that the developed approach is applicable for multi-stage productions which are distributed around the globe.

4. Approach Towards an Adaptive Quality Assurance

In this section, the developed approach is described. Finally, different benefits of the developed approach are pointed out. The development took place under consideration of the aforementioned requirements.

4.1. Procedure of the adaptive quality assurance

The procedure of the adaptive quality assurance is shown in Fig. 1 and described in the following.

Before the unit is being processed at the first production stage, the value of the raw-unit is stored into the unit-database. This data can, for example, derive from the company's ERP (Enterprise Resource Planning) System, which is connected to the company's purchasing department. The unit-database is a set of data designated to one single unit and extended with further data during the production.

In the next step, the unit is processed within the first production stage. The process data (e.g. cycle time, costs per hour) and as a result of these process data, the value, which is added to the unit within the processing, are stored into the unit-database triggered by the worker after the unit is processed. This is done after each process step which makes the quality assurance adaptive. Hence, the increasing value of the unit is logged.

Then, it is decided whether a quality control step is economical useful at the current stage. For this decision, the already mentioned decision-making support methodology to achieve an economical optimal solution concerning whether or not a quality control step should be implemented can be applied in case that the PAF model is deployed. For other quality cost models, this decision-making support methodology must be adapted. This decision-making support methodology is described in detail in [10].

The data which are needed for this decision (e.g. error rate of the previous (upstream) and next (downstream) production stage) are read out from both the unit-database and the quality-related-database. The quality-related-database comprises quality-related data like error rates of the production stages or test durations for the inspection of different characteristics. These are historical data based on previous activities. The quality-related-database is extended with further data continuously.

It is important to mention, that the quality-related data varies from product to product, but for some characteristics like diameters of drilled holes or coating thicknesses, they are comparable and can be used for future produced units. However, the comparability of different characteristics must be checked carefully.

In case, that no quality control step is economical useful, it is checked whether the last processed production stage represents the final production stage. If this is not the case, the unit is transferred to the next (downstream) production stage, whereby the previous mentioned procedure is repeated.

Otherwise, in case, that a quality control step is economical useful, an inspection plan indicating the characteristics which have to be inspected is generated and output by an output device (e.g. a screen directly mounted on the workspace) visible to the employee. This inspection plan is generated based on the results of the previous determination whether a quality control step is economical useful. Following this step, the unit is inspected according to the inspection plan using quality control equipment (e.g. caliber, feeler gauge) which is available at the workstation. The quality-related data of the inspection within the quality control are stored into the quality-related-database as well as into the unit-database in order to achieve a high degree of traceability which can be used for example in case of warranty claims.
If the inspected unit does not fulfill the quality requirements, the unit is discarded. A possible rework of these units is not yet taken into consideration within this paper but can be appended to the procedure easily.

If the inspected unit fulfills the quality requirements, it is checked whether the last processed production stage is the final production stage.

If the last processed production stage is not the final production stage, the unit is transferred to the next (downstream) production stage, whereby the previous mentioned procedure is repeated again.

Otherwise, if the last processed production stage is the final production stage, the final test is performed. The final test is important in order to ensure that no faulty unit is delivered to the customer. Quality characteristics which have already been inspected must not be inspected for a second time. Therefore, before the final test is performed, the unit-database is read out in order to determine which characteristics still have to be inspected and which characteristics have already been inspected. Based on this determination, an inspection plan indicating the characteristics which have to be inspected is generated and output. Finally, the quality-related data of the inspection within the final test are stored into the quality-related-database as well as into the unit-database.

4.2. Structure of the cyber-physical system

In the following, the developed structure of the cyber-physical system, which performs the presented procedure of the adaptive quality assurance, is described.

As mentioned previously, according to Drath and Siepmann, a cyber-physical system consists of three levels [16,17]. This three-part division serves as the basis for the structure of the cyber-physical system for an adaptive quality assurance within the production. The structure is shown in Fig. 2.

![Diagram of the structure of the cyber-physical system](image)

Fig. 2. Structure of the cyber-physical system (based on [16,17]).

Level 1 (Physical Objects) consists of technologies for the acquisition of process data of each production stage (e.g. cycle time, unit which is being processed) and the acquisition of quality-related data (e.g. error rates of the production stages or test durations for the inspection of different characteristics). For this context, these data can be collected for example with pressure sensors or RFID (radio-frequency identification) technology. Moreover, level 1 consists of technologies to output the information whether or not a quality control step is economical useful as well as to output the generated economic optimal inspection plans which includes information regarding the characteristics which have to be inspected.

Level 2 (Data Storages) consists of the databases described previously (Quality-related-database and unit-databases).

Level 3 (Service Systems) consists of algorithms and methodologies to process data like to determine whether or not a quality control step is economical useful. The transmission of data between the levels bases on the structure of Siepmann, described in the introduction [17].

Due to the global connectivity, cyber-physical systems enable to transmit data around the globe and therefore enable the applicability for multi-stage productions which are distributed around the globe. Furthermore, the swiftness of cyber-physical systems is beneficial for the increasing amount of product variants due to its high degree of flexibility.

4.3. Benefits

The developed approach towards an adaptive quality assurance which consists of the described procedure as well as of the structure of the cyber-physical system has different benefits, which are pointed out in the following.

First of all, the approach represents a basis for the further development of an adaptive quality assurance within multi-stage productions which are distributed around the globe in order to achieve a minimum of quality-related costs at any time despite an increasing individualization of manufactured products up to lot size one. Furthermore, an implemented adaptive quality assurance minimizes the effort within the inspection planning in manufacturing companies by designing the quality assurance within the production in real-time. Moreover, the approach ensures that it can be applied for different quality cost models. The strict storing of process data and quality-related data for each manufactured unit ensures a high degree of traceability which can be used for example in case of warranty claims. Last but not least, the stored data can be utilized for the cost accounting within manufacturing companies.

5. Conclusion and Outlook

This paper shows a novel approach towards an adaptive quality assurance which aims at achieving minimum quality-related costs at any time despite the trend of an increasing individualization of manufactured products up to lot size one. As this paper shows an early stage of the adaptive quality assurance, there are several topics for future research in order to develop the adaptive quality assurance further. As part of future research, the possibility to rework units which do not pass the quality control step will be developed. Moreover, the approach will be refined with mathematical-based decision supports and extended to a holistic procedure of an adaptive quality assurance for a common quality cost model. Once, this holistic procedure is developed, it will be validated by case
studies in an industrial environment. Last but not least, the data gathered in the data bases can be used for the statistical process control and, in turn to increase the process quality.

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