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# Function-Oriented Quality Control Strategies for High Precision Products

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**Abstract**

Companies are confronted with increasing product quality requirements to manufacture high quality products, close to technological limits, in an economic way. The implementation of adaptive quality control strategies (QCS) in production offers an approach to cope with this challenge. In this paper, new function-oriented QCS by means of selectively assembling multiple components are demonstrated based on a functional product model. The implementation of QCS for fuel injector systems, which must fulfil narrow tolerances regarding the product's functionality, show benefits in quality and cost-effectiveness. In the approach a functional model of the product and a simulation of the production system are implemented.


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*Keywords:* Assembly, Tolerancing, Quality Assurance

## 1. Motivation

Product quality is a rising requirement on behalf of producing company's customers: Technological production limits are reached, especially for high precision products with narrow tolerances of several microns and overall products size of few millimetres. High requirements occur especially within the automotive, medical and machinery and equipment industry. Herein, precision requirements trend towards narrow ranges in order to realize highly accurate and performant functions with an optimal degree of efficiency [1], [2], [3].

Technologically immanent process deviations make it impossible to manufacture components which permanently meet high quality requirements. Often the issue of a cost-efficient precision product realization is a conflict of objectives in manufacturing and assembly processes. On the one hand the objective is to save production cost with high throughput under higher deviations and on the other one preventing a high number of scraped units with more narrow tolerances under higher capabilities but lower throughput. Ultimately, the technological limits of the manufacturing processes are reached, producing cutting-edge products.

Designers tend to tighten tolerances in order to assure the necessary product function, although this could be accompanied by undesired interactions. Tolerance allocation decisions can profoundly impact the quality, the cost of the product and the share of scrap parts in mass production [4]. It is important to focus on value-adding steps in order to decrease production costs. Different types of waste like over processing, scrap, rework and storage affect the production cost and have to be minimized. Inline-control of quality features in real-time is one approach to detect errors at an early stage in production systems and prevent unnecessary value creation of defective components. [5], [6]

## 2. State of the Art

Existing tolerance allocation methods consider equal geometrical dividing, dividing to equal manufacturing capabilities or dividing to manufacturing related cost functions, e.g. [7], [8]. Few approaches include a simulative assessment of the functional fulfilment using components with inherent manufacturing deviations, e.g. [9], [10], [11], [12]. Their common aim is to assure the functional fulfilment of the product through

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optimal tolerances and appropriate prior design [13], [14], depending on the quantitative functional interaction between product characteristics, as well as process capabilities.

If manufacturing cost increase enormously or required tolerances exceed the technological manufacturing limits, the application of real-time adaptive production strategies in the production, compensating manufacturing deviations on an organisational level, offer new possibilities for cost-efficient high precision product realization. [1], [15], [3] Technological developments of "Industrie 4.0", such as sensors for traceability, as well as, sensors for precise inline measurement within lead time [16], [17], enable the adaptive production strategy application for intelligent, robust and economic production strategies beyond the manufacturing limits (see Fig. 1) [18].

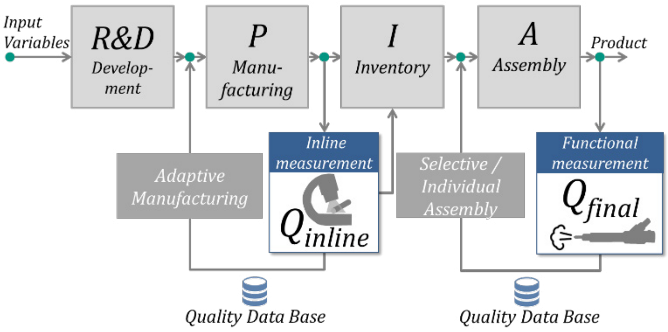


Fig. 1. Quality-based control cycles for cost-efficient precision production

Thus, geometrical and form deviations can be compensated within the assembly to a certain level through over-fulfilment of different geometrical and form characteristics in real-time (selective / individual assembly) [1], [12] Surplus parts of quality critical, associated product components can be prevented by adapting manufacturing processes in combination with the aforementioned selective assembly strategy to quality critical processes (statistical adaptive / individual manufacturing). The application of assembly and manufacturing strategies within the production, have been shown for the combination of multiple simple interdependences of characteristics. More narrow tolerance margins and a decrease of the overall production cost can be realized in comparison to conventionally assembled components [1], [5], [3], [19], [20], [21], [22]. A framework was introduced in [1], identifying the most promising and industrially relevant strategy combinations.

However, often precision products consist of several subsystems with sub-functions, interacting with the main functions of the product. Mostly, each of the sub-functions are dependent on several component characteristics, sometimes even interdisciplinary and on microscopic level, with increasing quality requirements due to rising functional demands. As a result, rising quality requirements are allocated by the designers to assure the functions. Fluctuating functional fulfilments of the subsystems, due to manufacturing deviations of relevant characteristics, lead to a high scrap rate and rising overall production cost of recent high-precision serial products. Compensating quality-critical process deviations for multiple component characteristics in quantity, type and interdisciplinary subsystems, e.g. mechanical, electrical and hydraulic systems, all affecting the productions functionality, have not been studied yet. Up to now, no possibility for a cost-efficient production of high-precision serial products is developed. In summary, it can be found that currently there is no research approach dealing with function-oriented adaptive quality control strategies (QCS) which considers the following aspects:

- Simultaneous tolerances allocation of components combined with adaptive production strategy methods
- Quantitative function dependencies between multiple diverse product characteristic deviations in the production, modelled probabilistically
- Real-time assessment of the product function in the production, based on inline measurements and functional product models
- Function-oriented assembly strategies for the individual compensation of assemblies with numerous diverse product characteristics
- Function-oriented manufacturing strategies for statistical compensation of diverse quality critical product characteristics

## 3. Research Approach

To overcome the aforementioned issues and limitations, a holistic research approach is presented in this article. Existing methods of tolerance allocation are combined with control strategies of the production which brings together the functional design requirements, probabilistically modelled manufacturing and assembly deviations and inline inspection uncertainties in a common model (see Fig. 2). Effects of adaptive tolerance allocation and adaptive production strategies on design, manufacturing, assembly and product function performances are evaluated in a quality controller quantitatively. The approach enables the production of high-precision products by implementing function-oriented adaptive quality control strategies (QCS).

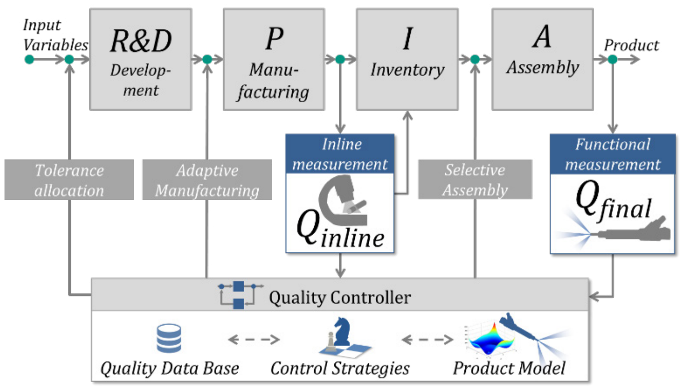


Fig. 2: Quality-based control cycles for robust and cost-efficient product design and production with functional product integration

The development of a functional product model enables the function-oriented integration of detailed product knowledge into the quality control strategies. Quantitative dependencies on manufacturing deviations affecting the functional fulfilment

of the products are contained to assess the introduced strategies with regard to technical and economic aspects.
The optimal strategy combination is identified by an assessment of technical and economic criteria. Detailed aspects of the approach are presented in the following.

### *3.1. Development of Functional Product Models*

A functional model of the interested product has to be developed in order to quantify manufacturing deviations of product characteristics to their degree of functional fulfilment. The functional model has to take the main effects of the manufactured characteristics and their deviations into account, realistically modelling complex interactions as well. Throughout, deviations of different product characteristic types can mutually compensate others, e.g. deviations of geometrical dimensions and electro-mechanical characteristics (e.g. of an piezoelectric crystal), dependent on their quantitative functional interactions.

A *finite elements simulation model* is used to model effects and relations of characteristic deviations to the functional fulfilment based on physical effects and subsystem responses. The aim is to recreate a functional relationship between components for a considered product. Interactions between manufacturing deviations, based on individual inspection data or probabilistic evaluations on manufacturing, are used to assess the technical functionality of the product in a quantitative way. The validation of the model can be done by appropriate functional product experiments under realistic conditions. Due to the high simulation effort, the finite element simulation is not suitable for real-time evaluation of product functionality. Therefore, a data-driven modelling approach can be used to derive the relevant interrelationships by reducing complexity. Statistical models and models of statistical learning can be used to provide a functional prediction in real time.

*Statistical models* of various manufacturing deviations and their degree of the functional fulfilment can be applied to model occurring results of the of the aforementioned finite element simulation. Suitable approaches are for example *classical statistical regression*, *multivariate adaptive regression splines* (MARS), *kriging* (Gaussian process regression) and *support vector regression* (using an appropriate kernel function). Simulation experiments under variation of characteristic deviations $X_i$ serve as input for the statistical model for each considered product function $Y_i$. Statistical design of experiments, for example, could serve as a tool to plan a minimal number of simulation experiments.

As an alternative, more elaborate approach, *statistical learning* techniques also can be suitable to model the functional relation between the manufacturing deviations of the real production and could be applied instead of the proposed statistical model approaches. They are particularly suitable, if a large data base is provided as a training data set (e.g. production data of the ramp-up or phase). A complex setup is given for which machine learning algorithms have been successfully applied in other domains [23], [24]. As one possible approach an *artificial neuronal network (ANN)* can be suitable for the present application (see Fig. 3).

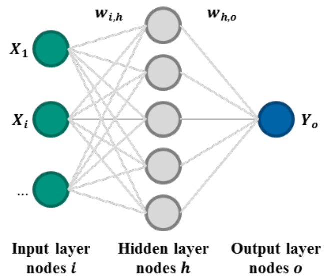


Fig. 3. Representation of ANN to model the functional relations of manufacturing deviations [15]

The ANN can be used as an elaborate, non-linear regression model between the manufacturing deviations and the degree of functional fulfilment. The weights $w_{i,h}$ and $w_{h,o}$ determine the parameters of the functional model. The manufacturing deviations are represented in the input layer $X_i$. After the learning phase, the algorithm can individually predict the degree of functional fulfilment of a product $Y_0$.
In order to consider the modelling quality of each approach, an analysis of the model adequacy is suggested. To determine the model uncertainty, various sources of uncertainty such as modelling error, space/time discretization, input parameter inaccuracies and linear algebra errors have be taken into account. [25] As a result, the appropriate approach for the application case can be identified to predict the product function in real time for production integration.

### *3.2. Function-Oriented Adaptive Quality Control Strategies*

Based on the gained functional product model, novel function-oriented QCS for multiple, interacting characteristics can be implemented in the quality controller. The functional product model then serves to predict the statistical and individual degree of product functional fulfilment by assessing the process capabilities or by individually selecting components in a virtual assembly process before the execution of the real assembly process.

From a statistical point of view, the functional product model can assess the recent production system capabilities. A probabilistic prediction of the functional fulfilment degree of the conventional produced products for is derived. Thereby, the manufacturing process capabilities and the functional product model are taken into account. Probabilistic process distributions with density functions $f_k(x_{P,k})$ of the manufacturing processes $D_k$ with the variates $x_{P,k}$ serve as deviation input quantities to numerically predict a functional fulfilment density function $f(y)$ modelled by the variates $x_{P,k}$, through weighted convolution subject to the gained functional product model function, e.g. from statistical regression with linear, $n$ degree polynomial (see equation 1). The weights are $M_k$ resp. $M_{ki}$. Hence, larger tolerances of expensive parts at lower process capabilities, for example, are statistically compensated through smaller tolerances of cheaper corresponding components at higher process capabilities, fulfilling the functional requirements all the time. Optimisation of process capabilities to a more pleasant combination is expected to enhance product quality and be more cost-efficient.

$$f(y) = M_0 + \sum_{k=1}^{n} M_k f_k(x_{P,k}) + \sum_{k,i}^{n} M_{ki}\, f_k(x_{P,k}) * f_i(x_{P,i}) + \ldots + M_{12\ldots n}\, f_1(x_{P,1}) * f_2(x_{P,2}) * \ldots * f_n(x_{P,n}) \quad (1)$$

Where the $*$ operation is the convolution, defined as:

$$f_k(x_{P,k}) * f_i(x_{P,i}) = \int_{-\infty}^{\infty} f_k(x_{P,k}) f_i(x_{P,i} - x_{P,k})\, dx_{P,k}$$

$$s.t.\ x_{P,k} = \frac{D_k - \overline{D_k}}{D_{k,max} - D_{k,min}}\ with\ x_{P,k} \in [0;1], \quad (2)$$

$$x_{P,i} = \frac{D_i - \overline{D_i}}{D_{i,max} - D_{i,min}}\ with\ x_{P,i} \in [0;1],$$

$\overline{D_k}$ resp. $\overline{D_i}$ is the mean of $D_k$ resp. $D_i$

From a point of view on the individual components, a novel matching criterion for selective / individual assembly is created based on the functional model. Through multi-criterial real-time optimization suitable function-oriented matches can be found, considering to assess all components individually available and needed for the product, with different interdisciplinary characteristics at the same time. An optimal component combination $ass_{a,i}$ of the currently available component measurements $m(co_{p,i})$ in the inventories $I_p$ is determined as a result (with $p=1, .., 4$; as different component types), taking available assembly sequences and information flows into account.

Furthermore, adaptive manufacturing strategies are enhanced by applying the statistical evaluation of the functional product model as well. Function-oriented, dynamic adaption of manufacturing parameters enables to react to corresponding quality critical processes drifting away. Thus, a high share of good assemblies can be assured through statistical compensation of corresponding component characteristics in combination with assembly strategies. Adequate reactions to the quality critical manufacturing deviation density function can be calculated by solving the mixed distribution problem (e.g. deconvolution) of the desired functional fulfilment density function with the. Deconvolution, as the inverse problem of the aforementioned convolution calculation, usually is to be solved numerically. The derived expectation value is then considered as the best nominal value for adaptive manufacturing.

Dynamic parameter set point adjustment of the manufacturing processes can be appropriate to prevent surplus parts in the selective assembly inventories, in case one manufacturing capability is significantly higher than the capability of the quality critical one. Appropriate set points for dynamical adaption of the manufacturing processes are suggested to calculate numerically via least square approach [26] and numerical deconvolution again, subject to the functional product model. The resulting distribution of the matching partner then is adapted to prevent surplus parts of the quality critical component, as far as possible. Process capabilities under varying set points are assumed to be constant over varying means. Thus, the overall capability of the resulting process deviations is decreased, but the corresponding matching partners to the quality critical component are provided in the inventories for selective / individual assembly strategies (see Fig. 4).

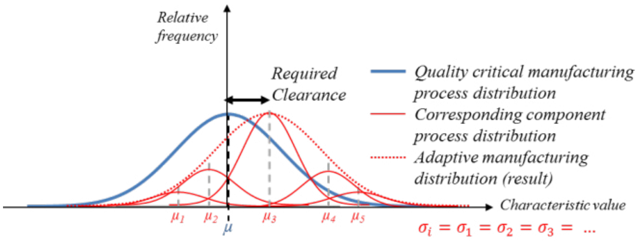


Fig. 4. Dynamically manufacturing adaption strategy: set point adjustment

### 3.3. Integrated Production Evaluation

The functional product model and related QCS are implemented in an integrated quality controller. An individual evaluation of the characteristics of product subsystems, with interdisciplinary characteristics for virtual preassembly evaluation is enabled in real-time. The quality controller then is integrated in a virtual twin of the real production system for discrete event-driven simulation of the present production system. Cause and effect relationships are modelled as realistic as possible through production-related characteristic information. In contrast to the afore introduced approaches [1], the recent quality controller is able to assess component combinations regarding their degree on functional fulfilment with more than two different characteristic types as well as the tolerance allocation in combination with adaptive production strategies. For each planning period $t$, the predefined QCS $s$ are evaluated and the technically and economically optimal strategy is selected, according to the approach in [1]. Previous production periods $t$-$1$ and their production-related information and quality inspections serve as simulation basis to assess the strategy optimum of period $t$. The relevant variables of the production system, such as inventory sizes $n_{s,p}$ and the numbers of classes $c_{s,p}$ (in case of selective assembly), are optimized in addition to the strategy. The overall objective is to minimize the occurring total production cost $C$, as in most cases it is the crucial performance indicator. Therefore, the objective is defined as:

$$min_{\Theta} C = min_s \left\{ \sum_{i=1}^{N_{eff}} C_P(\Theta) + C_Q(\Theta) + C_I(\Theta) \right\} \quad (3)$$

$C_P$ represents the production cost, including cost material, machines, labour and good assemblies, $C_Q$ the quality cost, including scrap cost of defective parts, and $C_I$ the inventory cost, referring to the components storage costs as well as opportunity cost in the inventories. All cost elements are accumulated within the required period to produce the ordered amount $N_{eff}$ of good assemblies. The decision variables $\Theta$ of the optimization problem are defined by:

$$\Theta = \begin{pmatrix} s \\ m \\ n_{s,p} \\ c_{s,p} \\ ass_{a,i} \end{pmatrix} \begin{matrix} s.t. & \\ s \in \{1;2;3\} & c_{s,p} \in [1;3;..2n_{s,p}] \\ m \in \{A;B;C\} & p \in \{1;2;3;4\} \\ n_{s,p} \in [1;n_{max,s,p}] & i \in \mathbb{N} \mid i \le N_{s,total} \end{matrix} \quad (4)$$

where $s$ is the assembly strategy, $m$ is the manufacturing strategy, $n_{s,p}$ are the inventory sizes and $c_{s,p}$ the number of classes, into which these are divided within selective assembly. Only impair class numbers are in industrial use, preventing bimodal component distributions in the inventories. The inventories are restricted by the maximum technical limits $n_{max,s,i}$. $ass_{s,i}$ are the realizations of the $N_{s,total}$ assemblies totally mounted by strategy $s$. Considered assembly strategies $s$ are:
(1) conventional (no selective assembly),
(2) selective assembly (with classes),
(3) individual assembly (no classes).
Considered manufacturing strategies $m$ are:
(A) conventional manufacturing,
(B) statistical adaptive manufacturing,
(C) individual manufacturing.

## 4. Use Case

Together with an industrial manufacturer, the research approach is studied in an exemplarily use case regarding the production system of a high-pressure injector for combustion engines in passenger cars and light utility vehicles. The product consists of several high-precision subsystems, related to different disciplines, such as mechanics, mechatronics and fluid mechanics. The principle of the indirectly controlled piezo injector is introduced in [27] (see Fig. 5).

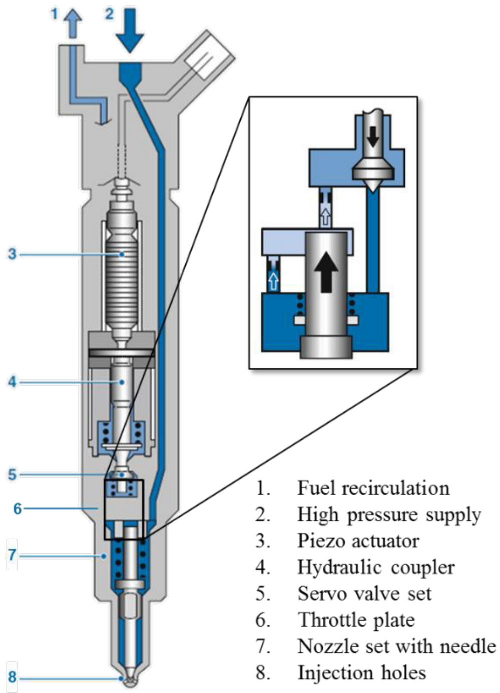


Fig. 5. Product Principle of the high pressure injector, cp. [27]

All subsystems of the product, such as *piezo actuator*, *servo valve*, *throttle plate* and *nozzle set*, all affect its general function of *injection* significantly. Functional quality requirements of the injection are the defined injection of a precise fuel volume with sub-millilitre tolerance, within few milliseconds, at more than 270 MPa fuel pressure. The product has to meet both challenges, high precision in volume portioning and high-dynamic control, with up to five injections per cycle to meet performance and efficiency requirements. [27]

The indirect fluid control of the product are the throttle plate and servo valve set subsystem functions. Little geometrical or form deviations in the range of a few micrometres already upset the flow rate equilibrium. High-precision control of the injector in such cases is no longer possible. Thus, high quality requirements are assigned to the relevant interdisciplinary characteristics to assure the product functionality of each subsystem. However, the technological limits of the manufacturing processes are reached, providing parts at such high quality requirements in order to produce a high yield. The production volume results in a comparatively high percentage of scrap, leading to an increase of the production cost.

An exemplary production system model of the industrial use case is illustrated in Fig. 6 consisting of four process chains, two as manufactured parts and two as supplied parts. The final components are joined in assembly stations ($A_1$, $A_2$, $A_{final}$) to the final product. Without loss of generality, the process chains of the mainly relevant component characteristics can be considered as single manufacturing processes each. Economic 100% inline inspections, e.g. using optical sensors or functional fluidic measurements, enable to assess the individual quality of each component and the final product at the end of the line ($Q_1$, $Q_2$, $Q_3$, $Q_4$, $Q_{final}$). After the inline inspections $Q_1$, $Q_2$, $Q_3$, $Q_4$ the inventories $I_1$, $I_2$, $I_3$, $I_4$ are located, in which components can be stored according to the QCS randomly, in classes or individually trackable.

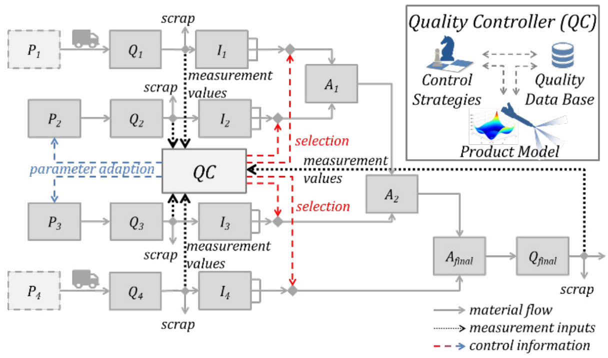


Fig. 6. Model of considered quality controller with functional model integration

The measurement uncertainty of inline inspection sensors is modelled according to previous uncertainty analysis, where *m(v),* the observed measurement value of the nominal characteristic value $v$, considers the measurement uncertainty $u$ as well. Thus, the impact of the measurement uncertainty of the inspection equipment on QCS decisions can be assessed.

It is assumed that the process capabilities of in-house manufactured part processes, $P_2$ and $P_3$, are equal or higher than those of the delivered part processes $P_1$ and $P_4$. Throughout, an adaption of the in-house manufacturing processes, shifting the relevant nominal dimension values of $P_2$ and $P_3$, can be considered as possible control variables. The assembly of few components within subsystems is already realized through selective assembly, resulting in increased product quality.

However, the complex functional interactions of all function-affecting subsystems and their functional deviations are not evaluated quantitatively yet. Thus, quality control cycles for the assembly of suitable subsystems are not implemented.

Hence, the integration of a quantitative functional product model, enabling function-oriented quality control strategies of tolerance allocation and adaptive production strategies, seems to be a promising approach for cost-efficient production of high-precision products. Therefore, the approach of data driven functional product models integrated into the production is currently being pursued with application to the injector system. A functional model is to be derived in order to predict the yield for the actual production line. The overall objective is to reduce the percentage of rejects. This means a reduction in production cost for the industrial manufacturer.

## 5. Summary and Outlook

In this article, a method for the real-time optimization of function-oriented adaptive quality control strategies based on a functional product model, quality controller and inline measurements is presented. The implementation of the functional product model into the production provides fundamental concepts to produce cost-efficient high-precision products in competitive markets. Therefore, the product functions affected by manufacturing deviations and the related production cost are considered in optimization. New function-oriented quality control strategies combining tolerance allocation with production strategies are promising, reaching the desired functional requirements with a cost-efficient production. Further research will be carried out on the basis of the use case presented to elaborate and validate the approach.

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