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Functional process adjustments to reduce No-Fault-Found product failures in service caused by in-tolerance faults

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ABSTRACT

This paper presents a methodology to determine optimal process adjustments, which prevents manufacturing products from falling into in-tolerance fault regions (a subset of No-Fault-Found events) taking into consideration product and process adjustments constraints. The proposed methodology utilizes the design relationship between KPCs and KCCs to determine process functional adjustments. The methodology is illustrated through three product and process design configurations, uncoupled, decoupled and coupled.

1. Introduction

Increasingly, manufacturing complexity of product and process coupled with high pressures to deliver products have resulted in various unexplored interactions among different phases in Product Lifecycle Management (PLM). These unexplored interactions may result in products malfunctioning in the field causing warranty and/or service problems. These problems negatively affect customers' requirements in terms of safety, dependability and satisfaction, and contribute to increased lifecycle cost [1].

In many cases products' tests at service center may not discover any fault and a No-Fault-Found (NFF) event is recorded [2]. The NFF phenomenon is a major problem when dealing with complex products and contributes on average to 45% of reported service faults in electronic equipment; up to 50% for aerospace industry [3]; 63% of the faults in cell phone manufacturers [4]; and more than 50% in automotive industry [5].

In general, some of the NFF's root causes include the erroneous characterization of Customer Attributes, Key Product Characteristics (KPCs), Key Control Characteristics (KCCs) and product utilization modes during early design stages; misdiagnosis of complex interactions between the KPCs and KCCs during design and manufacturing stages; as well as in utilization stage—changes in customer requirements and/or expectations, reliability deficiencies, and/or unpredicted KPCs changes.

A number of NFF events cannot be predicted at final product inspection during manufacturing or even diagnosed after the failing product is tested in service center because all KPCs are within designed tolerances. Such failures are classified in this paper as in-tolerance product failures and are a critical sub-set of NFF events [2]. Several researchers have reported on the existence of NFF caused by in-tolerance product failures in manufacturing of electronics, cell phones, aerospace and automotive components, resulting in enormous losses to industries [1–6]. The presence of in-tolerance failure regions for a given product(s) affects the Taguchi's quality loss function which can result in higher cost due to the increased warranty related product failures. The comparison of modified loss function $L(y)$ with standard quality loss functions are shown in Table 1.

The two main challenges associated with in-tolerance NFF product faults are: (i) identifying root cause(s); and (ii) determining a corrective action plan to eliminate and prevent the fault. Mannar et al. [6] developed the Functional Region Localization (FRL) methodology to identify the in-tolerance fault regions and suggested to avoiding these regions by re-evaluating the KPCs tolerances.

The FRL approach is expanded by proposing a methodology for *functional capability analysis* to identify optimum position of product (KPCs) mean, called "functional nominal" (FN), which minimizes desired products fallout rate in the case of products with field (service) failures that occur within design tolerances (in-specs) in [7]. The proposed functional capability analysis for the defined FN is conducted in KPC-coordinate system and does not provide information on how to adjust the process, which is represented in KCC-coordinate system. The adjustment procedure in KCC-coordinate system to attain FN in KPC-coordinate system is referred as *functional process adjustment* (FPA).

The two main challenges associated with obtaining FPA are: (1) the existence of a complex relationship between KPCs and KCCs which may lead to ill-conditioned problems; and (2) the existence of product and process constraints to perform the necessary process adjustments to reach the FN. This paper develops a methodology for selecting an optimum subset of KCCs which allow to adjust in-tolerance NFF product faults described in the KPC domain. The selected KCCs are used to identify process FN in KCC domain which will eliminate the identified in-tolerance product NFF faults.

The identification of FN in KCC-coordinate system involves the following steps: (1) identify and isolate in-tolerance fault region(s) that cause NFF problems in KPC-coordinate system; (2) identify product FN in KPC-coordinate system ($\mathbf{y}_f$) that minimize products fallout rate caused by NFF failures; and finally, (3) determine the

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Nomenclature

FPA	functional process adjustment
$\mathbf{y}_f$	functional nominal (FN) in KPC-coordinate system
$\mathbf{y}_d$	design nominal in KPC-coordinate system
$\mathbf{u}_f$	functional nominal (FN) in KCC-coordinate system
$\mathbf{u}_d$	design nominal in KCC-coordinate system

FPA in KCC-coordinate system ($\mathbf{u}_f$) taking into consideration all product and process adjustments constraints. The outline of methodology is depicted in Fig. 1.

The rest of the paper is organized as follows: Section 2 reviews current methodologies to determine the functional nominal (FN) in the KPC domain. The proposed methodology for functional process adjustment in the KCC domain is illustrated in Section 3. In Section 4 the proposed methodology is demonstrated through several case studies and numerical simulations. Finally, conclusions are presented in Section 5.

2. Determination of the functional nominal (FN) in KPC-coordinate system

This section describes an approach to determine the FN in the KPC domain based on the localization of in-tolerance NFF-region.

2.1. In-tolerance NFF-region in KPC domain

Identification and localization of the in-tolerance NFF-region in KPC domain uses the approach proposed in [6] and is based on the enhanced rough set approach to link warranty/service failures data with manufacturing measurements. This approach allows identifying relevant KPCs variables related to the in-tolerance NFF failures. It can also identify the in-tolerance NFF fault region within the original KPCs tolerance window. This can help to avoid service/warranty failure(s) through design changes and/or tolerance revaluation. This revised tolerance space is used to determine FN in KPC-coordinate system as presented in the next subsection.

2.2. Functional nominal in KPC-coordinate system

The in-tolerance NFF-region obtained is used to identify FN in the KPCs coordinate system ($\mathbf{y}_f$). The $\mathbf{y}_f$ represents mean location that is equidistant from the boundaries of the NFF-region and tolerances. It ensures the least probability of overlap between the process distribution of KPCs with NFF and the tolerance regions (Fig. 2). The FN is identified by translating the estimated process distribution of KPCs (represented by the ellipse in Fig. 2, and estimated based on KPCs' measurements using a predefined

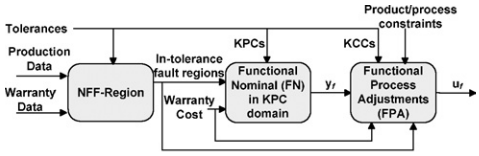


Fig. 1. Flow diagram of the FPA methodology.

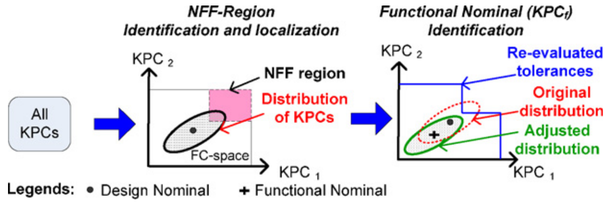


Fig. 2. Functional nominal (FN) in KPC domain.

confidence level, e.g., 95%), within the re-evaluated tolerance space to reach a nominal that minimizes the overlap with failure regions without exceeding the tolerance boundaries.

While determining the $\mathbf{y}_f$, we assume that the distribution remains constant and independent of its location in the KPC space. The $\mathbf{y}_f$ is determined based on minimization of Warranty Cost (WC) which represents the losses per shift. The WC is calculated as the sum of associated costs with each NFF-region and out-of-tolerance region. The cost associated with each specific NFF-region is determined based on the overlap of the KPCs distribution and the NFF-region multiplied by the unitary cost wc_i associated with ith NFF-region as presented in the following equation:

$$WC = \sum_{i=1}^{q} (\varphi \cap r_i) \times wc_i + (\varphi \cap o_t) \times wc_{o_t} \qquad (1)$$

where q is the number of identified NFF-regions within the KPCs tolerance, $vol(\varphi \cap r_i)$ represents the volume of overlap between the production distribution of KPCs measurements φ and either a failure NFF-region r_i or an out-of tolerance (o_t) region.

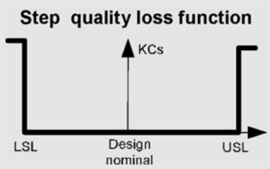
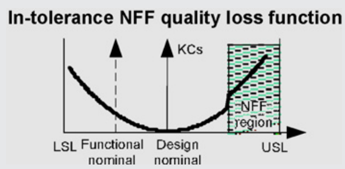
3. Determination of the functional process adjustments in KCC-coordinate system

Functional process adjustment requires mapping the FN from KPC ($\mathbf{y}_f$) to KCC ($\mathbf{u}_f$) domain, where the physical adjustment will take place. The $\mathbf{u}_f$ can be determined based on the product/process model linking KPCs and KCCs as shown in Eq. (2) and explained in Section 3.1.

$$\text{KPCs} = f(\text{KCCs}) \Rightarrow \text{KCCs}_f = f^{-1}(\text{KPCs}_f) \qquad (2)$$

Examples of process flow diagram showing mapping of information from different domains of PLM is presented in Fig. 3. The KPCs measurements in manufacturing are obtained

Table 1
Comparative analysis of quality loss function.

Figures			
Model	$L(y) = \begin{cases} 0 & y \le USL \wedge y \ge LSL \\ C & \text{else} \end{cases}$ where c is constant	$L(y) = ay^2$ where a is constant	$L(y) = \begin{cases} ay^2 + WC & \text{if } y \in \text{failure region} \\ ay^2 & \text{else} \end{cases}$ where WC is loss due to in-tolerance NFF product failure
Description	All products are acceptable inside the specification limit Cost function is determined based on expected rework cost	Loss increases as the products KPCs spread away from design nominal Cost function is determined based on design evaluation related to performance	Loss function have regions with high cost due to NFF failure region Cost function is determined based on warranty and service information
Example	Out-of-tolerance product failures: product rejection or rework is determined based on "crisp" tolerance threshold(s).	Six-sigma/variation related product failures: product performance is affected by variation.	In-tolerance No-Fault Found (NFF) product failures: products field performance is affected by unmodeled and unknown KPCs and KCCs interactions

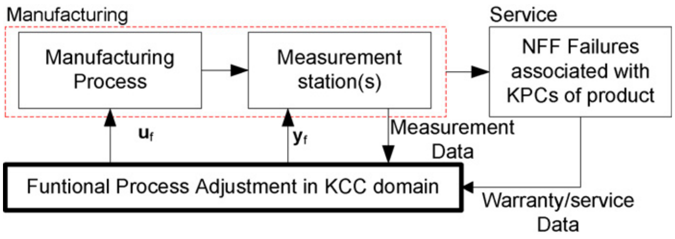


Fig. 3. Process diagram of proposed FPA methodology.

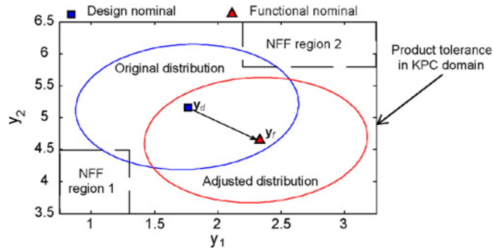


Fig. 4. Initial and final distribution in KPC space.

by off-line or in-line measurement gages located at the end-of-line or as distributed sensor systems [6,9]. The measurements obtained are used for product inspection and process control to ensure that all KPCs ($\mathbf{y}_i$) are within their tolerances. This measurement data are usually stored in manufacturing databases associated with product ID to ensure the traceability of the product.

The process of determining the $\mathbf{u}_f$ is more challenging than just calculating the inverse of the function $f(.)$ as shown in Eq. (2). The challenges are due to the fact that for many manufacturing processes function $f(.)$ is non-invertible (ill-conditioned system), and there exists product and process constraints which restrict the KCCs adjustments. Such constraints are caused by limited process flexibility/reconfigurability as well as safety requirements restricting the adjustments of some of the process variables (KCCs). Eq. (3) presents the generic formulation to determine the FN in KCC-coordinate system ($\mathbf{u}_f$).

$$\mathbf{u}_f = \min_u \|\mathbf{u} - f^{-1}(\mathbf{y}_f)\| \quad \text{s.t.}\ \mathbf{u} \in \text{feasible region} \tag{3}$$

The following subsections describe how to determine the relationship between KPCs and KCCs and the proposed methodology to solve Eq. (3).

3.1. Relationship between KPCs and KCCs

The relationship between the KPCs and KCCs explained by function $f(.)$ (Eq. (2)) can be identified analytically or experimentally. For example, in automotive body assembly process function $f(.)$, called assembly response function or stream-of-variation [8]. In this paper, it is assumed that this function exists for a given manufacturing process and it is linear. The linear relationship between KPCs and KCCs can be shown as

$$\mathbf{y} = \mathbf{D}\mathbf{u} + \boldsymbol{\varepsilon} \tag{4}$$

where $\mathbf{y} \in \Re^m$ is the output vector with m number of KPCs measured on the product, the input vector $\mathbf{u} \in \Re^n$ contains the n number of KCCs used in the process, matrix $\mathbf{D} \in \Re^{m\times n}$ is the manufacturing process characterization matrix, and vector $\varepsilon \in \Re^m$ represents all modelling errors and measurement noises.

3.2. Determination of functional process adjustments in KCC domain

The FN determination in KCC domain ($\mathbf{u}_f$) depends on the structure of matrix **D**. Table 2 classifies methods to determine the $\mathbf{u}_f$ based on the dimensions, internal structure and invertibility of matrix **D**, and the presence or absence of constraints. Table 2 also includes the characterization of the KPCs–KCCs relationship following the axiomatic design principles [10].

Case 1: **D** is a square ($m = n$), diagonal and non-singular matrix (uncoupled design). For this case the solution ($\mathbf{u}_f$) is obtained by calculating the inverse of matrix **D**. For cases involving product and process constraints, $\mathbf{u}_f$ can be obtained by solving Eq. (5) using constrained least squares (CLS) techniques [11].

$$\mathbf{u}_f = \min_{\mathbf{u}} \|\mathbf{D}\mathbf{u} - \mathbf{y}_f\|_2 \quad \text{s.t.}\ \mathbf{u} \in \text{feasible region} \tag{5}$$

There exist several numerical algorithms to solve Eq. (5) depending on the characteristics of the constraint functions (equalities, inequalities or quadratic forms) [11]. These algorithms can efficiently determine the solution of the constrained problem. If the constraints do not fit into any of the aforementioned categories, then Eq. (5) can be solved using the Enhanced Piecewise Least Squares (EPLS) method [12]. This approach enhances the traditional Partial Least Squares method by incorporating any type of constraints in the formulation. Compared with CLS algorithms the EPLS may not be as computationally efficient; hence, it is suggested that the CLS algorithms are utilized as a first choice.

Case 2: **D** is a square ($m = n$), triangular and non-singular matrix (decoupled design). Again, the $\mathbf{u}_f$ for decoupled design involving no constraints can be obtained using the inverse of **D** matrix. If constraints are present, then CLS or EPLS can be used.

Case 3: **D** is a square ($m = n$) neither triangular, nor diagonal and non-singular matrix (coupled design). For unconstrained case, $\mathbf{u}_f$ is calculated using inverse of matrix **D**. For constrained cases, the $\mathbf{u}_f$ can be obtained using CLS or EPLS.

Case 4: **D** is a square ($m = n$) neither triangular, nor diagonal and singular matrix (coupled design). Since the **D** matrix is singular, the LS approach is insufficient to obtain the $\mathbf{u}_f$. The solution based on the LS approach tends to be inflated when systems are singular leading to imprecise results [11]. The pseudoinverse of matrix **D** can be used to solve singular problems without constraints [11]. In cases where constraints are present, the EPLS method can be used as it can properly deal with singular matrices [12].

Case 5: **D** is a rectangular ($m \neq n$) matrix, does not have a predetermined structure and is non-singular. This kind of structure is most common for manufacturing processes and it is known as redundant design. For this case, in the absence of constraints, the $\mathbf{u}_f$ can be obtained by solving Eq. (3) using the LS solution as presented in Eq. (6) [11]. If there are constraints present, then either CLS or EPLS can be used.

$$\mathbf{u}_f = (\mathbf{D}^T\mathbf{D})^{-1}\mathbf{D}^T\mathbf{y}_f \tag{6}$$

Table 2
Analysis of methods to obtain $\mathbf{u}_f$ based on the classification of matrix **D**.

Matrix **D**			Methods to obtain FN ($\mathbf{u}_f$)	
Structure	Singularity	Classification [10]	Unconstrained case	Constrained case
$m = n$ (square matrix)				
Diagonal	**D** non-singular	Uncoupled design	Inverse of matrix **D**	C LS or EPLS
Triangular	**D** non-singular	Decoupled design	Inverse of matrix **D**	C LS or EPLS
Neither triangular nor diagonal	**D** non-singular	Coupled design	Inverse of matrix **D**	C LS or EPLS
Neither triangular nor diagonal	**D** singular	Coupled design	Pseudoinverse	EPLS
$m \neq n$ (rectangular matrix)				
Any structure	$\mathbf{D}^T\mathbf{D}$ non-singular	Redundant design	LS	CLS or EPLS
Any structure	$\mathbf{D}^T\mathbf{D}$ singular	Redundant design	Pseudoinverse	EPLS

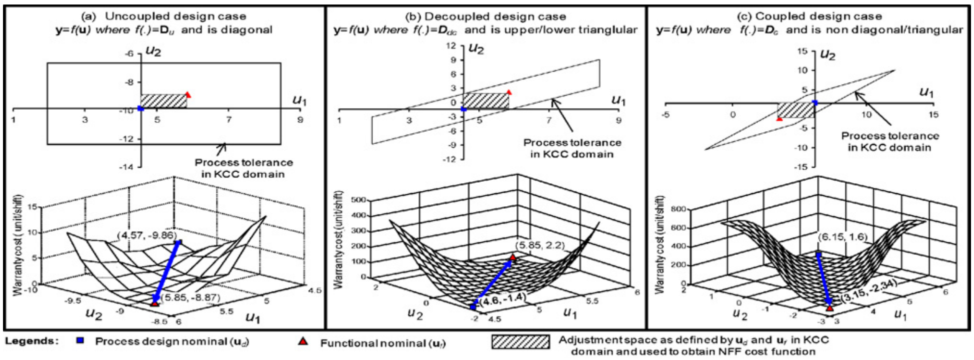


Fig. 5. NFF cost function in KCC-coordinate system.

Case 6: $\mathbf{D}$ is a rectangular ($m \neq n$) matrix that does not have a predetermined structure and matrix $\mathbf{D}^{\mathrm{T}}\mathbf{D}$ is singular. In this case EPLS or pseudoinverse methods can be used depending on the presence or absence of constraints.

4. Case studies and numerical simulations

The proposed methodology is illustrated by numerical simulations based on the modified Taguchi quality loss function as shown in Table 1, for different product design scenarios, i.e., uncoupled, decoupled and coupled. For visualization purposes the simulations are conducted considering a system of 2 KPCs and 2 KCCs where, KPCs represents the product measurements and KCCs are the process variables controlling the manufacturing process such as for example, fixtures locating parts.

The failure regions are identified by combining the service warranty data with manufacturing. In this paper, failure regions are simulated based on results from Mannar et al. [6] for cell phones where failure regions represent warranty issues evaluated through functional requirements (FRs). The prominent warranty issues in cell phone industries leading to in-tolerance failure regions are: audio, transmission, battery, and display defects. Similarly, the warranty issues leading to in-tolerance failure region in automotive manufacturing are excessive wind noise, squeaks/rattles, gap/flushness variations of closure panel & other.

For comparison, the different design cases are assumed to have the same KPCs and failure regions as presented in Fig. 4. This figure also includes the initial distribution (95% confidence ellipse) centred at the initial design nominal $\mathbf{y}_d = (1.75, 5.17)$ in the KPC domain.

Following the procedure described in Fig. 1, the $\mathbf{y}_f$ is identified by minimizing the overlaps with in-tolerance failure region and out-of-tolerance regions. In this case study, it was assumed that the warranty costs per product failed in NFF-regions 1 and 2 and the out of tolerance are 1, 1.5 and 2 units, respectively. The FN in KPC domain is identified as $\mathbf{y}_f = (2.25, 4.65)$ as shown in Fig. 4.

The 2×2 matrices used to relate the KPCs with KCCs for the uncoupled, decoupled and coupled scenarios are $\mathbf{D}_u = [0.38, 0; 0, -0.52]_{2\times2}$, $\mathbf{D}_{dc} = [0.38, 0; 0.97, -0.52]_{2\times2}$, and $\mathbf{D}_c = [0.38, -0.38; 0.97, -0.52]_{2\times2}$, respectively. The process design nominal ($\mathbf{u}_d$) and functional nominal ($\mathbf{u}_f$) in KCC-coordinate system for the three analyzed cases is shown in Fig. 5. Fig. 5 also shows the process tolerance region in KCC-coordinate system constrained by the product design.

The warranty cost for the three analyzed design cases is shown in Fig. 5 for the highlighted region. The figures present the total loss per shift associated with different parameter selection of KCCs such as fixture location. The simulation is performed with constant production rate of 320 products per shift. These figures demonstrate how warranty cost reduces as the manufacturing process is adjusted from the original $\mathbf{u}_d$ to the desired $\mathbf{u}_f$ (Fig. 5). The asymmetry of the warranty costs figures is due to in-tolerance failure regions warranty costs differences. For the case of the coupled design the costs on the extremes are too high and they tend to saturate because of the distribution incursion into the out-of-tolerance region. Fig. 5 presents a summary of the results from the three cases. The warranty cost at process nominal is 2.7 unit/shift. However, all of the warranty costs associated with FN have turned out to be 0 unit/shift (Fig. 4) causing a distribution to not overlap with either the in-tolerance fault regions or the out-of-tolerance space.

5. Conclusions

This paper presented a manufacturing process adjustment to eliminate warranty related No-Fault-Found (NFF) product failures in the field when all Key Product Characteristics (KPC) measured are within design tolerances (in-tolerance). The proposed methodology determined product and process *functional nominals* (FN) (in KPC and KCC-coordinate systems, respectively) to minimize process fallout rate caused by field (service/warranty) in-tolerance product NFF failures. The process FN in KCC-coordinate system is used for manufacturing process adjustment. The methodology integrates service/warranty data with manufacturing measurement, and existing model of relationship between KPCs and KCCs, known for some processes as Assembly Response Function or Stream-of-Variation model. The paper discusses identifying functional process adjustments for various KPC/KCC relationships classified as uncoupled, decoupled, coupled and redundant design models with and without constraints.

The proposed methodology is numerically verified for three different designs, i.e., uncoupled, decoupled, and coupled designs. The results show that the suggested process adjustments can potentially reduce events of NFF failures thereby resulting in minimizing warranty costs associated with NFF failures. However, the improper selection of FN in KCC-coordinate system can lead to considerable losses either because of high product failure in field or rework in manufacturing.

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