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Toward meaningful manufacturing variation data in design – feature based description of variation in manufacturing processes

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Abstract

The need to mitigate the effects of manufacturing variation already in design is nowadays commonly acknowledged and has led to a wide use of predictive modeling techniques, tolerancing approaches, etc. in industry. The trustworthiness of corresponding variation analyses is, however, not ensured by the availability of sophisticated methods and tools alone, but does evidently also depend on the accuracy of the input information used. As existing approaches for the description of manufacturing variation focus however, almost exclusively, on monitoring and controlling production processes, there is frequently a lack of objective variation data in design. As a result, variation analyses and tolerancing activities rely on numerous assumptions made to fill the gaps of missing or incomplete data. To overcome this hidden subjectivity, a schema for a consistent and standardised description of manufacturing variation is suggested. It extends existing ISO GPS annotation by information about influences on the manufacturability of a chosen design solution and in this way enables the systematic acquisition of variation data meaningful for design practice.

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Keywords: Robust Design; Process Cabalitiy; Manufacturability, Tolerance; Manufacturing Variation database

1. Introduction – manufacturing variation in design

To meet the increasingly stringent quality requirements as well as to continuously improve productivity, every company is facing the challenge of manufacturing variation. Summarised by the universal axiom [1] of:

Manufacturing imprecision: All manufacturing processes are inherently imprecise and produce parts that vary.

The variation of produced parts requires companies to invest significant time, effort and cost in quality-related activities to detect non-conforming parts and prevent them reaching the market. These visible variation-related costs are however just the tip of the iceberg! What lies beneath are the internal, hidden consequences for an organisation. They arise when manufacturing variation is not addressed systematically but mitigated by numerous inefficiencies built-in to business procedures, production processes as well as designed parts.

Despite the indisputable achievements of production-focused quality initiatives, such as Total Quality Management, Lean Manufacturing or Six Sigma widely adopted since the early 1980s, many manufacturing companies consequently still experience a variety of variation-related quality-costs. High safety factors, late design changes, excessive inspection processes, high scrap rates, etc. are unfortunately seem to be still prevalent in industrial practice [2], largely determining a the competitiveness of manufacturing companies.

Nomenclature

C_p, C_{pk}	exemplary process capability indices
CAE	Computer Aided Engineering
GPS	Geometric product specifications
GD&T	Geometric dimensioning and tolerancing
GMσD	Global manufacturing variation database
KC	Key characteristics
PCDB	Process Capability Database

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In light of the above, there is nowadays little disagreement that an early consideration of inevitable manufacturing variation in already during design is conducive to success. In the last decades, this insight has led to the emergence of a number of quality-oriented design methodologies, e. g. Design for Manufacture and Assembly, Design for Six Sigma or Robust Design, as well as to a wide adoption of sophisticated methods and tools for the analysis and the virtual verification of chosen design solutions [3, 4]. In a comprehensive variation management procedure, product features whose expected deviations from nominal result in an unacceptable loss, so called product key characteristics (KCs), are identified and incorporated in a variation model [4, 5], which then allows to accommodate variation up front by means of statistical analyses or tolerance optimizations using Computer Aided Engineering (CAE) tools.[1]

Despite the availability of guiding procedures as well as corresponding methods and tools, there are however two key challenges for a systematic variation analysis. Even if the wide range geometric features, dimensions, material properties, etc. is systematically reduced to a manageable set of relevant KCs, a (CAE-based) variation analysis still requires *complete and accurate data on manufacturing variation* as well as *a homogeneous description of manufacturing variation* (usually a full statistical description for all considered input parameters) [6].

While most of academic literature on modeling techniques, statistical simulations, etc. assumes these conditions, this assumption is far from the reality in industrial practice [7]. The main reason is that existing approaches for the description of manufacturing variation almost exclusively focus on the control of production quality and were not conceived for design purposes [4, 5, 7]. Although the variation of a function-relevant KC is, in some cases heavily, affected by the arrangement of adjacent features, materials, etc., this manufacturability of a chosen design is therefore neither well understood nor taken into account systematically. For a new product, the knowledge which is essential for an accurate description of the expected variation is instead only available from key engineers and thus thinly dispersed across the different departments involved. As a result, many variation analyses follow largely individual procedures and rely mostly on a subjective assessment. Particularly the application of CAE tools is often based on numerous estimations to fill the gaps of missing or incomplete data as illustrated in Fig. 1. This leads to a *hidden subjectivity* of many analyses in practice and a risk of late and disruptive design changes when a suboptimal design is passed over to production.

To enhance the credibility of (CAE-based) variation analyses and to overcome the above described *hidden subjectivity*, this contribution suggests a schema for a consistent description of manufacturing variation. The aim is to systematically extend existing approaches towards a structured and standardized description, not only of the KC under consideration, but also all other parameters which have

[1] e. g. well-know and widely adopted tolerancing software such as 3DCS (www.3dcs.com), CETOL 6σ (www.sigmetrix.com), RD&T (www.rdnt.se) etc.

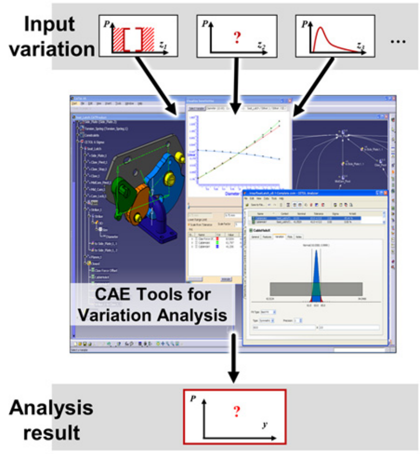

Fig. 1. Relevance of input information for variation analyses (picture of CAE tool adopted from http://www.sigmetrix.com/)

an essential influence on a part's manufacturability and thus the manufacturing variation to expect. The schema's purpose is consequently to offer guidance for the acquisition of objective variation data in existing production lines which can then be used for design purposes, i. e. as surrogate data set for improved variation analyses and tolerancing activities in future development projects.

The remainder is organized as follows. The background of this research, i. e. available approaches for the description and communication of manufacturing variation, is presented in section 2. Afterwards, Section 3 concisely summarises the aim and four basic premises for the conceptualisation of a schema which allows for a consistent description of manufacturing variation and is illustrated by means of a non-functional example part in section 4. Concluding, the potential of the schema is discussed in section 5.

2. Background – description of manufacturing variation

A coherent strategy to manage and communicate manufacturing variation between the different involved departments is a fundamental building block of every manufacturer's quality assurance activities. Three different, widely adopted approaches are described, namely *Geometric Tolerancing* for a specification of tolerable variation, generic information on the achievable production performance provided in *Standards and Guidelines* as well as the creation of *Process Capability Databases* (PCDBs) offering knowledge about specific manufacturing processes,.

2.1. Geometric Tolerancing

Gaining popularity since the 1990s, the concept of geometric tolerances is nowadays commonly accepted and widely adopted, particularly in large companies. Lead by international working groups, the system for geometric tolerances (terminology and approaches) has been continually refined and standardized over the last decades to offer a stable mean enabling design engineers to unambiguously dimension and tolerance all geometric features. The corresponding ISO GPS standards [8], the ASME GD&T annotation respectively [9], establish consistent protocols that can be universally understood and in this way enable a simplified communication between stakeholders as well as a better understanding of design solutions in terms of variation.

It has to be noted though, that the use of geometric tolerances follows a largely unidirectional procedure [4]. Focusing on the specification of individual geometric features, existing tolerance symbols enable designers to explicitly document the nominal geometry as well as the allowable variation, e. g. in engineering drawings or CAD tools. This design documentation is then passed over to production and metrology as basis for manufacturing operations as well as for all quality assurance activities.

Contrarily, neither GPS nor GD&T standards offer a consistent protocol which allows a flowback of information to design as illustrated by the example in Fig. 2. While the circularity symbol can for example be used to specify the required accuracy of all round parts, e. g. of the switch's cylindrical features, it is likely that manufacturing processes show a (significantly) different variation when producing cones, spheres, etc. instead.

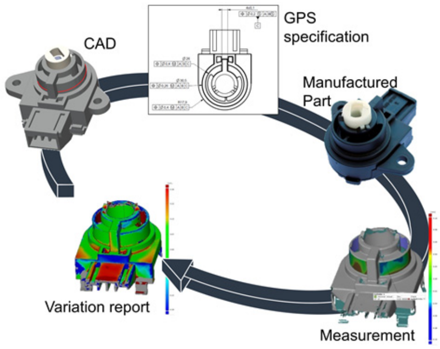

Fig. 2. Sequential procedure of specifying and verifying the tolerable variation of geometric features by means of GPS/GD&T tolerances

2.2. Standards, guidelines on manufacturing variation

In practice, the obvious limits of geometric tolerances laid out in the previous section frequently have a decisive impact on design and tolerancing activities. The absence of objective information on the achievable manufacturing accuracy encourages designers to rely, in some cases exclusively, on simplified tolerance guides. Examples are general or industry sector specific standards [e. g. 10, 11], guidelines for the choice of manufacturing processes [12] as well as company-internal tolerance guidebooks.

While all of these documents can serve as a first rough orientation, there are various drawbacks. The example of *"Standards and Practices for Plastic Molders"* published by the society of the plastic industry illustrates a subset of them, see Fig. 3. While most of the available documents focus exclusively on dimensional tolerances, the moulding guidelines extend this information slightly. However, guidance on geometric tolerances is still very limited as only the achievable flatness of the walls as well as the concentricity of the cylindrical features are described. Moreover, the given information is largely product-specific and the dependency on other characteristics, such as the dependency of the achievable tolerance window on the size of the geometric feature [12], is neglected completely.

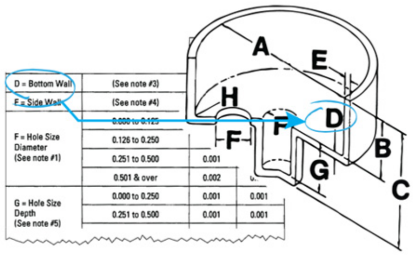

Fig. 3. Available tolerance guidelines for injection moulding processes (picture adopted from [11])

2.3. Use of Process Capability Databases

In an attempt to overcome the frequently insufficient information about expected manufacturing variation, several authors in academic as well as in industry literature suggest the generation of process capability databases [4, 6, 13, 14, 15], hereinafter referred to as PCDB. The basic idea is to capture and centrally store data from existing production lines and to use this information as a surrogate for an evaluation of the expected manufacturing performance in the future. Usually based on commonly adopted process capability indices, such as C_p, C_{pk} values, the aim is to provide a support tool for variation analyses and tolerance allocation activities. However, although these benefits of PCDBs for designers have been addressed in earlier research [7, 13, 14], the adoption of existing (proprietary) database solutions seems to be limited to production control purposes so far [7].

To foster the adoption of PCDBs in design practice, literature points out a number of key barriers for their implementation [4]. Particular importance is usually assigned to the database structure, most notably the indexing scheme which defines how the acquired data is referenced in a PCDB. As a diversity of product characteristics, process parameters, external influences, etc. affects the final manufacturing variation, it is a critical success factor which largely defines the quality and the accessibility of data pertinent to a particular design and corresponding production conditions as well as the trade-off between data specificity and costs for data acquisition and data management [4, 7, 14].

At the same time, the authors would like to argue that surprisingly many of previously written publications largely neglect the complexity of this task. The few exemplary indexing schemes available in literature [e. g. in 4, 14] are relying on a strict delimitation of influencing factors in different categories. The sample database structure in Fig. 4 for example only allows for a search of variation data pertinent to one single feature depending on its size, the used production process as well as the chosen material, i.e. one single design solution. On the one hand, it consequently does not provide information about the part's manufacturability which is usually depended on the overall arrangement of adjacent features. On the other hand, it also completely neglects the dependency of the resulting process variation on changing dimension, crucial for a change of initial design solutions and an optimised tolerance allocation in many cases

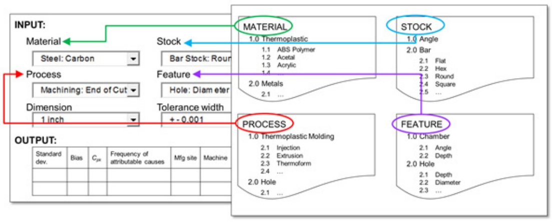

Fig. 4. Sample interface and underlying indexing scheme (adopted from [4])

In addition and equally important, Fig. 4 also illustrates another drawback of existing PCDB indexing schemes. Although many contributions claim to provide manufacturing variation data for geometric features [14, 15], they effectively seem to focus rather on dimensional than geometric tolerances from the author's perspective. A detailed discussion of the question if generic C_p or C_{pk} indices are suitable for the evaluation of geometric tolerances [16] could not be found in PCDB-literature.

3. Objective – Closing the Gap in the Quality loop

At present, existing approaches standards, guidelines and knowledge management solutions consequently leave a gap in the quality loop between Production Engineering and Metrology towards Engineering Design, see Fig. 5. The questions, how to acquire manufacturing variation data and how to efficiently convey this knowledge about the expected production capabilities back to designers, have not been answered satisfactorily yet. While commonly used process capability measures primarily focus on basic linear dimensions, a characterisation of geometric features is neither suitable for a meaningful description as existing standards focus largely on an unambiguous specification of allowable variation in design. The same holds true for research on Knowledge Management Systems in the field of GPS/ GD&T [17], on the transfer of tolerance information based on neutral data file formats in integrated measurement processes [18] as well as on the semantic interpretation of geometric tolerance information for the calculation of tolerance stack-ups [19]. The exemplary focus is a seamless transfer of specified geometric requirements from design to production and metrology or the use of existing tolerance information. An extension of generic tolerance symbols towards the large number of variation-relevant characteristics (the specific feature form, adjacent features, size ranges, etc.) which define a part's manufacturability, and thus the resulting variation, is not considered.

Despite all efforts to provide information on the expected manufacturing performance in database solutions, the result is a lack of objective and meaningful manufacturing variation. Engineering designers therefore still have to rely on their subjective estimation or incomplete and moreover out-of-date tolerance guides. As a result they are mostly following largely individual, unregulated and informal procedures when being confronted with verification tasks in design practice.

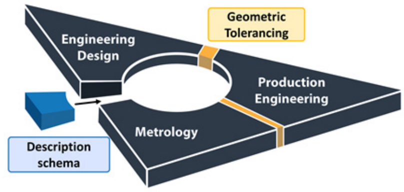

Fig. 5. A description schema for manufacturing variation to close the gap in the quality loop

To close the gap in the quality loop, this research aims at the creation of a consistent schema for a standardized description of manufacturing variation. Providing a structured overview about all variation-relevant influences, the schema will allow for the acquisition of meaningful variation data in existing production lines. It will enable engineers to convey their domain-specific expertise about the capability of production processes effectively and could, in the long-run, form the basis for a well-established knowledge management system for variation management.

As illustrated in the previous section, this is not a trivial task. First of all, the list of factors with an impact on the ultimately acquired variation data is tremendous, including for example the product's geometries, dimensions and materials, production parameters and context, the operator influence, as well as the measurement system used. Secondly, the interactions between these *variation-relevant influences* are usually highly complex, potentially leading to unexpected effects on the variation observed. Moreover, a description schema must be familiar to engineers to ensure that data can be retrieved [14], and thus to allow for its application in practice. In addition, there are numerous further challenges, such as the suitability of C_p or C_{pk} values for geometric tolerances, long-term vs. short-term capabilities, data integrity, implementation activities, etc. However, this initial contribution focusses on four basic premises for the development of the description schema which are derived from the aspects pointed out above and will be illustrated by means of an example product in the following section:

- **Reference to GPS annotation:** To ensure a consistent and useful schema, the recorded manufacturing variation will be described with reference to GPS annotation, which however has to be extended by additional information.
- **Consideration of influencing dimension and features:** In addition to single features, the schema will incorporate information on other variation-relevant dimensions and features of the part affecting its manufacturability.
- **Surrogate validation purpose** The main purpose of the schema is the validation of design solutions and tolerances based on surrogate data, i. e. data which matches a new design as closely as possible or a reliable approximation.
- **Trade-off between costs and benefits:** For an effective use, the schema's complexity will be carefully aligned with the user's requirements to avoid costs for data acquisition, management, inquiries etc.

4. Basic premises for the development of a feature-based description schema for manufacturing variation

This initial contribution clarifies the above mentioned premises using a non-functional sample part. In this way, it creates the baseline for development of a description schema for manufacturing variation which will offer the possibility to systematically and comprehensively describe a geometric feature by its specific form as well as a clearly defined set of further variation-relevant influences.

4.1. Reference to GPS annotation

While the concept of geometric tolerances offers a mean to unambiguously dimension and tolerance all geometric features, existing guidelines still rely on a description of dimensional variation, see section 2. To underpin the importance of the nowadays widely accepted and adopted systems for geometric tolerancing, and thus to allow for an effective use and an easy implementation in design practice, the description schema will be strictly based on ISO GPS terminology. The variation of a functional feature resulting from manufacturing will always be described using existing GPS symbols, hereinafter referred to as *variation classifiers*, and the corresponding variation value. However, a consistent schema requires an extension of this basic classification by sub-classifiers, the *feature classifier*, which detail the form of a geometric feature before it is specified by the *feature dimensions* on a third level of description. This is important as the resulting variation is likely to depend on its specific form as illustrated by the example of the difference between a cone's and a pin's circularity in Fig. 6, see also section 2.1.

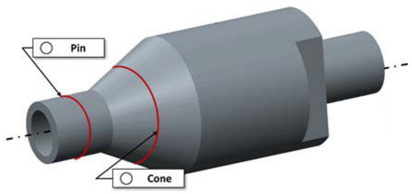

Fig. 6. *Variation classifiers* and *Sub Classifiers* for a feature-based description of manufacturing variation

4.2. Influencing dimensions and features

The indication of *variation classifiers*, *feature classifiers* and *feature dimensions* provides a possibility to unambiguously reference, thus to also retrieve, the measurement data for specific feature types. At the same time, the final variation of a specific process does however not depend solely on one single feature. Instead, it is usually significantly affected by the part's manufacturability, i. e. the overall arrangement of geometric features and their dimensions as pointed out in section 2.3. A meaningful manufacturing variation framework consequently requires an extension of this basic description by variation-relevant, adjacent features or dimensions as shown in Fig. 7. Depending on the manufacturing process, the concentricity of the two opposite axles of the sample part is, for example, likely to be influenced by the distance l between them. Similarly, the variation of the specified circularity is susceptible to be influenced by the defined dimensions of the pin-hole arrangement, i. e. the wall thickness t.

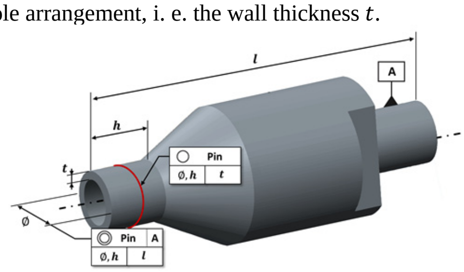

Fig. 7. Consideration of influencing dimensions and features

4.3. Surrogate validation purpose

Adopting the basic concept of PCDBs, i. e. the use of measurement data from existing production lines, it has to be noted that the basic purpose of the suggested description schema is a surrogate validation of design solutions and tolerances. Enabling to effectively acquire, document and convey knowledge about the performance of manufacturing processes, the schema will provide variation data based on previous projects that matches as good as possible the new design under consideration. At the same time, already small changes of the variation-relevant product characteristics might lead to unexpected changes of the resulting process variation. While an exhaustive database would offer a straight forward solution for this issue, see discussion in section 5, an improved communication of manufacturing variation based on the description schema requires a direct benefit for all the stakeholders involved. As shown in Fig. 8, the achievable tolerance per *variation classifier*, *feature classifier* and *feature dimension* is therefore systematically described in dependency of the *influencing dimensions and features* described in the previous section. In many cases, an overview about the variation effect of *feature dimensions* and one single *influencing dimension*, e. g. the part length on the concentricity in Fig. 8, is likely to be extended towards a consideration of a combined measure such as t/D ratio (thickness to diameter) on the circularity.

		Influencing dimensions – length *l*					
Variation classifier feature classifier Feature dimensions	Range	< 3%	3 to 6%	6 to 9 %	9 to 12%	12 to 15%	>15%
	< 5%						
	5 to 10%						
	10 to 15%			Variation value			
	> 15%						

Fig. 8. *Variation classifiers* and *Sub Classifiers* for a feature-based description of manufacturing variation

4.4. Trade-off between costs and benefits

Finally, the schema must systematically account for the complexity of manufacturing variation as both, the acquisition of variation data as well as its maintenance, are cost- and time-consuming tasks. A too detailed list of incorporated features, interactions, size ranges, etc. could consequently have an extremely detrimental effect on its usability. To ensure an effective creation and its beneficial use, the schema is therefore not only production technology specific. In addition it is systematically aligned with the user requirements, in other words with the company-specific product ranges and the most relevant, most often used product characteristics. For the necessary prioritisation and the identification of the variation-relevant influences laid out above, a variety of commonly applied approaches from (quality oriented) design methodologies, e. g. a *Key Characteristics and Variation Flow Down* [4, 5], can be used.

5. Discussion

The description schema suggested in this contribution is an essential step towards objective data on the performance of manufacturing processes. Incorporating and standardising the frequently domain specific knowledge of design-, production- and metrology engineers, it allows to generate, document and convey information about manufacturing variation and its impact effectively within an organisation. Initially focusing on closing the quality loop, thus on an objective and meaningful feedback on the measured variation of parts from production and/or metrology to design, it allows for an improvement of all variation analyses and to design in quality and robustness to their products.

At the same time, the presented, mainly product-focused list of variation-relevant influences could easily be extended to further widen the scope of the schema's application. In addition to geometry data, i. e. *feature classifiers, feature dimensions* and *Influencing Dimensions and features*, Fig. 9 proposes an exemplary set of supplementary categories.

Class	Type	Characteristics	Add. Influences
Company data	Industry Sector	...	...
Geometry data	Feature classifier	Feature dimensions	Influencing dimensions/features
Material data	Material Type	...	...
Metrology data	Measurement system	...	...
Process data	Production Technology	...	...

Fig. 9. Potential variation description categories

While the basic type in the different classes usually has to be indicated to capture meaningful variation data, more detailed information on the variation effects of material changes (*material data*), on the influence and potential of measurement systems (*metrology data*) or the production process itself, i. e. the used process parameters and settings (*process data*), will allow production engineers to make well-founded decisions on manufacturing technology, and metrology experts to ensure that quality is appropriately controlled throughout the value chain.

Finally, the authors would like to underline that, although the presented schema is initially conceptualised as a purely company-internal approach, Fig. 9 includes a *company data* field. The underlying aim is to overcome the limits of the schema's surrogate modeling purpose. The vision is to extend available modeling approaches for tolerance information [e. g. 17, 18, 19] and to create a Global Manufacturing Variation Database (GMσD) which provides data comparable across processes, industries, materials, regions, suppliers and a wide range of product geometries describing a part's manufacturability. Providing a standardized way of describing manufacturing variation data which can then be anonymized and aggregated, this research is consequently a first key step to make this vision a reality and create an innovative, quality-focused information management system offering a Big Data approach for R&D, production and supply-chain management (Please visit the website http://robustdesign.org/GMoD for more information).

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