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Design to Process Capabilities: Challenges for the Use of Process Capability Databases (PCDBs) in Development

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1 Introduction

In approaches such as Robust Design, Tolerance Management, Design for Six Sigma (DfSS), etc. there is little disagreement that a better understanding of inevitable production variation is conducive to the success of development projects [Eifler et al. (2013), Arvidsson and Gremyr (2008), Karmakar and Maiti (2012), Breyfogle (2003)]. At the same time, information on the achievable manufacturing accuracy or the supplier's performance is usually inaccurate and largely qualitative in early development stages. Design decisions as well as the choice of manufacturing processes, therefore, often rely on experiential approaches or expert judgment. There are numerous examples that this subjective assessment of potential variation and a mostly informal communication between design and production engineers can result in non-satisfying product or manufacturing solutions. Whereas overestimated production capabilities may lead to low yields and a cost/time overrun, conservatively underestimated capabilities affect quality through the reduced design space, or through increased play, rattle/noise, size or weight.

A possibility to overcome the subjective assessment of variation in development projects is a Process Capability Data Base (PCDB) offering valuable insight into the actual or expected performance of production processes (Tata

and Thornton, 1999). But although the potential benefits as well as initial challenges for the use of PCDBs have been addressed in earlier research, e. g. by Delaney and Phelan (2008), Kern (2003) or Tata and Thornton (1999), a widespread adoption in industry cannot be observed. As already stated by Okholm et al. (2014), there are many open questions and a methodical support how to generate, provide and use generalized production variation data still seems to be missing.

To foster the use of corresponding databases and to stimulate further research, this paper gives an overview about the scope of potential applications for a PCDB in product development. Furthermore, the expected manufacturing accuracy of specific product characteristics/features is discussed. For the generalization of measurement data, a DOE (Design of Experiments)-based approach is proposed to identify influencing factors related to the production accuracy of each geometric feature, using the example of metal shear forming processes.

2 Background

A decisive drawback for a coherent management of variation in practice is that most of the existing modeling and analysis approaches assume complete and accurate knowledge whereas objective information about process capabilities is usually not available in early development stages (Tata and Thornton, 1999). The basic idea of a PCDB, explained in section 2.1, consequently seems to be straight forward. However, the applicability as well as challenges of a design oriented database need to be discussed in section 2.2.

2.1 Process Capability Data Base

In addition to other sources of variation in the product life cycle, e. g. ambient conditions or unexpected loads (Ebro et al., 2012), manufacturing inaccuracies need to be taken into account as early as possible in the development process. Parts are therefore designed with allowable geometric variations, i. e. suitable tolerance windows, to ensure that the product will assemble and function as intended (Schleich and Wartzack, 2013). At the same time, there is a clear lack of suitable tools offering objective information on production variation data in early design stages. Available software solutions focus primarily on monitoring or optimization task in production. The stored process capability data is often largely unused in product development (Tata and Thornton, 1999).

Inspired by earlier work, Okholm et al. (2014) therefore conceptualize and generate an example PCDB for injection molded components. Based on exist-

ing Quality Control (QC) procedures, multiple components are measured and valuable information from measurement reports, e. g. mean shifts and standard deviations, are then made available in a database. Flexible tagging schemes, statistical analysis tools as well as suitable graphical displays and design guidelines enable the designer to sort and to compare process capabilities for specific geometry features, materials, suppliers, etc., see Figure 1.

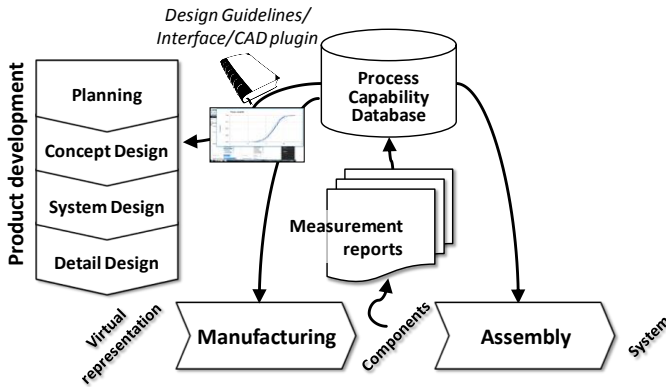


Figure 1: Process Capability Data Base

2.2 Challenges of PCDB usage in engineering design

At the same time, an overview about different application areas for such PCDBs in development, and thus the potential benefit, is still missing to the authors' knowledge. Moreover, one of the most crucial factors for a successful generation and storage of process capability data is completely neglected so far. Whereas graphical displays proposed by Thornton and Tata (2000) or Okholm et al. (2013) provide the designer with objective information about the variation of single product features, other influences as well as existing interactions between product characteristics or process parameters are not considered.

In a first step, Okholm et. al (2014) point out the importance of part size for the prognosis of an expected tolerance window. Based on different standards for injection moulding processes, measurement data is normalized with respect to dimensions, see Figure 2. An additional important aspect considered but not solved, is the estimation of long-term process performance. A variety of influences leading to wear of tools, changing ambient conditions, etc. are usually taken into account by a simple adjustment of process capability indices from the recommended value $C_{pK} = 2$ to $C_{pK} = 1,5$ due to the resulting mean shift (Breyfolge, 2003).

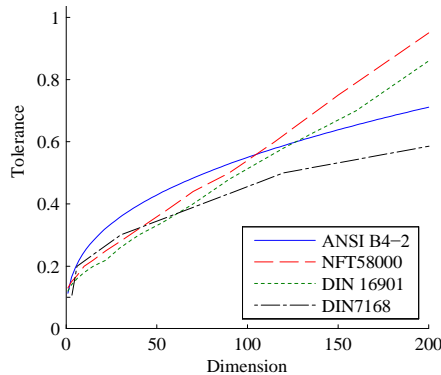


Figure 2: Influence of part dimensions on achievable tolerance windows for injection moulded components (Okholm et al., 2014)

However, the methodical use of PCDBs for design purposes requires not only the consideration of single influences on the resulting production variation, but needs to be extended to the impact of existing interactions between them. If the resulting tolerance windows are significantly impacted by additional product characteristics, process parameters or their combination, the information given in Figure 2 can for example be completely misleading.

For the development and usage of PCDBs as well as for further research, there are consequently two decisive questions:

- **Scope of application:** What is the potential benefit of a PCDB for different development tasks and what is the methodical support needed to enable the designer to use the given information?
- **Interaction effects:** How can interactions between different design and/or process parameters that may have an effect on the resulting variation of manufacturing operations be incorporated in a PCDB?

3 Using PCDBs for design purposes

The availability of objective process capability data in a database could support a variety of design tasks. However, methodical support of a PCDB is necessary for a real shift from a late and costly evaluation of production feasibility to a proactive Design to Process Capabilities (DtPC). To identify benefits of this new approach as well as further research questions, the different applications areas of a PCDB are summarized (*section 3.1*). Afterwards, challenges for the generalization of measurement data in statistically designed experiments are presented (*section 3.2*).

3.1 Design to Process Capabilities (DtPC)

The product development process is an iterative process rather than a linear one. The results of design decisions are continuously reviewed, potentially leading to design changes, i. e. iterations to earlier development phases (Pahl et al., 2007). Following the description of tolerance activities, e. g. in Schleich and Wartzack (2013), Figure 3 illustrates potential benefits of PCDBs in product development. Usually, the choice of a concept and the definition of geometries (*Design*) are followed by the definition of tolerable geometric variations in three subsequent tolerancing steps. The identification of required part or datum features (*Tolerance Specification*) is followed by the setting/optimization of tolerance windows (*Tolerance Allocation*) that are then basis for a verification of functional implications and necessary changes (*Tolerance Analysis*). However, as already pointed out, the feedback from production frequently relies on expertise and experience, mainly from previous products. Furthermore, the functional relevance of tolerances is not necessarily known by the production expert. The main implication is that the manufacturability of the design and the specified tolerances is usually not evaluated until a detailed design is passed over to *Production*.

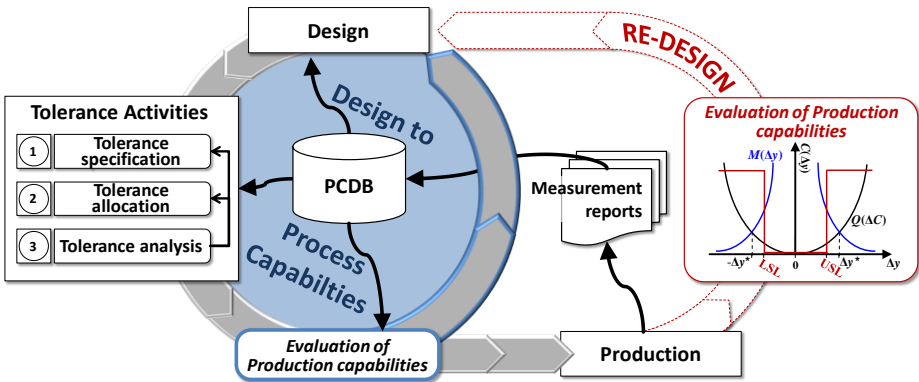


Figure 3: Design to Process Capabilities

To overcome late and consequently costly *Re-Designs*, a PCDB offers objective information about production variation in early development stages, enabling design engineers to significantly reduce the size of the iteration cycles. The PCDB provides objective, quantitative feedback regarding the estimated manufacturability of a product and its functional performance. This will allow critical surfaces and features to be identified earlier and suitable production technologies to be chosen.

Taken as a whole, four main application areas of a PCDB can be distinguished and need to be analysed further:

Table 1: Application areas for PDCBs in development

Design for a tolerance optimum
The fundamental aim of PCDB usage in product development is the choice of optimal tolerances. The integration of objective production variation data into tolerance activities supports the definition of tolerable variation Δy^* , minimizing the overall costs $C(\Delta y)$ resulting from quality loss $Q(\Delta y)$ and manufacturing effort $M(\Delta y)$, see also Figure 3. Decisive questions for a methodical Design to Process Capabilities approach thereby result from the consideration of geometric tolerances, i. e. the notation (GD&T) as well as a suitable measurement procedure for manufactured parts.
Evaluation and optimization of concept robustness
In addition, available and easily accessible production variation data also facilitates the evaluation of ambiguity in a design or the choice of suitable surfaces. Through the development of suitable modeling approaches, e.g. based on models of organs or interfaces/working surfaces, the identification of function relevant part or datum features and the optimization of chosen solutions can be supported before the actual numerical tolerance values are specified. However, to attend this aim, an extension of existing Robust Design methods as well as an integration of corresponding tasks into a coherent Design to Process Capabilities procedure seems to be necessary.
Concurrent choice of manufacturing technologies
In parallel to the optimization of concept robustness, a PCDB will also allow for an objective choice of suitable manufacturing processes in early design stages. Although the trade-off between technological capabilities and economic opportunities is of outstanding importance and highly influenced by development decision, corresponding decisions are frequently left to production engineers (Swift and Booker, 2013). Any implications and predeterminations of the chosen product solution are consequently neglected to a great extent.
Benchmarking of process performance
A long-term aim for the use of production variation data is the generation of a global PCDB which comprises different production technologies, different OEMs as well as their suppliers. The benefit in a mass manufacturing scenario is obvious. A support for outsourcing and supplier management decisions can offer significant economic benefits to an organization and shifts the focus of interchangeable parts to a detailed analysis of the interchangeability of processes (Karmakar and Maiti, 2012). Such a database would allow companies to compete and benchmark themselves against other companies using the same production processes.

3.2 Generalization of measurement data

One critical success factor for the use of PCDBs in development projects is the generation and storage of generalized process capability data. The information provided must be valid for different designs, i. e. applicable independently of specific conditions of the development task. For the generation of generalized measurement data, there is consequently a clear need for a preliminary analysis of relevant influencing factors, both in terms of product characteristics and process parameters, as well as of their interactions which also may affect the resulting variation of manufacturing operations. Corresponding challenges (*section 3.2.1*) and the possibility of a DoE-based analysis of influencing factors (*section 3.2.2*) are illustrated using the example of metal shear forming processes.

3.2.1 Example process: metal shear forming

In this paper, a DOE-based approach is used to, on the one hand, investigate the impact of different influencing factors in metal shear forming processes, and on the other hand to elaborate deeper insight and a methodical support how to generate and to use process capability data for design purposes. In metal shear forming processes, axially symmetric components are produced using a roller tool forcing flat sheet metal blanks onto a mandrel as shown in Figure 4 a). Even though not as widespread as other forming techniques, e. g. deep drawing, the process offers some inherent advantages. Simple and low cost tooling, surface quality, mechanical properties, etc. led to an increasing use of metal shear forming for the production of lightweight components (Wong et al., 2003).

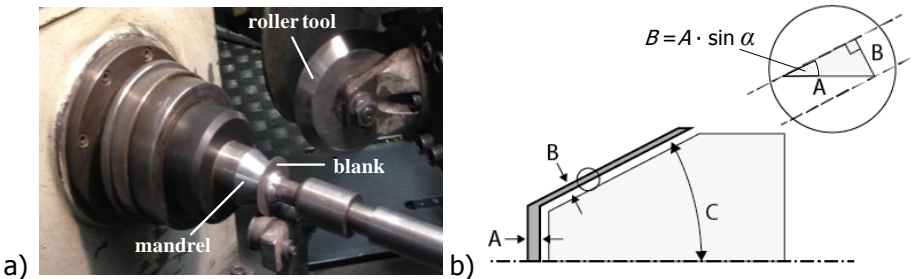


Figure 4: Description of a) Metal Shear Forming process by b) the law of sine

However, in comparison to other usually CNC controlled manufacturing processes metal shear forming is often still relying on a so-called playback control (Wong et al., 2003). As it is thus highly dependent on the recorded

tool path and the experience of operators, the underlying dependencies and interactions of different influencing factors are frequently not fully understood and even explanations in literature seem to be contradictory, e. g. in Wong et al. (2003) and Kleiner et al. (2005). Moreover, trade-offs between the accuracy of different quality characteristics exist and play a decisive role for the design of components. An example is the definition of the final wall thickness B , which is usually calculated based on the starting wall thickness A as well as the required angle α , as shown in Figure 4 b). Both parameters are specified by the designer, who thereby influences process forces leading to different effects on product characteristics, such as circularity, surface quality, etc. To provide generalized measurement data of shear spun components, they consequently need to be taken into account.

3.2.2 Experimental investigation of metal shear forming

As a baseline for the generation of a PCDB for shear spun components, existing relevant influences as well as existing interactions are analysed in a preliminary investigation. Three groups of experimental runs using cone molds/mandrels of $\alpha = 22 - 27^\circ$ compared to the rotational axis were conducted. Other aspects of the experimental setup are summarized in Table 2.

Table 2: Application areas for PDCBs in development

Production:	<ul style="list-style-type: none"> Leifeld PNC 106 spinning machine with CNC support radius of roller edge $r = 4,5 \text{ mm}$
Measurements:	<ul style="list-style-type: none"> Mitutoyo Euro-M 544 measuring machine Hand held thickness caliper (precision $\pm 0,02 \text{ mm}$)
Workpieces:	<ul style="list-style-type: none"> Material EN.4404 SS steel Plate thickness $h = 2 \text{ mm}$

According to basic procedures of statistically designed experiments, for example described in Jiju (2003), screening experiments were performed for different angle sizes to identify key design as well as process parameters. Suitable intervals for the experimental analysis were chosen based on available literature, e. g. Wong et al. (2003) or Kleiner et al. (2005), and lessons learned from previous pilot experiments. Figure 5 summarizes the impact of the different control factors, i. e. the *Feed Ratio*, the *Surface Velocity* and the specified clearance between roller tool and mandrel (*Reduction*) which is specifically calculated to realize different cone angles. In addition, potential interaction effects are taken into account.

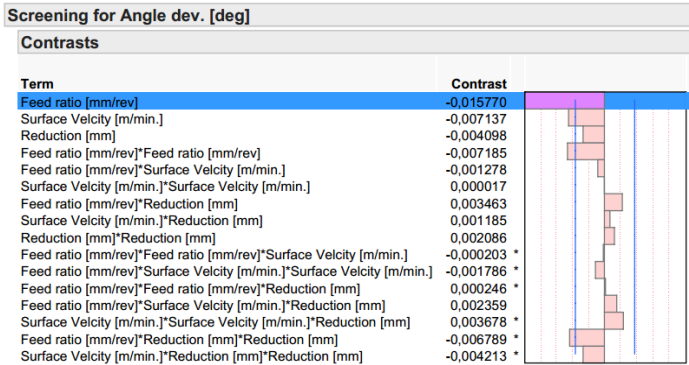


Figure 5: Results for screening experiments

As shown in the Pareto plot in Figure 5, the process parameters *Feed Ratio* and *Surface Velocity* as well as possible interactions are the main contributors to a deviation of the cone angle $\Delta\alpha$. They were consequently analysed in a Full Factorial Design with 3 levels for each control factor afterwards.¹ However, whereas the investigation and optimization of the process parameters is usually the task of production engineers, the clearance between roller tool and mandrel (*Reduction*) is directly defined by the required cone angle specified in design. Consequently, existing dependencies need to be fully understood before measurement data/a PCDB for metal spun components can be generated.

The contour plots in Figure 6 therefore concentrate on the clearance specified for the conducted experimental runs. One result of the analysis is that there are clear differences between optimal process settings in terms of variation or precision of the metal shear forming processes. Using a mean value of the resulting cone angle in 3 experimental runs for the same parameter set, the deviation of the cone angle appears to be solely a function of the surface velocity and completely insensitive to changes of the specified clearance, see Figure 6 a). However, an additional analysis of the possible variation indicates that the clearance plays a crucial role for the generation of generalized measurement data. The calculated standard deviation of the response per parameter set shows that potential variation of the cone angle is clearly affected by the specified clearance, see Figure 6 b), which consequently need to be taken into account.

¹ see for example Jiju (2003) for further explanations of DoE

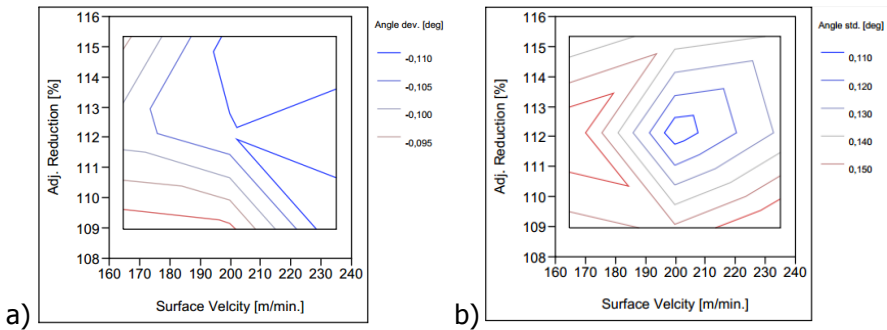


Figure 6: Analysis of a) precision and b) variation of Metal Shear Forming

In total, the conducted experiments allow also for a first overview about the process capability achievable in metal shear forming processes. Based on the assumption of normal distribution, which according to the normal probability plot in Figure 7 seems to be a good fit, the expected C_{pK} values can be calculated. Disregarding the parameter changes in the first place, the conducted experiments consequently can be already used to get a first idea of the process capability of metal shear forming processes.

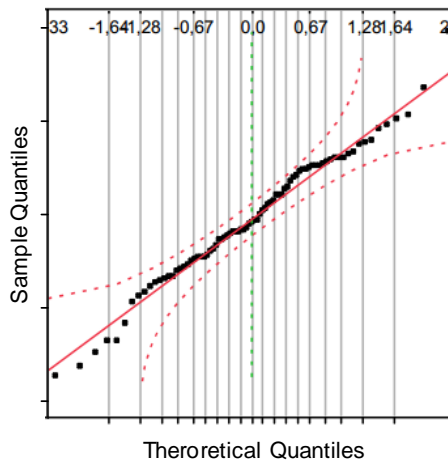


Figure 7: Normal probability plot for resulting cone angle

4 Discussion and Conclusion

The idea of a PCDB is straight-forward and offers an enormous potential for an improved communication between design and production departments as well as for a better understanding of the inevitable variation in manufacturing processes. However, a variety of challenges has to be solved before a widespread adoption in industry is possible.

To foster the use of objective production variation data for design purposes and to stimulate further research, this paper gives an overview about the scope of application of PCDBs and summarizes potential benefits of a new Design to Process Capabilities approach. It is concluded that a deeper insight into production processes and a better understanding of existing dependencies between product characteristics, process parameters as well as their interactions is necessary for the generation of measurement data in PCDBs. The proposed DoE-based analysis of metal shear forming processes thereby illustrates first results as well as further research questions for the generalization of measurement data.

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