Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 43 (2016) 41 – 46

www.elsevier.com/locate/procedia

14th CIRP Conference on Computer Aided Tolerancing (CAT)

Enabling reuse of inspection data to support robust design: a case in the aerospace industry

Julia Madrid[a,]*, Johan Vallhagen[b], Rikard Söderberg[a], Kristina Wärmefjord[a]

[a]Chalmers University of Technology, 41296 Göteborg, Sweden
[b]GKN Aerospace Engine Systems, 46181 Trollhättan, Sweden

* Corresponding author. Tel.: +46-317-721-344. *E-mail address:* julia.madrid@chalmers.se

Abstract

The use and reuse of information and knowledge from manufacturing are crucial to secure the quality of the product throughout the product realization process. Robust design, variation simulation, virtual verification and root causes analysis are activities that require inspection data to ensure a robust process. In many industries, the level of inspection data reused is rather low. In this study, general barriers for reusing data concerning manufacturing processes have been identified in scientific literature and compared with specific barriers identified in a case study performed at an aerospace engine manufacturer. As an output of this comparison, barriers to the reuse of inspection data have been classified in three types: informational, technical, and organizational. In addition, the informational barriers are decomposed in four questions: *Why*, *What*, *When* and, *How* to measure. A support to answer those questions and overcome the informational barriers is proposed.

Peer-review under responsibility of the organizing committee of the 14th CIRP Conference on Computer Aided Tolerancing
Keywords: Inspection planning; Quality assurance; Knowledge management; Robust design.

1. Introduction

New business demands on manufacturing companies require fast, flexible and highly customized product and production development processes. The objective is to deliver more variants of high quality products, reducing cost and reaching the market faster than before. To do so, the aim is to shift the competence of controlling quality towards earlier stages in the development process, before production starts. A proactive approach to assure quality would reduce the need for physical prototypes and manufacturing rework. Quality can be virtually assessed, controlled and optimized, making products more robust and insensitive to manufacturing variation [1, 2].

In order to virtually verify both product and production concepts the need for probabilistic design, variation modelling, variation analysis tools and simulations has increased [1, 3, 4]. These new methods and tools require using as much manufacturing process knowledge and inspection data as possible in the early stages of the product development process.

Much of the research on improving and predicting quality assumes the existence of process capability information but how to deliver such information is less discussed. Thus, some researches have focused on enabling the reuse of manufacturing knowledge and information [5, 6]. Andersson et al. [6] provided a framework to support the reuse of manufacturing experience as a source of knowledge. Moreover, research on Knowledge Base Engineering (KBE) focuses on creating computerized support to reuse manufacturing knowledge [7].

However, the level of reused inspection data in design activities is still rather low in many industries, as reported by [8-10]. Inspection measurements are used to monitor quality during production but are not efficiently utilized as a source of knowledge during design in order to create more robust product and processes [10, 11]. Therefore, research has focused on supporting the communication of capability data to designers either by the creation of process capabilities databases [8, 12] or the creation of information models [10]. But less research has been done on enabling the reuse of inspection data in design by supporting the process of generating adequate process capability data.

Peer-review under responsibility of the organizing committee of the 14th CIRP Conference on Computer Aided Tolerancing
doi:10.1016/j.procir.2016.02.137

This paper contributes to the area of reuse of manufacturing knowledge, considering inspection data as the source of knowledge, by supporting inspection planning activities. Two questions are addressed:

- RQ1: What are the barriers to reuse inspection data?
- RQ2: How can the inspection planning and execution be supported so that it generates adequate process capability data to be reused?

This paper begins presenting the different users of inspection data. In section 3, a case study at the aerospace industrial partner is presented, where specific barriers to the reuse of inspection data to support life calculations are identified. In order to verify those findings, generic barriers to the reuse of inspection data in design activities have been identified in scientific literature, see section 4. In the final section, support for the generation of inspection data to enable its reuse is proposed.

2. Users of inspection data

All manufacturing processes are disturbed by variation [13]. Variation can be represented in statistical terms. A quality improvement would consist of centering the probability distribution of the quality characteristic at a target value and then reducing variation. Therefore, inspection data and statistical methods play a central role when assuring quality, both in production and even in early stages of the product development process [2, 13, 14].

2.1. Production, the traditional user

Until the 80s the way to assure quality, or rather to control quality, was by acceptance sampling and SPC [2, 14, 15].

A review of the most relevant SPC methods can be found in [14]. The control chart proposed by Shewhart [16] is one of the primary techniques of SPC. In the control chart, when unusual sources of variation are present, sample statistics will plot outside the control limits, indicating investigation of the process should be done and corrective measures should be taken. In addition, root cause analyses are carried out during production by utilizing variation data to detect the problems within the manufacturing process [17]. The systematic use of these methods is a good way to reduce variation. However, these methods are based on data from ongoing production, thus quality is improved in late stages of the product realization process.

2.2. Quality assurance activities, the new users

The increased attention in robust engineering [18, 19] has occurred due to it is preferable to reduce variation during the design phase, before production starts. Comparing concepts and optimizing design parameters, in order to increase the quality of the product, has a lower cost than reducing variation during manufacturing.

Quality assurance can be seen as a set of activities which are employed throughout the product development process to provide the necessary evidence that the intended quality will be achieved and maintained [15].

In the case of product dimensions and tolerances, as quality characteristics, research on methods and tools to deal with geometrical variation has gain increased attention [18]. Within this area, Söderberg et al. [1] proposed a Geometry Assurance process, which is a set of activities and tools linked to the product development cycle in order to assure geometry. Geometry assurance consists of controlling the effect of geometrical variation from early design concepts phases, through verification, preproduction and finally during production, see Fig. 1.

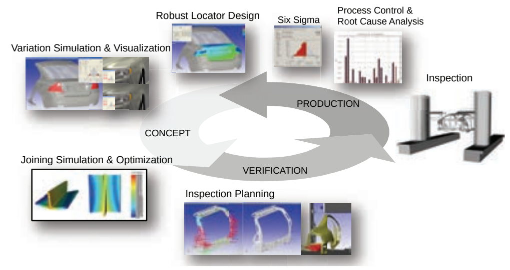

Fig.1. Geometry assurance process by Söderberg et al. [1]

Inspection data is generated and used during the production phase. The purpose is to monitor production processes and to detect and correct errors by using methods for root cause analysis and six sigma [17].

In addition, inspection has the objective to capture the information about the process capabilities in order to be reused in the next concept phase, where inspection data is reused for variation simulation [20]. Virtual development activities are the new users of the inspection data.

Today many actors and activities during the product realization process need inspection data as an input [9], which is the reason why the number of inspection points can become quite large. Inspection strategies and planning have the objective to find the minimum and optimal set of inspection features to feed all those activities [21].

3. Barriers to the reuse of inspection data – Case study in the aerospace industry

In this section a case study carried out at an aerospace industrial partner is presented. Barriers to the reuse of inspection data in a design activity, fatigue life calculation, are identified. The discussion of the barriers can be found in section 5.

3.1. Background and problem description

The turbine structure in the rear part of a turbofan engine has a range of functional criteria from various fields of engineering. One of the functionalities is to withstand significant thermal and structural loads, which is related to the life of the component.

For the larger engines of today, the turbine structures are welded assemblies consisting of cast, forged and sheet metal parts. Different welding methods are employed for their fabrication. Fig.2. shows the different welds of the product.

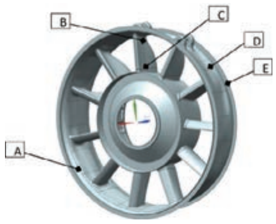

Fig. 2. Different welds in the Turbine Structure

Welding quality problems, together with geometrical variation, are outputs of this type of fabrication process. Welding quality problems are related to weld defects, such as cracks and pores that directly affect the life of the component [22]. The two main Non-Destructive Testing (NDT) methods used to inspect these types of metallurgical defects are Xray and FPI (Fluorescent Penetrant Inspection) [23].

In welded structures, the fatigue life of the component is determined by crack propagation analysis, where initial weld defects need to be taken into account [24].

Today, fatigue life calculations are conservative and based on theoretical input. Manufacturing and inspection capabilities are underestimated due to the lack of process capability data. Thus, in reality, engine components have longer fatigue life than current calculation methods can confirm. Empirical manufacturing data is necessary for statistical analysis to draw a realistic distribution of weld defects, which in turn could be used as an input to probabilistic methods for the fatigue life calculation.

3.2. Methodology

In this study the researchers have used the problem solving methodology DMAIC within the Six Sigma framework [14, 25] in order to collect and analyze both qualitative and quantitative data. DMAIC stands for the five phases: Define, Measure, Analyze, Improve and Control. Barriers to the reuse of inspection data to support fatigue life calculations have been identified through the phases Define, Measure and Analyze. Thus, only results from these phases are shown in the paper.

The purpose of the *Define* phase is to get a characterization of the problem. Three main activities were accomplished during this phase. First, interviews with fatigue analysts and literature review about fracture mechanics have been carried out to find the voice of the customer (VoC), that is, which information from inspection data fatigue analysts need in order to make fatigue life calculations. Second, quantitative historical inspection data on weld defects was collected to make a first Exploratory Data Analysis (EDA) [26], in order to understand the status of the current inspection data. Third, a group discussion with experts from different relevant areas, such as fatigue calculation, manufacturing and inspection methods, was made to elicit the problems concerning the reuse of manufacturing knowledge and inspection information to perform fatigue life calculations. The qualitative data generated during the session was analyzed with the KJ method (affinity diagram and interrelationship diagram) [27].

For this particular case, the purpose of the *Measure* phase was to understand how the process of generating adequate quality inspection data is currently performing and how reliable the current measurements are. The actual way of inspecting and documenting data was studied for the different inspection methods and at the different workshops. Employed methods were interviews, observations, inspection documents reviews, visits to the workshops and process mapping. In addition, three main areas were studied in order to perform Measurement System Analysis (MSA):

1) Inspection method capabilities [23].

2) Probability of Detection, POD [28], which is the statistical parameter to quantify the NDT reliability.

3) Levels of reproducibility and repeatability.

During the *Analyze* phase, information gathered in previous phases was analysed in order to find the causes of the problem. An Ishikawa diagram has been used for this purpose.

3.3. Results

The description of the current situation can be seen in Fig.3. That is, the data generated during the inspection processes of the turbine structure is not stored with the purpose of being utilized for statistical analysis to support fatigue life calculations. Records from the inspections are only stored for the purpose of communication during the repair processes in the workshops, for the use during production. Consequently, the distribution of weld defects and the required information to support fatigue life calculations cannot be derived from the inspection data. Instead, experts' judgments are the input to these calculations.

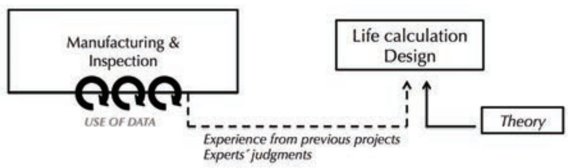

Fig.3. The current state

In order to allow for statistical analysis, the current inspection and documenting process needs be improved with the objective to generate and make accessible the adequate data and information to support fatigue life calculations (see Fig.4.)

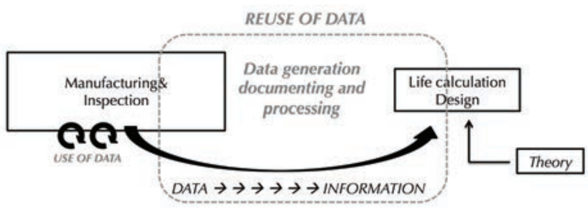

Fig.4. The future desired state

The study identified certain barriers (see Fig. 5.) affecting the process of data generation, documenting and processing that prevent the reuse of inspection data to support fatigue life calculations.

The identified barriers are:

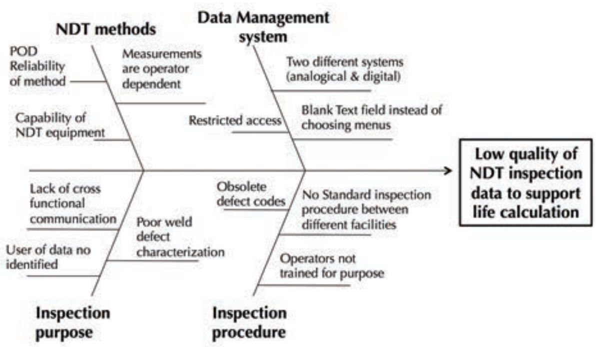

Fig. 5. Barriers to the reuse of inspection data to support fatigue life calculation

- The purpose of the current inspection processes is not connected to support fatigue life calculations. Life calculation is not considered as a user of the data, thus the characterization of weld defects is poor for this purpose. Weld defects codes are obsolete and not adequate. *What* to measure is not properly defined.
- Inspection operators are not trained to generate data for life calculations. Thus, *How* to measure is not properly defined for that purpose.
- Weld defects are not inspected after each welding operation step but only after the complete welding of the final assembly. Therefore, information about *When* a defect is generated is lost.
- There is a lack of standard inspection procedures at the different workshops. Thus, NDT-measurements become operator dependent.
- In the Data Management-system a text field is used to document the defects, which enhance subjectivism when documenting.
- The NDT-operators report weld defects in two different systems, one digital and one analogical.
- Capabilities of inspection equipment are not optimized to generate good quality data for life calculations. In addition, the POD for the statistical proven Xray method is non-existent.
- Lack of cross-functional communication between inspection and life calculation departments.

4. Barriers to the reuse of inspection data – Literature study

In this section, scientific literature has been reviewed with the objective of finding barriers and problems, when reusing inspection data during design, identified by other researchers.

Complete and accurate process capability data and information are required inputs to a number of design activities that ensure a robust result. In order to improve and predict quality, it is assumed to have at hand such process capability data [8]. Companies have created databases with the intent of being used for establishing tolerances, simulating variation, prioritizing process improvements or understanding the cost impact of parameter values. Ideally, databases should be fully populated with up-to-date and accurate data and linked to CAD and simulation packages [8, 9]. An ideal data reuse process would support estimations on manufacturing product quality outcome and costs to enable design trade off analyses and producibility analyses. However, the reality shows that data is not being utilized by design [8-10]. On their survey, Tata et al. [8] identified several barriers to design usage of manufacturing data. Furthermore, Wandebäck et al. [9] discuss in their paper the use of measurement data in computer-aided tolerance management and identify also certain industrial problems.

As a synthesis of these two research studies, barriers to the reuse of manufacturing data and information can be classified as follows:

- Data pertinent to design is not available. The SPC data used to monitor and control process performance is not the same data needed by design. Designers and other new stakeholders are not contemplated as possible users of measurement data. Therefore, these new users are not proactive in identifying *What* needs to be measured, what types of features, product characteristics, process parameters or material data they need.
- Poor characterization of the defects (non-conformances) and deficient form to present the data and information. There is a lack of comprehensive understanding of *What* to measure. But also *How* to measure, metrics, and how to present the data are questions that need to be addressed. Thus, access to the data is hindered due to the inability to interpret such data by persons that are not knowledgeable about how data has been gathered, for example, designers. In addition, visualization of the data in an appropriate way can increase the understanding of manufacturing variation and provide the user with all necessary information, see [8, 29] and [9, 30].
- Poor population and out of date data. Lack of inspection strategies, thus lack of planning *When* to measure and how much can lead to insufficient data to be able to get significant statistical results.
- Untrusted data. Measurement System Analysis (MSA) is important to determinate if the measurement system can generate accurate and precise data. In addition, special causes of variation are not often indicated.
- Limited access to database. These are obstacles of a technical nature related to infrastructure and inadequate systems. Examples are incompatibility between different databases, lack of PLM system, lack of connection with CAD system. In addition, there can be problems related with permission request, which can make the way to access to the data very tedious and time consuming.
- Lack of management support in terms of investing in resources such as adequate equipment, data maintenance and training.
- Other barriers involve not having systematic procedures for using the manufacturing data and information. Poor communication between design and manufacturing.

Similar barriers, concerning the collaborative interaction between design and manufacturing, have been identified by other researches [5]. However, focus was put into utilizing the potential of manufacturing knowledge reuse, considering experience as the source of knowledge, not exclusively the inspection data, as covered in this paper.

5. Discussion about the barriers

In this section, a table summarizing the barriers found in the case study and the literature review is presented and discussed, thus closing RQ1.

Quality improvements focus on reducing variation, but first, it is required to understand how variation is generated. Thus, there is a need to measure the manufacturing process and get data and information to be able to use it to control production but also to reuse it for quality assurance activities.

Why companies are not reusing data in design activities depends on certain barriers. The barriers to reuse data identified in the case study presented in this paper are confirmed in the literature review.

Barriers to the reuse of manufacturing data and information are classified in three main categories in this study: informational, technical, and organizational, see table 1. Same classification has been used by [8]. First, barriers of informational nature can be related to the quality of the data content, how pertinent and adequate the data that the inspection process generates is. Second, barriers technical in nature are connected to the quality of the measurement system and finally, there are barriers of organizational nature, with regards to the collaborative interaction between design and manufacturing. Still, these three types of barriers are interconnected. For example, the quality of the measuring system implicitly affects the quality of the data.

The discussion in this paper is focused on the first type of barriers, those of informational nature and related to the quality of the data content.

The reasons for the inspection and measurement process not generating the adequate data content are first because it is not clearly defined *Why* to measure. The activities to assure quality are not identified. Without a quality assurance cycle [1] the new stakeholders of the data are not contemplated. Second, *What* to measure that defines the quality of the product is not properly identified. The product characteristics linked to product functionality, and the process parameters causing variation in those product characteristics are not properly identified as measurement features. In addition, *How* to measure also needs to be planned, deciding which are the metrics to verify those product characteristics and process parameters during the product development process. Finally, planning *When* to measure in the process in order to either capture the phenomena that simulations want to model or to make root causes analysis during production, is necessary.

Table 1. Classification of the barriers to the reuse of inspection data into design

Type		Generic Barriers (Literature study [5,8,9,29,30])	Specific Barriers (Case study)
Informational nature	*Why*	Designers and other stakeholders are uncomtemplated as possible users of measurement data	Fatigue life calculation is not considered as user of inspection data
	What	What need to be measured, product characteristics, process parameters or material data, is not identified	Poor weld defect characterization
	How	How to measure, metrics, and how to present the data, need to be defined	Inspection operators are not trained on how to generate data for fatigue life calculation purposes
	When	Lack of planning when to measure leads to poor population and out of date data	Weld defects are only inspected after the complete welding of the final assembly
Technical nature		Inadequate data management-systems. Incompatibility between different systems	The design of the data management-system induces subjectivism. Two different reporting systems
		Untrusted data. Deficient MSA	The inspection data is operator dependent
		Deficient inspection equipment	Capabilities of NDT methods are not optimized
Organizational nature		Poor comunication between design and manufacturing	Lack of cross functional communication between inspection and fatigue life calculation departments
		Lack of management support to invest in resources such as equipment, data maintenance and training	Lack of standard inspection procedures

6. Proposed support for inspection planning

In this section a solution is proposed to answer the questions "*Why*, *What*, *How* and *When* to control and measure", thus overcoming the first type of barriers, of informational nature, and closing RQ2. Answering these questions will support the inspection planning activity, thus enabling an inspection process that generates adequate quality data content.

The first step is to implement a quality assurance cycle [1] to understand the new users of the manufacturing data, thus to understand why to measure and pull the required information. The second step is to model the creation of product quality during the manufacturing process, that is, identifying what causes variation and how variation propagates through the product system along the different steps of the manufacturing process. The model the authors proposed in [31], see Fig. 6, can serve that purpose. In the model, top-level product requirements directly linked to product functionality are systematically broken down to product characteristics at each assembly level and consequently at each manufacturing operation. Linking the transformations of key product characteristics operation by operation to the product functionality tells *What* to measure: what product characteristics (Q) to measure before (Q^i) and after the operation (Q^{i+1}), as well as what manufacturing parameters (q) need to be measured to control the product characteristics

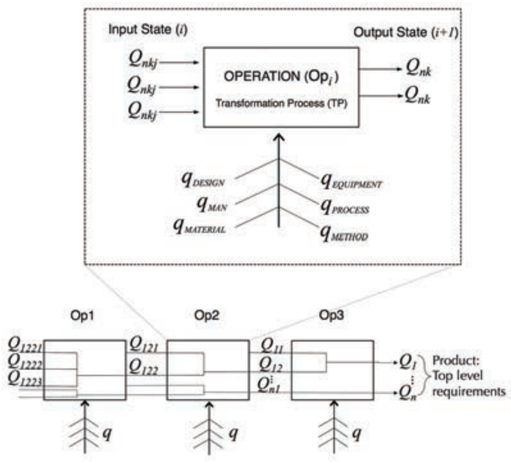

Fig.6. Model of variation generation and propagation by Madrid et al.

output of each operation. In the case of welded structures, weld bead geometry is a product characteristic (*Q*) output of the welding operation, which directly affects the fatigue life, thus the functionality of the component. Welding parameters or fixture positions are examples of manufacturing parameters (*q*) important to measure and control during the welding operation. By modeling the process in this way, it is also possible to track variation through the different operations so it becomes clear *When* to measure throughout the process. Having identified what and when to measure, *How* to measure is dependent on the users´ needs. Depending on why and who will use the data, the metrics to verify the product characteristics and manufacturing parameters need to be set in order to get adequate information.

Mirdamadi et al. [32] also considered the answers to the three questions: "What to control? How to control? When to control?" as the core of the inspection planning activity. In their study, the authors proposed a support to answer the first question "What to control" by creating an adapted Failure Mode and Effects Analysis (FMEA) framework to identify the key product characteristics to control. Moreover, Chen, Z. et al. [33] also proposed a framework of measurement to assist the assembly for wing-fuselage based on key product characteristics tree decomposition as the way to map and identify the measurement characteristics. In these two studies, the authors focused on identifying and prioritizing the relevant product characteristics that have an impact on product functionality in order to know what product characteristics need to be measured. In the same way, the model proposed in Fig.6, utilizes a product characteristic (*Q*) decomposition to identify what product characteristics to measure. Additionally, this model links those *Q* to what manufacturing parameters (*q*) to control and at which manufacturing operation. The objective is to enable the study of the interactions between product characteristics, as the operation outputs, and the manufacturing parameters, by gathering the adequate data.

7. Conclusions

Manufacturing companies are not reusing inspection data, as a source of manufacturing knowledge, in order to optimize product quality during design activities. It is more common to use the inspection data only to improve the on-going production process, not using the full potential of data.

This study contributes to the field of manufacturing knowledge reuse by identifying and classifying barriers to the reuse of inspection data in design activities.

In addition, the contribution to the field of inspection planning is made by proposing a structured approach to clarify *Why*, *What*, *How* and *When* to measure, thus helping to remove some barriers with regards to the generation of adequate data content, informational barriers. Deeper insight into manufacturing processes and a better understanding of dependencies between product characteristics, process parameters as well as their interactions is necessary for the generation of adequate measurement data. A better understanding of the production variation leads to producing adequate inspection data to reuse.

Acknowledgements

This work has been funded by VINNOVA and the NFFP6 program.

References

[1] Söderberg, R., Lindkvist, and Carlson. *Virtual geometry assurance for effective product realization*. in *NordPLM'06, Göteborg*, 2006.
[2] Taguchi, G., S. Chowdhury, and Y. Wu, *Taguchi's Quality Engineering Handbook*. 2005: Wiley.
[3] Runnemalm, H., H. Tersing, and O. Isaksson, *Virtual Manufacturing of Light Weight Aero Engine Components*. Proc. ISABE, 2009.
[4] Committee,A.M.E.C.A., *21st Century Advanced Manufacturing Modeling & Simulation Roadmap Focus Area Recommendations*. Jan 2013, NDA.
[5] Krogstie, L. and P. Andersson, *A Case Study on Reuse of Manufacturing Knowledge-Comparing Defense Practices with Automotive & Aerospace Practices*. Procedia CIRP, 2012. 3: p. 430-435.
[6] Andersson, P., *Support for re-use of manufacturing experience in product development from an aerospace perspective*. 2011: Luleå tekniska universitet.
[7] Verhagen, W.J., Bermell-Garcia, van Dijk, Curran, *A critical review of Knowledge-Based Engineering: An identification of research challenges*. Advanced Engineering Informatics, 2012. 26(1): p. 5-15.
[8] Tata, M.M. and A.C. Thornton, *Process capability database usage in industry: myth vs. reality*. ASME DFM Conference, 1999.
[9] Wandebäck, F., P.-J. Wahlborg, and R. Söderberg, *Use of measurement data in computer-aided tolerance management*. JED, 2002. 13(1): p. 63-76.
[10] Dantan, J., et al., *Information modeling for variation management during the product and manufacturing process design*. (IJIDeM),2008. 2(2):107-118.
[11] Lindau, B., et al. *Body in White Geometry Measurements of Non-Rigid Components: A Virtual Perspective*. in *ASME IDETC*. 2012.
[12] Okholm, A., Rask, Ebro, Eifler, Holmberg, Howard *Improving process capability database usage for robust design engineering by generalising measurement data*. in *13th International Design Conference*. 2014.
[13] Srinivasan, V., *Role of statistics in achieving global consistency of tolerances*, in *Global Consistency of Tolerances*. 1999, Springer. p. 395-404.
[14] Montgomery, D.C., *Statistical Quality Control-A Modern Introduction, John Whiley & Sons*. Inc., New York., 2009.
[15] Sandholm,L.,*Total Quality Management*. 2000:Studentlitteratur.
[16] Shewhart, W.A., *Economic control of quality of manufactured product*. 1931: ASQ Quality Press.
[17] Carlson, J.S., *Root cause analysis for fixtures and locating schemes using variation data*, in *Global Consistency of Tolerances*. 1999, Springer.
[18] Schleich, B., Anwer, Zhu, Qiao, Mathieu, Wartzack. *Comparative Study on Tolerance Analysis Approaches*. in *(ISoRD'14)*. 2014.
[19] Hasenkamp, Arvidsson, and I. Gremyr, *A review of practices for robust design methodology*. Journal of Engineering Design, 2009. 20(6): p. 645-657.
[20] Wärmefjord, K., *Variation Control in Virtual Product Realization-A Statistical Approach*. 2011, Chalmers University of Technology.
[21] Wärmefjord, K., J.S. Carlson, and R. Söderberg, *A Measure of the Information Loss for Inspection Point Reduction*. ASME JMSE, 2009. 131(5)
[22] O'Brien and Guzman, *American Welding Society, Welding Handbook Welding Processes*. 2007.
[23] Volume, A.H., *17: Nondestructive evaluation and quality control*. ASM International, 1989. 795.
[24] Suresh, S., *Fatigue of materials*. 1998: Cambridge university press.
[25] George, M., et al., *The Lean Six Sigma Pocket Toolbook*. 2004: McGraw-Hill Education.
[26] De Mast, J. and A. Trip, *Exploratory data analysis in quality-improvement projects*. Journal of Quality Technology, 2007. 39(4): p. 301.
[27] Shiba, S., *The Steps of KJ: Shiba Method*. 1987, English, mimeo.
[28] Georgiou, G.A., *POD curves: derivation, applications and limitations*. Jacobi Consulting Limited Research Report, 2006. 454.
[29] Thornton and Tata, *Use of graphic displays of process capability data to facilitate producibility analyses*. AI EDAM, 2000. 14(03): p. 181-192.
[30] Wandebäck, F., et al. *Variation feedback and 3D visualization of geometrical inspection data*. in in *ASME IDETC*, 2009.
[31] Madrid, J., Söderberg, Vallhagen and Wärmefjord, *Development of a conceptual framework to assess producibility for fabricated aerospace components*. CIRP CMS, 2015.
[32] Mirdamadi, S., et al. *An adaptive approach to failure modes and effects analysis for Computer-Aided Inspection Planning*. in *(IEEM)*, 2012.
[33] Chen, Z., et al., *A framework of measurement assisted assembly for wing-fuselage alignment based on key measurement characteristics*. International Journal of Manufacturing Research, 2015. 10(2): p. 107-128.