ICED13
INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

PERFORMANCE MEASUREMENT SUPPORTING CLOSED LOOP TOLERANCE ENGINEERING – AN INDUSTRIAL CASE ON TOLERANCE AND VARIATION COLLABORATION

Lars KROGSTIE (1,2), Bjørn ANDERSEN (2), C.J. VERBERNE (3)
1: Gjøvik University College, Norway; 2: Norwegian University of Science and Technology, Norway; 3: Nammo Raufoss AS, Norway

ABSTRACT

Tolerances and Variation are interlinked and omnipresent throughout any engineering organization dealing with design and manufacturing of physical artefacts, but is disproportionally visible in recent academic literature. This industrial case obtains its empirical findings from focused and structured in-depth interviews with industrial professionals within a high precision manufacturing company. Qualitative analysis of data provides insight and understanding in the underlying reasons for repeated deviations related to tolerances and variation. The resulting proposed outline of Performance Measurement (PM) metrics for the engineering team is expected to contribute to a strengthening of focused collaboration on tolerance and variation related activities. Low level PM metrics supporting Closed Loop Tolerance Engineering (CLTE) are of academic and industrial interest as such tolerance and variation metrics have a direct or indirect link to top level metrics via their influence on product quality and product function. The novelty of the paper is found in applying the CLTE-model for data gathering and in the addressing of PM in industrial improvement actions on tolerances and variation.

Keywords: integrated product development, collaborative design, organisation of product development, tolerances and variation, CLTE

Contact:
Lars Krogstie
Gjøvik University College
Department of Technology and Management
Gjøvik
2815
Norway
lars.krogstie@hig.no

1 INTRODUCTION

Tolerances and variation play an integrated and important role for industry practitioners within product development and manufacturing. Literature however, seldom addresses the effects of engineering collaboration on tolerances and variation. This paper explores these effects within product development and manufacturing in a novel way by applying the research principles of Closed Loop Tolerance Engineering (CLTE). This research is based on a practical problem within high precision manufacturing industry. It is based on findings from twenty-one in depth semi-structured interviews with engineering professionals from multiple disciplines. The root causes of a number of instances of nonconformity is searched for. This research aims at *understanding* some of the reasons for the repeated deviations related to tolerances and variation. As soon as a sufficient understanding is gained, an additional aim for this research is to suggest performance metrics which can *improve* tolerances and variation practices within design and manufacturing departments. Performance Measurement (PM) is both an accepted and often discussed way to trigger organizational change and to manage improvement. The possibilities and limitations of metrics covering the very complex collaborative activities related to tolerances and variation are hence explored.

This paper is structured according to the following logic. The theoretical background highlights issues related to tolerances, variation and PM. The methodology chapter describes the methods of Closed Loop Tolerance Engineering (CLTE) interviews and the data gathering. Results from the interviews are then presented and discussed. The conclusion presents an outline of performance metrics for CLTE. The paper ends with suggestions for further research.

2 THEORETICAL BACKGROUND

The industrial importance of good tolerances and variation management and collaboration is high. Creveling (Creveling 1998) states *"tolerances are critical to the successful manufacture and performance of the product over its intended life cycle"*. In accordance with the desire of Andreasen and Wallace (2011) to bring academia and industry closer, this paper aims at making a contribution by showing the link to industrial practice, strengthen the attention on tolerances and to focus on how performance metrics can support the active engineering collaboration on tolerances and variation.

Tolerances and Product development

Product Development (PD) is a complex task including several participants and activities. The Pahl & Beitz classic book on PD (Pahl, Beitz et al. 1996) lists no less than 120 models, where only a few focus directly on tolerancing. A lack of awareness of tolerancing, and in particular Geometric Tolerancing & Dimensioning (GD&T) in engineering education is addressed by authors such as Watts who states (2007) *"GD&T has gradually been removed from the curriculum at universities and has been replaced by other product development courses"*. Zhang and Huq (1992) address this topic as well, describing GD&T to be *"trainable but not teachable"*. Watts addresses what he calls the *"GD&T knowledge gap in industry"* as he claims to see that *"all industry is suffering often unknowingly"* of the lack of *"adequate academic attention"* in mechanical engineering design courses. The lack of addressing tolerancing topics directly (not limited to GD&T applications) can be seen as a paradox as any product needs a description of how it should be manufactured. Such a description will include tolerances, and tolerances should not occur at random.

Tolerances are omnipresent throughout any engineering organization dealing with design and manufacturing of physical artefacts (Henzold 2006). Designers safeguard functionality through tolerances, the manufacturing department applies them as limits for production, inspection departments uses them as quality acceptance criteria, and so forth. *Tolerance engineering* can be seen as all those engineering activities which directly focus on tolerances. *Tolerancing,* on the other hand, is basically all those activities that lead to the definition of a clear recipe of how the product is to be manufactured. Tolerancing is hence a subset of tolerance engineering activities, where tolerances are part of the communicating language.

According to a review of product development models by Horvàth (2004), a stronger focus on human relations in engineering design is visible during the last decades. Hence, the important activities of tolerance engineering are nowadays often "hidden" within the activities of *embodiment design* or *detail design* in respected product development models (Pahl, Beitz et al. 1996). There appears to be a gap between two traditions in the Product Development literature. First, the *"process and human* *oriented"* branch represented by (Ullman 2003; Cross 2008; Ulrich and Eppinger 2008; Lindemann 2010). This branch focuses on development processes, innovation and collaboration, but often lacks a direct focus on tolerances. Secondly, the *"tools oriented"* tolerancing literature which often sees tolerances as a language for communicating specifications (Nielsen 2012), as an object for optimization (Kunert, Auer et al. 2007) or as a topic for norms (Srinivasan 2008). This branch hardly focuses on human aspects at all. The technical tolerances and the participating engineers are coexistent in industry, but are seldom addressed together in literature.

Variation and Manufacturing

Tolerances and variation in terms of process capabilities are closely interlinked. Tolerances represent normative descriptions of *how to* manufacture, and process capabilities as expressed in measured variation represent the empirical values of how it *actually got* manufactured. Manufacturing performance is often measured through quality, i.e., the ability to produce conformal parts. The conformity is measured against specification limits that are often directly linked to the technical tolerances of the product drawings. One way of measuring conformity and quantifying the level of variation is through the Process Capability (C_{pk}) measure that expresses the variation within a set of measurements in relation to the given control-limits. Process capability is thus a measure of variation in manufacturing processes. A large body of literature exists for this topic, starting with Shewhart's early ideas of Statistical Process Control (SPC), but also the Deming management classics (1982) and its successors could be mentioned. Several of Deming's famous 14 principles of management focus on the awareness and the reduction of variation but do to a low extent address the link to tolerances.

Performance measurement

Engineering design is often described to be a messy and complex process with many stakeholders and activities (McCarthy, Tsinopoulos et al. 2006). Still, product development is not a series of random happenings, but in most cases a quite structured business process. Therefore, also product development processes can be understood, measured and improved. Kaplan and Norton presented the Balanced Scorecard (BSC) approach for designing performance measurement systems (1996). This model highlights that the performance measurement system should consist of more than only financial measurements. They separate between *leading* and *lagging measurements*. They argue that financial measurements are *lagging measurements* which only tell the performance of the past. Kaplan and Norton argued that the financial metrics should be supplemented by metrics that drive future performance. Drivers for future performance are often called *leading indicators* and CLTE-activities can represent some of those.

3 METHODOLOGY

The researcher followed the case company for almost two years. Although the researcher gathered several other impressions through observations, participation, conversations and document studies, this paper focuses mainly on empirical data captured through interviews.

Research design

Addressing and researching how an organization handles tolerances and variation is challenging as both tolerances and variation are omnipresent. Closed Loop Tolerance Engineering (CLTE) is a conceptual model that focuses on the relations between four activities within product development and manufacturing (Krogstie and Martinsen 2012).

The research design is based on CLTE and an interview guide for semi-structured interviews was developed based on the CLTE activities of *"functional requirements, tolerancing, process capabilities* and *product performance".* The CLTE model focuses strongly on the relation between the activities and the utilization of the knowledge potential (both in terms of progress/reflection).

CLTE can be defined as *"The systematic and continuous re-use and understanding of product-related knowledge, with the aim of designing robust products and processes with the appropriate limits of specifications".*

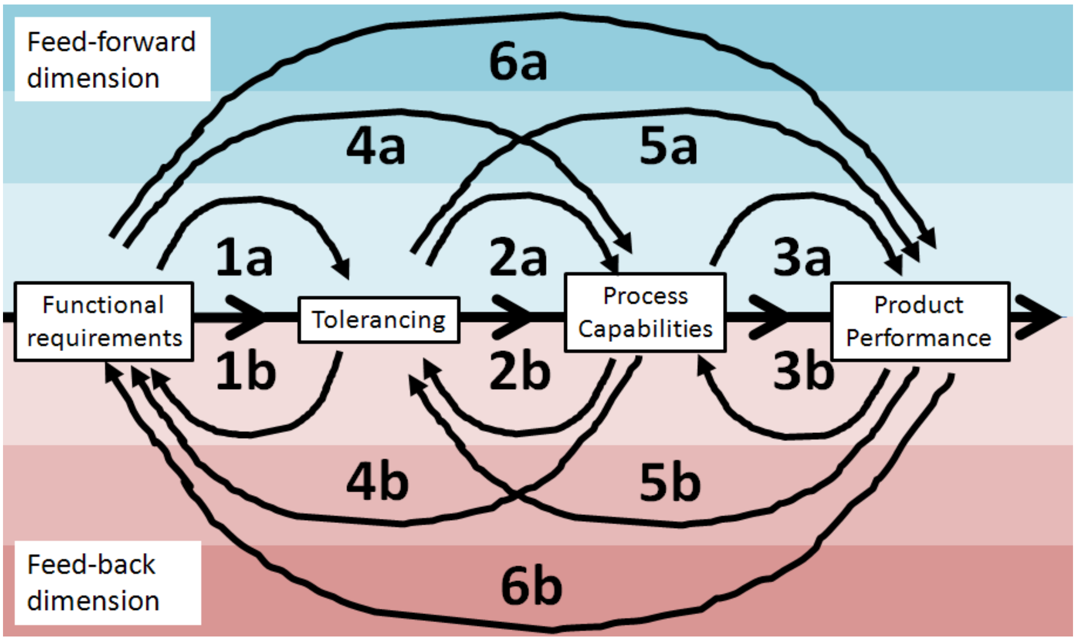

Figure 1: Activities and relations within CLTE.

Semi-structured, digital recorded interviews were chosen as the vehicle for gathering quantitative data with a direct focus on case study topics. The strength of interviews was acknowledged by Yin (1994) in their ability to provide *insight* as they serve *explanations and causal inferences* (p.102). The structured interviews were designed to last approximately for one hour, a duration recommended among others by Tjora (2012) (p.107). For all interviews, a template was used to capture data on how the interviewees worked on CLTE-activities and the measurement of those.

Interviewee selection

The aim of the interviews was to gain impressions on tolerances and variation from different business perspectives. Hence the selection of participants was done within the functional areas of among others *designers*, *manufacturing employees* and *project managers*. The selection of participants was done based on the impressions gathered over approximately 2 years of regular presence at the company. People regarded as "key employees" by the researchers and/or other employees within multiple engineering disciplines (mechanical, chemical, and electronics) representing both low and high volume products were invited for interviews. This deliberate selection provided a balanced view on CLTE-related activities from several functional areas of the company.

Data analysis

For this project the researcher used the nVivo[1] software tool for post-processing qualitative data. This included transcribing the recorded interviews to written text and coding. Coding within qualitative research includes the identification and sorting of re-occurring text elements in the empirical data. Tjora (2012) distinguishes between the process of coding and categorization, and recommends the approach of "text-based" coding (p.179). This means that text elements are used directly instead of coding based on theory, hypothesis or research questions.

4 THE CASE COMPANY

The aim of this research was to gain a rich in-depth impression of the complexity of tolerance and variation collaboration. The company is seen as an ideal case for CLTE-research as a large amount of its manufacturing processes are related to high-precision manufacturing as well as it manufactures products with a high demand for reliability. It also utilises a rich mixture of disciplines as the company develops and manufactures products including mechanical, chemical and electronic components.

[1] More information on nVivo10 under www.qsrinternational.com

Existing Performance Measurement in the case company

The case company is currently far along in a process of revising its performance measurement system toward a balanced set of metrics. Corporate and business unit metrics are placed above the scope of this research, which holds a strict focus on technical issues related to tolerances and variation. Consistently delivering a high precision product with superior quality and product performance is essential for market acceptance and financial outcome. Tolerances and variation is on a low level directly linked to quality and product performance (mid-level) and the top level financial and market impact. Collaborative engineering efforts on tolerances and variation has been in progress for decades, and novel low level metrics supporting tolerance engineering activities are expected to further strengthen and focus the positive development on those activities within the organization. The identification of those metrics in relation to the engineering activities are to be defined through the interview findings in this research.

5 RESULTS AND DISCUSSION

This section presents the results from 21 interviews (each 1 hour) with employees of the case company. Four major areas of findings emerged from the interviews, as shown in Table 1. Each topic is analysed and discussed in terms of empirical data describing the symptoms from the different perspectives. The interview statements outline the organizational consequences of insufficient CLTE-attention and aims at understanding the root causes of each symptom. Empirical findings are compared with relevant literature for selected areas. Each of the four general topics will be dealt with individually.

Table 1: Four general topics and their corresponding symptoms.

Topic:	*Symptom:*
i) Tolerance and Variation	Non-conformance between tolerances and variation as manufacturing fails to meet the specified parameters of the product.
ii) Process Control	Uncertainty about variation and reasons for “falling outside” specified limits.
iii) Project Execution	Weak culture for Performance Measurement on project activities supporting cross functional collaboration on tolerance and variation..
iv) Underlying Assumptions	Hard to trace the underlying assumptions behind both defined functional requirements and tolerances.

i) Tolerances and Variation

Tolerances and variation are at the centre of the CLTE model. One common definition of the term “tolerances” is “*limits of specifications*”. On a unprepared direct question of what the respondents` defined as “tolerances” they often replied *“tolerances; is what the part shall fulfil”*, a statement that points both back to the intended function in terms of functional requirements as well as forward to the actual product performance. The different functional areas related their limits to those parameters which are relevant for their work situation. Mechanical engineers frequently saw tolerances to be limited only to geometrical tolerances and the nature of Geometrical Dimensioning and Tolerancing (GD&T) (Jorden 2009), (Nielsen 2012). Process engineers referred to tolerances in the context of assembly to be related to acceptance criteria for function. Engineers dealing with chemical components referred to tolerances in terms of filling weights or mixing ratios. A development engineer from the electronic area had a quite open definition of tolerances as general limits but frequently referred to tolerances manifested through limits for electrical voltage. The manifestation “variation” is seen in the CLTE activity of handling process capabilities and SPC-data.

Descriptive empirical findings

Both quality managers and project managers in the mechanical manufacturing area stated that they spend valuable time dealing with the non-conformance waiver processes related to a mismatch between required limits and obtained precision in manufacturing. The established company routines pick up these mismatches and by that prevent the failure to be passed on to the customer, but the waiver process ties up noticeable resources. The outcome of a non-conformance waiver process can be very different from case to case. In extreme cases, the production batch will be trashed and has to be remanufactured. In other cases a manual sorting of the batch is the chosen solution. Another option is that the non-conforming part will be accepted with a “*use-as-is*” acceptance. This acceptance

represents an allowance from the customer to ship the parts "*as-is*" based on an engineering judgment of its impact on function and safety. However, the respondents do in general claim that the frequent use of "*use-as-is*"-allowances undermine the respect for the manufacturing limits. Some other observations made were; the risk to re-use existing historical limits of specifications and applying these without the required critical examination of the correctness of the previous limit. Further, that limits were often defined in a (seemingly superfluously) too tight fashion. This practice is described in literature by Zhang stating *"many parts and products are certainly over-toleranced or haphazardly toleranced, with predictable consequences"* (1997) (p.6).
The importance of adequate knowledge on manufacturing capability was highlighted by several participants, however from different perspectives and functional practices. The mechanical manufacturing departments reported to a large extent an active use of online SPC for their processes. Other functional areas, such as the assembly department or departments dealing with mixing of chemicals, reported less frequently the use of tools for SPC tracking. Reasons mentioned for this were low-volume production batches and the safety risk to introduce electronic components in the departments handling the mixing, pressing and heat-treatment of explosive components. The mechanical departments, which had been using tools for SPC for a while mostly reported positive experiences. A clear statement was that the operators gained new insight into their ability to actively influence the process through the adjustment of parameters they could influence upon. The display of the process path at the operators' workplace helped them to maintain an increased level of awareness of process capabilities in the department. In addition SPC data could be used as basis for both ad-hoc daily communication between process engineers and operators as well as in more formal start-up meetings and evaluation meetings.
Large part of the reasons for defining tight tolerances with a weak link to the manufacturing capabilities was found in the historical organization of the company. A quality manager and a design manager, each with more than three decades of experience within the company, described the previous situation and transition into the current status semi-identically in separate interviews. *"Earlier we had a much lower level of education among the engineers".* They also addressed the historical physical distance between the "product office" and the draftsmen. Up until 15 years ago there was a low degree of involvement between the two groups. There also existed a historical culture for defining tolerances as tight as possible, opposed to defining them as tight as needed. One experienced design manager stated "*we sometime even recognise the "personality" of the different engineers on existing drawings. When we see tight tolerances from certain employees that we know to be extra careful, we can almost assume that the parameter has been over-specified".*
The introduction and active use of SPC increased the organization's ability to gain knowledge of process capabilities through visualization of such data. This process knowledge is a useful asset in making fact-based decisions. The participants reported that this knowledge is (now) used to face "strange requirements" that originate from the customer. Both the increased level of education, the co-location of the development team and the increased use of fact-based tools such as SPC data boosted the "guts" to face the customer with challenging questions related to functional requirements and tolerances. A few examples of tolerance simulation and analysis were mentioned. However, there is a strong potential in further increased use of tools for tolerance simulation and analysis within the company.

Researchers' normative recommendations

The following bullet points summarize the suggested remedies for *tolerance and variation mismatch*:

- Further strengthen the collective competence of the team to question tolerances and functional requirements as defined by the customer.
- Increase the understanding of the functional behaviour through tools for simulation and analysis.
- Continue to develop a culture for function-based tolerance definition.
- Support and develop increased reuse of SPC data in the development department.
- Bring designers and manufacturing employees together in the work on tolerance analysis and discussions of process capabilities.
- Empowerment of the designers to search process knowledge and to gain personal contact points in the manufacturing department.

ii) Process Control

The company manufactures products of large variety. The interviewees represented both high-volume manufacturing of single-piece metallic components, low-volume complex assembly processes as well as intricate chemical mixing processes.

Descriptive empirical findings

One highly experienced engineer responsible for the production of one type of chemical components highlighted the challenge in understanding the influence of parameters and covariance. Often seven to eight components are included within one composition in a mix that will be used for four different products with slightly different requirements. "*My nightmare is when I need to replace an existing component with another as the co-variance between parameters and their impact on product performance is hard to judge"* this person stated. Several other employees talked about testing, parameter impact and the understanding of linking parameter variation to product performance variation. Still, few of those mentioned the tool Design of Experiments (DoE), which describes a way of planning, executing and analysing experiments based on statistical methods that provide more information with fewer experiments. DoE is proven to be a very powerful tool, among others reported by Simms and Gavin (2002).

The researchers noticed a large difference between the departments talking about "process capabilities" in the right context and those tending to talk about variation. Departments producing mechanical products showed an extensive use of SPC and claimed to be using this tool to make conscious adaptations in the process to stay within the inspection limits (tolerances). Other departments, such as chemistry, occasionally saw variations something slightly less mystical than black magic. They all claimed to be able to control the process, but many described it as cumbersome and tedious to do so. Participants from such departments also said it was easy to "fall outside" the limits in terms of not knowing when the uncertainties would add up to falling outside of the range of accepted performance. Such departments mainly used traditional quality assurance practices.

Researchers' normative recommendations

Good experiences in the use of SPC in some departments should clearly be used as inspiration for other lagging departments. The areas where SPC tracking can be implemented are not at all limited to tracking geometrical measures. Any parameter that can be measured can also be logged. Increased process control and increased product understanding can additionally be gained through the use of designed experiments (DoE). A significant reduction in the amounts of testing is expected to be possible and at the same time gaining more understanding of parameter impact and co-variance patterns in particular.

The following points summarize the suggested remedies for *process control:*

- Implement SPC tracking of all processes that can be measured.
- Stop accepting variation and "falling outside" without initiating actions which improve the understanding of the process capability (C_{pk}) and subsequently improve process control.
- Use DoE together with testing. Combine physical testing and computer aided simulation/analysis.
- Integrate the measurement lab more strongly into operations and product development.
- Gradually change the attitude from test- and measurement departments from being a "service provider" to a discussion partner.

iii) Project Execution

Project execution in a complex product development project is performed in the tension field between strict project control and leaving freedom for innovation and work mode improvements. Both approaches can be either suitable or challenging approaches for managing projects dependent on the context. This research is performed in a geographic region where a less strict project management culture has proven to be the most effective. This approach requires skilled and motivated employees with a willingness to collaborate and share knowledge. Performance measurements on individual level are traditionally used to a low extent as individual metrics can be perceived as control and thus reduce individual initiative and motivation.

Descriptive empirical findings

All interviewees were questioned on the measurement of CLTE activities in the projects they had worked on. Few reported that the results of their work had been measured either individually or within the engineering team. Despite this low degree of Performance Measurement (PM) on activities related to tolerances and variation, we clearly sensed that this company is used to "getting things sorted out". Still, in other parts of the CLTE interviews not addressing PM explicitly, the *project execution* was often commented. Clearly, a large amount of the projects were driven by skilled project leaders and staffed with motivated engineers with the right knowledge. Due to finite resources and given deadlines, project leaders were reported to constantly make compromises between gaining project progress and solving the engineering task "well enough" without over-engineering. These processes demand a well-functioning communication between the departments. The interviewees did to some extent request clearer management control of projects, in particular on projects led by junior project leaders. The fact that project managers were given a large degree of freedom in terms of which tools they employ was also mentioned as an asset. This has been a decisive factor in winning new customers in a fierce international competition. The downside of this asset is however also visible when proven powerful tools are not utilized in projects. Some examples were mentioned of letting projects through design gates although they were clearly not "green". Repeating this practice without very good reasons for doing so is expected to reduce the respect for design gates in general.

Researchers' normative recommendations

Project managers are found relatively free to employ (or not to employ) those tools the project manager finds adequate for solving the task. However, the knowledge-based tools such as Finite Element Method (FEM) for functional analysis and simulation, tolerance simulation tools (e.g. VIS-VSA[2]), designed experiments (DoE) and the reuse of manufacturing information (SPC-data) are suggested to be prescribed to a larger extent. All those tools either draw on existing knowledge from other departments or have led to obtain progress in a development project earlier. These tools support the main ideas of Closed Loop Tolerance Engineering. CLTE-thinking includes the systematic and continuous reuse and understanding of product related knowledge and is expected to increase the team's awareness of tolerances and variation in a structured way. The increased awareness is expected to improve the engineering collaboration within the projects.
The following points summarize the suggested remedy to improve *project execution:*

- Re-introduce stricter demands to pass design gates.
- Introduce PM of critical areas directly linked to tolerance and variation-related activities.
- Support Closed Loop Tolerance Engineering thinking throughout the project.

iv) Underlying Assumptions

The topic of "underlying assumptions" was addressed when discussing both functional requirements and tolerances. Development engineers mentioned the difficulty of challenging the assumptions behind the defined interface tolerances since "the interface people" are often very rigid and cannot always make a plausible explanation for the reasons behind the given tolerances. The "interface people" are in this context the engineers that control the acceptance limits on parameters in the direct intersection between the case company and the customer. Functional requirements were roughly divided into two categories; the external requirements and the internal requirements. The two categories showed differences in how easy the underlying assumptions could be traced and understood.

Descriptive empirical findings

External requirements were often stated to be on one side clearly defined, but on the other side to be demanding to trace back to their assumptions. Participants gave the impression that the willingness and ability to challenge ”strange” functional requirements had increased dramatically the latest years. The increased courage to raise fundamental questions was explained through increased knowledge in the project teams through a larger amount of engineers with higher education as well as the increased amount of internal research and improvement projects. The latter a clear proof of the positive effect of re-using earlier experience, although not yet in a perfectly structured way. Although functional

[2] More information on VSA under http://www.plm.automation.siemens.com/

requirements defined by the customer were more frequently challenged now, it did not necessarily mean that the customer was either able to or willing to answer the queries.
The underlying assumptions of tolerances were also addressed. One of the most effective ways of verifying the underlying assumptions was, according to the participants, to ask a colleague. This is perfectly in line with the statements by Lindemann et. al. (2010), which concludes that in nearly 90% of the information requests, the designer contacted another person (p.187). The use of this strategy to figure out the underlying assumptions works well in those cases where the engineer is still present in the engineering environment. However it appeared to be increasingly more difficult to trace the assumptions for projects that were more than 5-10 years old.

Researchers' normative recommendations

The following points summarize the suggested remedy to capture unknown *underlying assumptions:*

- Constantly challenge each other (internally/externally) on established "truths".
- Constantly search for the real functional requirements for any product or part.
- Develop a system for capturing the crucial assumptions underlying critical tolerances.

The four main areas listed above represent no complete list of all reasons that might cause challenges in the engineering practice on tolerances and variation. Still, they represent a step forward towards strengthened collaborative CLTE activities. An increased direct focus on engineering details such as tolerances and variation is essential as they directly or indirectly impact top level metrics in the company. A PM system based on individual metrics is not recommended as it likely will fail to cover the complexity of product development and manufacturing. Applying PM for team motivation is, according to Spitzer (2007), only possible through right *context, focus, integration,* and *interactivity.* Thus, focal areas for improved CLTE-performance where collaborative metrics can encourage increased engineering efforts on activities on tolerances and variation are pointed out. Still the final definition and operationalization of such collaborative metrics needs thorough insight into the organizational details to succeed. Low-level metrics are of no value if they are not integrated with metrics supporting high-level decision making. The wise selection of focal areas related to tolerance and variation-related activities, combined with only a few CLTE metrics driving collaborative engineering should be implemented and expanded in terms of use in consecutive projects.

6 CONCLUSION

This paper has presented findings about how tolerances and variation is handled by professionals within a high-precision-manufacturing case company. The main message of this paper is that tolerance complexity is easily underestimated and that good tolerance & variation management requires good technical skills, collaboration and management attention. The rationale for researching tolerances and variation simultaneously has been addressed with reference to relevant literature. The research rationale is strengthened as the case company faces continuous challenges in their work on tolerances and variation. Although this research is based on data from only one company it is assumed to have strong relevance for other industries, as tolerances and variation is omnipresent within all kinds of product development and manufacturing.
The findings from interviews with people from various disciplines in the company show that even a successful company displays shortcomings in how tolerances and variation are handled. On an overall level, a general problem is that manufacturing performance does not match the defined tolerances. This leads to waste, in the form of extensive testing and rework or procedures to have sub-standard quality parts accepted "*as-is*". Occasionally, where products fail to meet tolerance limits, those specifications seem to be not very deliberately set. Tolerances are typically set unnecessarily tight, either out of tradition, lack of knowledge, failure to reuse manufacturing data, etc. It also became clear that manufacturing departments applied different *process control* approaches. Those departments using SPC had considerable better chances to know whether a process run would end up within the limits. Some of the problems could be traced back to how product development *projects* are executed. Projects were allowed to proceed through decision gates without all requirements fulfilled, Performance Measurement on tolerance and variation-related activities was only used to a limited extent, and project management was not involved very much in tolerancing matters. The final topic of findings revolves around *underlying assumptions* of tolerances, where it was found that in many cases

tolerances were set some time ago and where the assumptions for the setting of the tolerances had been lost and no system existed for storing these.

Based on the four identified findings, the research has proposed some actions on how the company can further improve its performance. These include strengthening the general awareness of tolerances and variations, stimulating a culture of daring to question customer-defined tolerances, extending the use of tools like SPC, DoE, etc., focusing on process capability and using data about manufacturing performance to influence the design process, firming up the management of development projects, introducing measurements of critical areas directly linked to tolerance and variation-related activities, and more actively store and challenge underlying assumptions on tolerances.

Since this study relies on data from one case company only, further research should be undertaken to verify whether other companies, in similar manufacturing context as well as otherwise comparable conditions, face the same challenges.

ACKNOWLEDGMENTS

The researchers gracefully acknowledge the case company for extensive research access and support. A special thanks to the employees participating as interviewees. Without their willingness to answer all the questions openly and honestly this research would not have been possible.

REFERENCES

Andreasen, M. and Wallace K. (2011) ‘Reflections on Design Methodology Research‘ *International Conference on Engineering Design - ICED11* Copenhagen, The Design Society.

Creveling, C. M. (1998). *Tolerance design*, Massachusetts, Addison Wesley.

Cross, N. (2008) *Engineering design methods: strategies for product design*, Chichester, Wiley.

Deming, W. E. (1982) *Out of the crisis* Boston, Massachusetts Institute of Technology.

Henzold, G. (2006) *Geometrical dimensioning and tolerancing for design, manufacturing and inspection* Burlington, MA, Butterworth-Heinemann.

Horváth, I. (2004) ‘A treatise on order in engineering design research‘ *Research in Engineering Design* vol. 15, no. 3, pp. 155-181.

Jorden, W. (2009) *Form und Lagetoleranzen*, München, Carl Hanser Verlag

Kaplan, R. S. and Norton D. P. (1996) *The balanced scorecard*, Boston, Harvard Busin. School Press.

Krogstie, L. and Martinsen, K. (2012) ‘Closed Loop Tolerance Engineering – A Relational Model Connecting Activities of Product Development‘ *Procedia CIRP* vol. 3, no. 0, pp. 519-524.

Kunert, J. and Auer, C. et al. (2007) ‘An Experiment to Compare Taguchi's Product Array and the Combined Array‘ *Journal of Quality Technology*, vol. 39, no. 1, pp. 17-34.

Lindemann, U. (2010) *Human behaviour in design: individuals, teams, tools*. Berlin, Springer.

McCarthy, I. P., Tsinopoulos, C. et al. (2006) ‘New Product Development as a Complex Adaptive System of Decisions‘, *Journal of Product Innovation Management*, vol. 23, no. 5, pp. 437-456.

Nielsen, H. S. (2012) *The ISO Geometrical Product Specifications Handbook* ISO / Danish Standards.

Pahl, G., and Beitz, W. et al. (1996) *Engineering design.* London, Springer.

Simms, C. and Garvin, J. S. (2002) ‘“It’s a black art”: “design of experiments” switches on the light‘ *Managerial Auditing Journal* vol. 17, no. 1, pp. 65-71.

Spitzer, D. R. (2007) *Transforming performance measurement: rethinking the way we measure and drive organizational success*. New York, American Management Association.

Srinivasan, V. (2008) ‘Standardizing the specification, verification, and exchange of product geometry: Research, status and trends‘, *Computer-Aided Design* vol. 40, no. 7, pp. 738-749.

Tjora, A. H. (2012) *Kvalitative forskningsmetoder i praksis*, Oslo, Gyldendal akademisk.

Ullman, D. G. (2003) *The mechanical design process.* Boston, McGraw-Hill.

Ulrich, K. T. and Eppinger, S. D. (2008) *Product design and development.* Boston, McGraw-Hill.

Watts, D. (2007). ‘The ``GD&T Knowledge Gap" in Industry‘; *ASME Conference Proceedings*, Issue 48051, pp. 597-604.

Yin, R. K. (1994) *Case study research: design and methods*, Thousand Oaks, Calif., Sage.

Zhang, H.-C. (1997) *Advanced tolerancing techniques.* New York, Wiley.

Zhang, H. C. and M. E. Huq (1992). ‘Tolerancing techniques: the state-of-the-art‘, *International Journal of Production Research* vol. 30, no 9, pp. 2111 – 2135.