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Beyond Lean and Six Sigma; Cross-Collaborative Improvement of Tolerances and Process Variations - A Case Study

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Abstract

Good tolerance- and variation management is essential to achieve high value adding products with cost-effective processes. The link between Tolerance Engineering and popular manufacturing improvement philosophies such as Lean and Six Sigma is, however, not always that clear. The possibilities and limitations of these two approaches on Tolerance Engineering are discussed in this paper. The case describes cross-collaborative improvement work within industry on tolerance and variation management which is similar to a work model called "Closed Loop Tolerance Engineering" (CLTE). The case is focused on the process of revising existing drawings and tolerance specifications for the manufacturing of products with a long lifetime. Although both Lean and Six-Sigma have been important for the improvement work in the case company for several years, there is still a gap to be filled on tolerance and variation management. The novelty of this paper is found in the link between an industrial case on improvements and an academic model (CLTE) for cross-collaborative engineering on variation and tolerances.

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Keywords: Tolerances; Variation; Lean; Six Sigma; CLTE; Collaboration;

1. Introduction

The management of product specifications, process variations and quality inspections is central to any manufacturing company, and tolerances represent the main way to specify limits to geometry and other parameters. Optimal tolerances are important for product function, correct fit in assembly processes, selection of process steps, inspection strategy and manufacturing methods, and thus bridge several steps in the product lifecycle. Lack of coherence between the product design, manufacturing and the inspection can lead to quality problems. The tolerance standards such as Geometrical Dimensioning and Tolerancing (GD&T) [1] can be seen as a general "language" to communicate the limits of specifications related to geometrical parameters. Zhang [2] states: *"A bridge between design and manufacturing, functional tolerances are absolutely necessary….."*. Creveling [3] states "*tolerances are critical to the successful manufacture and performance of the product over its intended life cycle"*. Optimisation software has given the designer new tools for optimising tolerances. The link to manufacturing and inspection is, however still crucial to achieve cost-efficient manufacturing with good quality. Current quality and efficiency paradigms such as TQM, Lean and Six Sigma [4] do to some extent address variations management in manufacturing and quality inspection. There is, however, still a lack of a good connection between tolerance synthesis in the design phase, manufacturing process capabilities and variations as well as quality inspection. The case in this paper shows how collaboration focused on tolerance- and variation-topics enabled to bridge the gap between product development, manufacturing & inspection; an approach similar to Closed Loop Tolerance Engineering [5].

2. Theoretical Background

In spite of the central role tolerances play in manufacturing, they seem not to have a prominent place

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in engineering and academic literature. Literature such as Day [6] and the standards such as ASME Y14.5M [7] covers the essentials of GD&T but focusing on their purpose as tolerancing norms mainly in the product design phase. The ISO/TC213 committee [8], [9] works on joint GD&T principles for design, manufacturing and metrological principles. The human aspect in the tolerance management process is, however, not addressed.

A lack of awareness of tolerancing in engineering education is addressed by authors such as Watts [10] *"GD&T has gradually been removed from the curriculum at universities and has been replaced by other product development courses*. Zhang et al. [11] address this to some extent, 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. Parameter Design activities after the 1950, such as the Taguchi Method [12], take a Design of Experiments (DoE) approach to product and process design, and Nair [13] organizes the discussion between engineering and statistical-based approaches at an early stage.

An accessible entry point to tolerance engineering can be found in a literature review such as that by Hong [14]. Horvàth [15] justifies the latest trend towards human aspects in engineering design as seen in books by Lindemann [16], Badke-Schaub [17] or Frankenberger [18]. Product design literature such as Cross [19], Ulrich & Eppinger [20], Ehrlenspiel [21] and Pahl & Beitz [22] are all examples where GD&T unfortunately is given little focus. Creveling addresses collaboration on tolerances directly in his book on Tolerance Design [3].

3. Tolerancing in Lean and Six Sigma

Lean is a philosophy that promotes continuous improvements with its roots in the Japanese automotive industry [23]. Six-Sigma is another strategy for problem solving and engineering improvements with its roots in the American electronics industry. Both initiatives have been powerful movements for improved product quality, optimised material flow, reduced waste and numbers of defects within manufacturing and service worldwide. The zero defects philosophy in these approaches implies a need for understanding and reduction of variation in manufacturing. Tolerance management is, however, only indirectly addressed. Deming [24] focuses directly on "variation" in several of his managements principles but does not address tolerances as such. Even though Lean and Six Sigma initiatives have further been moved towards product development through initiatives such as Lean Product Development (LPD) and the loosely defined Design for Six Sigma (DfSS) [25], the focus on Tolerancing is still lacking. An illustrative comparison between the principles, practices and tools of LPD and DFSS is provided by Fouquet et. al. [26]. Hasenkamp [27] argues that the important driver for implementing a robust design is the awareness of variation. We will argue that awareness of tolerances and their link to manufacturing variation holds similar importance.

4. Closed Loop Tolerance Engineering.

The model of Closed Loop Tolerance Engineering (CLTE) is presented [5] as a contribution to closing the gap between product design, manufacturing, inspection and product performance. The CLTE model (see Fig 1) contains four *activities;* (i) defining functional requirements, (ii) defining tolerances, (iii) considering production capabilities and, (iv) confirming functional performance. CLTE activities are organised into two dimensions; (a) The normative dimension which includes the activities (i) & (ii), and (b) the empirical dimension, which includes the activities (iii) & (iv). A bridge is needed to connect the product development participants (how things should be) and the manufacturing participants (how things really are) with regard to their work on tolerances. Each activity stands in a relation to a following or preceding activity. CLTE contains altogether 6 pairs closed loops of relations. Each *relation* has some key elements which represent typical examples of the context-dependent content in each relation. An explanation of the participants, practices, information, knowledge and tools for this context is listed in [5].

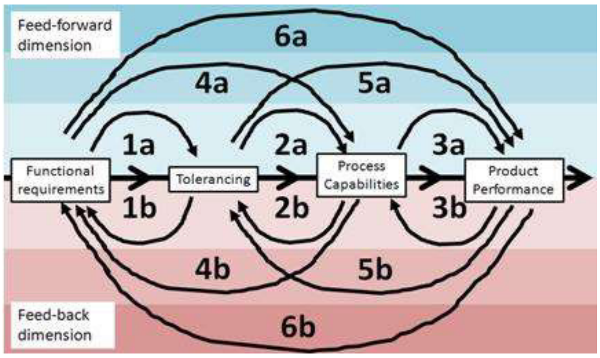

Fig. 1: Four activities and the 6 pairs of closed loop relations in CLTE

CLTE includes several *participants* as it can be considered as an integrated engineering workmode. The need for cooperation across functional borders within product development is described among others by [28] and [21]. In a typical CLTE context, participants will be; designers, project leaders, quality assurance (QA) engineers (incl. meteorology), manufacturing operators, test engineers, process engineers, foremen etc. The CLTE *tools and practices* support the participants in making appropriate choices when working with the four main activities. The lack of tools or wrong application thereof can, in the same way, prevent appropriate choices. Practices are related to the arenas where participants meet and exchange information and knowledge gained by the use of tools or captured directly from experience related to the activities. Closed Loop Tolerance Engineering includes the exchange of tolerance-related *information and knowledge*. The information exchanged in this process can be formal, in terms of instructions, drawings or other written documents, as well as informal and orally transferred information exchanged between participants. A selection of *key elements* in CLTE is organized according to the 6 pairs of CLTE relations in [5].

The six *feed-forward* relations that point to the right in the model cover the relations that provide progress in a CLTE. They all point toward a more mature activity of the development process and end in a physical product with a given product performance. The six *feed-back* relations pointing to the left in the model cover the relations providing the reuse of existing relevant knowledge needed in CLTE. The utilisation of these relations are of importance as they represent valuable information preventing design flaws, the definition of unrealistic specifications or can suggest alternative methods for manufacturing. One of the benefits of the CLTE model is the balanced use of the relations. No development project should only rush along on the feed-forward dimension possibly taking shortcuts in not utilising the potential in reusing knowledge from earlier projects. In the same way, a bias towards too much reflection and reuse should be prevented as it might hamper the innovation of a development project.

5. Case Study

A case study on collaborative tolerance engineering was carried out to gain empirical data on tolerance engineering practices. The case study is placed in the *"centre of the muddy discussions"* [29] of function-based vs. manufacturing-based tolerances and aims at describing some human aspects of tolerance engineering. The selection of this case company is appropriate as a large amount of its manufacturing processes are related to high precision manufacturing leading to high demands to match tolerance definitions and process capabilities. The case selected is the internal process of revising existing drawings and tolerance specification for the manufacturing products with a long manufacturing lifetime. Research methods are individual interviews, document studies and observations in meetings covering four different products over a timespan of approximately eight months as well as a 1.5 hour focus interview with 6 project participants (2 process engineers, 2 design engineers, 1 QA engineer and 1 project manager). The focus interview was recorded, transcribed, coded and categorised according to research principles presented by Tjora [30] as well as Karlsson [31]. An outline of the empirical findings is presented in the section below.

6. Case Study Results

The focus interview was carried out around six main questions that were presented to the participants in due time before the meeting. The questions covered; (i) comparisons to previous product review attempts, (ii) successful elements for a «new product review practice», and (iii) suggestions for further improvements to the workmode in upcoming reviews. In addition aspects on; (iv) ensuring that tolerance changes do not impact product function, (v) how change requests are communicated with the external customer and (vi) the customer agreement on tolerance changes. The statements are organised into process-, human- and technical aspects.

6.1. The Improvement Process

A mismatch between the tolerances and the process capabilities was perceived by the manufacturing department and a further reduction in the level of non-conformity was desired. The historical reasons behind the non-conformity problems were explained by changes in inspection routines and process monitoring in recent years. The department had, to a large extent, departed the traditional obsolete [32] post process random sample inspection routines in favour of modern Statistical Process Control (SPC), as well as Coordinate Measurement Machines (CMM). These changes have given rise to new awareness of tolerances, variation and process capabilities with increased product quality. Altogether a richer set of data and the possibility of predicting failures with a more sophisticated statistical approach currently exist compared to a decade ago. The paradox in the increased number of non-conformity deviations is seen together with new inspection technology which improved the overall quality of the products. The greater number of deviations identified was explained by technical aids and the increased quality awareness within the department. The technical and human awareness of the link between tolerances and process capabilities is seen in *Relation 2* in the CLTE model. During a kick-off session, the review process was limited to 4 products or product families. Participants from QA, product development, metrology and those responsible for products were informed as to the background and the importance of the product review by the process engineers from the manufacturing department, who initiated and managed the process as a whole.

6.2. Human aspects

The review process brought together people responsible for focused tolerance engineering of mass products. In this process, the manufacturing department took clear management responsibility for the review process as opposed to previous attempts where leadership responsibility had been less clearly allocated. The processes started off by defining the scope of the project and by identifying of troublesome parameters. Considerable time was spent in this phase to ensure that all parameters were scrutinised with regard to their correctness, not only in the individual part, but also in their assemblies with interface parts as well as across product families. The latter included unifying the way semi-identical parts from different product families were dimensionally toleranced. The thorough examination of the product parameters was regarded as a win-win situation by the participants as e.g. those responsible for the product could get together to properly understand the difficulties that the manufacturing department was facing. Colosimo supports the collaboration on tolerances stating: *"Tolerancing is now a complex activity which involves both design and manufacturing personnel"* [33]. It was seen to be important to get rid of the ambiguity towards the correctness of the technical documents as some non-conformity deviations were given "use-as-is" acceptance, a practice that over time reduced the operators respect to run "green parts". The process was seen as useful in terms of providing an arena for an open discussion on measurement practices and metrology among experts. Product managers and designers could highlight the design intention and the functional purpose of parameters. Further, the manufacturing department could describe details related to manufacturing which increased the useful mutual understanding. Wade said 46 years ago "*The better product designer is the one who, ...has a thorough knowledge of manufacturing processes and the limitations of those processes to hold tolerances. Similarly, if the manufacturing engineer has an equivalent understanding of how the product designer determined his piece-part tolerances, then he can work more effectively with Product Design in the resolution of problems"* [29]. The statement is still valid but not yet fully utilised.

6.3. Technical Aspects

Non-conformity deviations, technical drawings, SPC data and to some extent, tolerance simulations supported the decision making in the review process. Non-conformity deviations were based on variation beyond acceptable limits. The now obsolete inspection practice from several years ago, which wasted possible information, was replaced by the SPC practice which gathered a rich set of data. This structured set of data provided information about the process stability over years. One process engineer stated it like this *"it is convincing to look backwards on our capability on each single measure over years to observe our process-stability"*. Although SPC data was seen as a very powerful support in decision making, the importance of engineering experience to draw knowledge out of the data was emphasised. A large set of the non-conformity deviation reports were based on very small deviations. As some of the parts were produced with a long lifetime, the previous drawing measurement principles took traditional measurement principles into account. The increased use of CMM was reported to give opportunities but also limitations. One example was mentioned in highly detailed areas. Although radii-transitions or small radii-segments theoretically can be measured in CMM, the practical usefulness of such measurement data is limited or even misleading. The drawing (as such) is a document of major importance for manufacturing and represents a legal document towards the customer. However, it is a misinterpretation of the design intention when all measurements on the drawing are included into the CMM program. An experienced designer stated it this way "*drawings should always describe the intention that the designer has for the part*". As the drawings are very detailed there is a risk of losing the overview. In some cases it was possible to change the measurement principles into a selection of datum points that supported product function, manufacturing and inspection in a better way. An experienced engineer compared a drawing with a journey. "*If you are traveling to Lisbon there are several ways to choose. Making drawings clear is about taking the efficient and secure way to the target"*. In the same way as an engineer is challenged on communicating his design intention, the QA engineer is challenged on his skills to communicate the intention by measuring. Further, the CMM engineer faces similar challenges when CMM programs are built up and when CMM results are presented. The challenge is to prevent the intentions from being lost in translation between the different departments.

7. Discussion

Process-related elements and the mix of passion and fact-based decision making are further discussed.

7.1. Process elements of Lean and Six Sigma by Intuition

The process engineers who initiated and managed the product review process were asked whether they supported their actions using toolboxes like Lean, Six-Sigma or similar and they claimed not to do so. This is surprising as the case company has been using both Lean and Six Sigma elements for several years. Still, without being aware of it the process showed recognisable elements from both Lean and Six Sigma. Lean elements included the reduction of waste, employee empowerment and continuous improvements. The Six Sigma acronym DMAIC covers the phases of; *definition, measurement, analysis, improvement* and *control* in a Six Sigma project. The improvement initiative had its "kick-off" in a session where manufacturing operators were asked to give their input on the work situation, which is similar to Lean employee involvement. A limited scope was *defined* (4 products) and a relatively thorough examination of the problem was carried out in a limited group of skilled employees. Further, SPC data was used as *measurement* data from the manufacturing side, deviation reports from QA and the engineering knowledge based on previous test results from the product development side. A thorough *analysis* of the problem was supported by visual aids in relatively short but regular meetings where participants from different functional areas collaborated on a limited technical topic. The *improvement* actions were agreed upon directly within the relatively small group of experts. The whole of responsibility gathered in the group enabled rapid decision making with the subsequent *implementation* of changes on drawing and process documents. The tolerances were adjusted solely to improve the link between tolerances and process capabilities. As the changes were agreed upon and implemented, the process engineers stressed the need to *control* how the products were produced. A widened tolerance should not be interpreted as permission to produce the parameter less precisely. Hence, elements of Lean/Six Sigma are visible although the process is run without a strict methodology. Textbooks tend to mystify Six Sigma, and a few efforts are taken towards the demystification [34], here Peterka [35] makes a clear message stating; *"Six Sigma is about using common sense to make things easier rather than making things more difficult"*. This statement corresponds with the approach for the review process where a simple and focused approach was used.

7.2. Passion and eagerness of participants

The process engineers however replied. *"we did not support our approach on any particular philosophy, for us it was the main aim to run a good process"*. This passionate belief in improvements unconsciously avoided using the names of Lean and Six Sigma. A similar, but conscious avoidance of the Lean notion is seen in the implementation of an improvement program at a Canadian automotive supplier where their initiative Common Sense Manufacturing (CSM) [36] was defined simply to be *"a passionate belief that there`s always a simpler and better way"*. This is a message that is so clear and applicable that it makes it worth spreading all over the world. In the same way, applied in the Norwegian context, the engineers in this case did not care about what name the baby was given, but attacked the problem with passion and a wish to improve and simplify.

7.3. Fact-based decisions supported by technical tools

The use of SPC and CMM increased the awareness of variation in the manufacturing and metrology context. Both technical tools supported decision making based on facts rather than assumptions. A similar workmode was less developed within product development. Although the company utilises tolerance analysis in current development projects the reviewed products were not developed with CAD-integrated tolerance simulation models. To be able to judge whether a proposed change of tolerances was acceptable in terms of unchanged functional performance, the engineers did to a large extent use their engineering knowledge. An experienced engineer in the case company described this judgement in the following way: *"this is not just any kind of judgement, it is a judgement based on decades of collaborative experience"*. There was a split view on the usefulness of tolerance simulations in the process. In principal terms, the computer aided tolerance chain analysis will be able to predict any changes in functional behaviour of the product based on the suggested changes in tolerances. Still the full answer to predicting functional behaviour was not found in the tolerance analysis only. The clever reuse of knowledge across functional departments closes the knowledge loop within the engineering organisation. In up to 90% of engineering requests for information, an engineer chooses to contact another person [16], a similar pattern is desirable in tolerance engineering to build knowledge bridges between departments.

8. Conclusions

The case study addressed several of the same issues that Wade pointed out as cumbersome related to tolerancing nearly 50 years ago [29]. The impact which even small changes have on product performance and functional behaviour cannot always be quantified, at least not without reference to a robust tolerance analysis model.

With the support of tolerance simulation, the engineers can solve many of the tolerance synthesis hurdles; a large part of the consideration is still however left to the engineering human judgement. Closed Loop Tolerance Engineering (CLTE) is a conceptual model that focuses on the relations between four activities within product development and manufacturing [5]. The aim of the model is to provide a simple and yet comprehensive, model of the activities within any product development project from a product idea to the maturity of a mass product. The geometrical centre of the CLTE model is at the same time the thematic centre of this paper as it addresses tolerances in terms of limits of specifications and process capabilities in terms of manifestation of variance. Despite the fact that there are hundreds of process models on product development in literature, where 120 of those models are listed in Pahl & Beitz [22] (p.20-24), the CLTE model covers a research gap seen between the engineers and their work on tolerances. The literature review and this case study indicate that there is a weak link between Lean/Six Sigma and Tolerance management. CLTE can be a model to increase the awareness of collaboration on tolerances and is a contribution with a focus on the micro-elements of engineering. The case study showed how the nitty-gritty details of tolerances and variation are all over engineering practice, and how they still cause daily challenges and waste. An increased focus on tolerance engineering is promoted within industry and practice. The authors believe that CLTE thinking can raise awareness of on the importance of tolerances.

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