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On Knowledge-based Development: How Documentation Practice represents a strategy for Closing Tolerance Engineering Loops

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Abstract

Knowledge from multiple sources is required for defining tolerances in new product development (NPD). Successful outcomes in product development (PD) depend on the collective ability to integrate this knowledge into the product. Assessing variability and tolerance capabilities are essential parts of PD-knowledge as they represent limits of specifications with wide-ranging impact. Reducing the engineers time spend on (re)defining tolerances and searching for the right information can prevent substandard NPD performance in terms of quality, lead time, cost and product innovation. Hence, two topics of significant importance for achieving leanness (i.e., effectiveness *and* efficiency) in PD are towering tolerance knowledge and associated documentation practices. This paper presents the results of a survey among engineering professionals of two industrial companies made to study documentation and tolerance practices in different industrial environments. The results reveal similarities between the challenges that the companies face, including implementation of effective documentation (e.g. Knowledge-Briefs, A3 reports), visualization of physical relationship between product performance attributes and design parameters (e.g. trade-off curves) and the transfer of knowledge between projects for organizational learning. This paper makes a contribution to the body of knowledge related to (lean) NPD by documenting current industrial challenges and practices in achieving viable internal tolerance engineering routines and processes, along with the needs for documentation tools.

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1. Introduction

Tolerances are often referred to as the omnipresent backbone of engineering [1]. Successful tolerancing practice in product engineering enables efficient manufacturing and high-quality products in the market place [2]. This requires processes for defining, checking, documenting, storing, and retrieving tolerance information along with knowledge of (inter)relationships between parameters [3], as well as experience and know-how of products and production capabilities. When performed correctly, towering tolerancing knowledge improves effectiveness and reduces uncertainties in NPD [4]. Additionally, tolerancing processes within internal business-quality system are sometimes taken for granted, considered to be tedious or lacking explicit focus [6]. The reason may be that companies are suffering unknowingly at a system level from their shortcomings at a detail level in the tolerance engineering (TE) practice [5]. Furthermore, the lack of adequate processes for communicating and documenting (re)useable tolerance knowledge may cause repeated problem solving, vagueness of own capabilities, etc. The overall outcome is typically substandard NPD performance, where resources are used on reactive problem-solving and firefighting instead of creating customer value [7]. An additional factor for lack of value is design engineers spending significant time searching for and organizing

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information [8]. TE activities may fall under the category of NPD practices commonly referred to as 'knowledge-based development' (KBD), aiming to (re)use and improve existing product and manufacturing knowledge. Knowledge needs to be created, captured, standardized, stored, and reused in an effective manner [9]; e.g., by linking it to the product architecture [10]. Hence, practices and tools for good communication, collaboration and documentation are essential. For lean NPD execution, a framework for KBD can serve as a tool for linking several sources of generalized product information directly to a new product design and relate it to associated tolerances.

The aim of this research is to investigate how existing knowledge on tolerance capabilities is captured and reused within product development (PD), and how it can support the definition of more viable tolerance limits. This paper presents the results of a survey conducted among engineers in two Norwegian case companies. The following research questions are posted: RQ1: How do KBD professionals perform (lean) documentation practice? RQ2: How interlinked is documentation and Tolerance Engineering practice among KBD professionals?

2. Documentation and tolerances within KBD

The primary objective of Lean Product Development (LPD) is to create value to the customer [11, 12] by minimizing waste, improving quality (innovation), reducing time-to-market and product(ion) cost. Two important components of the lean philosophy are organizational learning and continuous improvement [13]. One central tool in this regard is the PDCA (Plan-Do-Check-Act) cycle [7], in which improvements and iterations are done continuously in small steps, aiming to reach the ultimate goal of a perfection through a learning-spiral with each cycle closer to the target than the previous one. Knowledge is one of the few permanent sources for competitiveness as reuse saves time and prevents repeated problem-solving and unnecessary design loops and may mitigate risks [14], providing a company with more resources, to spend more time on innovation and adding value rather than conducting 'rework'. LPD represents an extended framework of KBD, which means that the two concepts are more-than-compatible in many respects [15].

2.1. Lean documentation tools

One challenge in LPD is to make knowledge capture and reuse more efficient. The knowledge brief (K-brief) may be used as a collaborative problem-solving tool, providing a concrete documentation structure to implement PDCA following the lean principle of continuous improvement [7]. Overall, the K-brief is a type of mentoring tool, whose purpose is to make the author's thoughts visible while the documentation follows important targets of the whole organization or team. A common type of K-brief is the so-called A3 report [16] named by the paper size used. When used as a problem-solving tool, it serves to visualize problems at hand, goal, process, solution and risk elements in a standardized form, depending on the application and problem formulation. The mindset of A3 thinking includes some important elements such as logical thinking, objectivity, and systems viewpoint [16].

2.2. Knowledge processes and management

Knowledge documentation and reuse are frequently related to the two dimensions of knowledge: tacit and explicit [17]. Tacit knowledge includes an individual's belief, viewpoint, specific know-how, craft, and skill. Explicit knowledge, on the other hand, is articulated and communicated between individuals. Using a K-brief for documentation challenges the author to express seemingly tacit knowledge in a visual manner, and turns it into explicit knowledge which serves as a tool for organizational learning. In knowledge management, four basic processes are essential [9], see Table 1. A K-brief deals with all these processes.

Table 1. Knowledge process types and their typical requirements

Knowledge process.	Typically requires
Creation	Organizational culture
Storage / retrieval	Dynamic and updated systems
Transfer	Adequate searching functions
Application	Ability to turn knowledge into effective action

Two major issues are reported in connection with research on learning cycles [7] with K-briefs [16]. First, writing a K-brief is important for the writer's understanding of the problem. Going through this documentation process, the author will have to rethink his/her work, fit it into the framework of A3 thinking, and get a deeper understanding (tacit knowledge). The second point is that a standardized way of documenting knowledge makes it easier and more effective for the reader to uncover important material. K-briefs speed up communication and improve transfer of explicit knowledge, letting the graphics 'talk' [16].

2.3. Tolerance Engineering

Tolerances represent limits of product or process specifications that typically are defined at an early stage of PD [2]. This stage represents the "developers' dilemma" as decisions with significant impact on costs are taken, typically with lacking insight in all limiting conditions [18]. Thereby, tolerances sometimes end up being defined on previous design legacy by draftsmen or basic level designers [19]. Despite good design practice in industrial companies, inappropriate tolerance definitions still occur in many of the same companies. Zhang (1997) states "*many parts and products are certainly over-toleranced or haphazardly toleranced, with predictable consequences"*. As a consequence, negative effects of inappropriate tolerances can become visible at a later stage of product-development increasing cost and degrading product quality [20]. At the later stages, changing tolerance definitions requires very high efforts [21], which makes front-loading of the NPD process a desirable strategy [4]. Good TE relies on the ability to address relevant information that is trustworthy and pass it to knowledge creation [22]. TE becomes less likely to be a legacy-based activity when trustworthy knowledge is captured and made accessible.

3. Methodology

In this study empirical data on knowledge-based TE practice and related tools and documentation processes have been gathered through a web-based survey. The survey was designed according to guidelines recommended by [23]. It was carried out among two well-established Norwegian companies, both of which are developing high-quality, high-technology products.

Company A (CoA) is located in Norway and has both national and international customers, while Company B has different global locations for both development and production. The strategy of CoA is to develop unique PD projects for customers. CoA designs different kinds of advanced products, whereas production is done by other companies. The main competence is project and engineering management. The strategy is to avoid product ownership, and to design products for mass, medium or single unit production.

Company B (CoB) develops and produces low volume engineer-to-order products. Products have the same overall functionality, but need to be adapted to meet different customer needs. Although the companies operate with different industry sectors, they have different PD strategies and product portfolios, they have the similar challenges as described above. Both have a strong focus on increasing effectiveness of PD processes and implementing the 'lean' concept. CoA made some good experiences in implementing K-briefs in the form of A3-documentation, while CoB is mainly focusing on standardization.

The survey approach was chosen in order to gather broad and rich data [24] on the documentation- and TE practice. The driver for this work has been the desire to improve the companies' competitiveness by focusing explicitly on TE practices, and supporting KBD tools for documentation. The respondents were chosen from different functional responsibilities; like design engineers, process engineers, project leaders, QA engineers and others to cover a wide range of persons that somehow are dealing with PD processes.

Introductory survey questions mapped the company affiliation, level of education, seniority at the company, and leadership responsibility. The participants were presented with a series of statements related to the current practices on topics related to documentation and tolerances. The answers were given on a 6-level Likert-scale ranging from 1 (don`t agree) to 6 (fully agree). This "forced option" [25] prevents the selection of the "neutral" middle alternative. From altogether nearly 80 unique questions statistical data were extracted both based on individual questions, and groups of questions. The survey closed with options for participants to give individual comments to the survey topics.

Altogether, 70 out of 97 invited engineers responded anonymously the survey, resulting in a response rate of 72%. Data was exported to SPSS and analyzed with statistical tools. Subsequent to data gathering and analysis, results were presented and discussed within the companies with the purpose of raising the awareness to organizational challenges related to documentation and tolerancing practice.

4. Analysis of survey results

Statements targeted documentation practices were split into participants that have experience in using A3 documentation (A3) and those who had no experience. Especially CoA had made progress in implementing A3s as documentation tool in the last five years in addition to other documentation. In CoB very few participants were used to A3s. Overall the group of survey respondents had a nearly balanced amount of participants working with A3 (51.4%) and without (48.6%). The survey was designed to provide pairs of similar statements in order to detect the differences between the two groups related to learning outcomes in the documentation process. An extract of those differences are displayed in Table 2. Statements with a response $n<10$ were not evaluated due to low statistical power. Key questions are presented in Tables 2-4 with data for sub-groups (left/right) or centered for all respondents.

4.1. Documentation practice

The statement that A3 is an objective, logical, problem oriented tool, that requires training and experience for application [16] could be confirmed by answers to questions that were aimed in this area. A comment from a participant also underlines this: *"A3 is a great presentation and discussion tool. It is very challenging to make an A3 that is easily understandable for colleagues outside the project and they often need guidance to understand it"*. Nevertheless, it appears that leaders have a stronger trust in A3 documentation practice than non-leaders. Leaders have significant stronger belief that A3s support objectivity (Q10, $p=0.020$), logical problem solving (Q11, $p=0.001$), and continuity (Q12; $p=0.015$) in PD. In contrast to high acceptance among leaders, there is apparently high variation of the A3 acceptance in CoA. When comparing A3 users and non-A3 users, it is noticeable that A3 users bring documentation for discussions with others, but usually not in form of an A3 (Q1, $p=0.000$).

For some A3 questions, the standard deviation (St.D) is very high, which reduced the significance of the accordant findings. Nevertheless, they were considered as important since it indicates high discrepancy in the respondents' trust, acceptance, and experience with A3s. A3 is accepted among some, while others use A3s, for documentation but do not use them actively and retain other documentation instead.

Visualizations [26] are an important part of A3 documentation and, among these, "trade-off curves" [27]. Participants are not used to making trade-off curves and creating them is not a well-established practice. All groups evaluate their abilities to create them as low, but A3-users show a tendency to be better in creating them than non-A3 users (Q2, $p=0.200$), additionally leaders rate themselves significantly (Q13; $p=0.047$) higher than non-leaders. Hence, persons who are used to A3 thinking and visualization appear to have less difficulty in making trade-off curves.

4.2. Learning with/without A3-documentation

When asking if "the process of creating documentation is more valuable than the report itself" (Q3, p=0.083), A3 users support this statement stronger than non-A3 users. A comment may support this: *"The process of making an A3 is important – not the documentation"*. When asking if documentation helps to develop one's own knowledge, the A3 users (Q4, p=0.488) show a very high variance in their opinions. Furthermore, A3 also seems to better transfer tacit knowledge into explicit knowledge. Comparing A3 and non-A3 users of CoA on the accordant statement (Q5, p=0.192), shows a positive tendency for A3 users and a negative for non-A3 users. Here, it should be kept in mind that the standard deviation is high in both cases; hence, it seems that this ability is strongly dependent on the individual. Overall, the individual learning potential seems to be better when creating an A3 report rather than other documentation.

Table 2. Statistical values; differences between A3-users and non-A3 users

Q	Question topic	A3 users [M/St.D]	Non-A3 [M/St.D]
1	It is natural to bring (A3) doc. for discussion	3.46/1.63	5.00/0.94
2	I am used to create trade-off curves	2.39/1.39	1.93/1.33
3	Doc-process has higher value than doc. itself	4.19/1.45	3.53/1.33
4	Doc. helps to develop my own knowledge	4.76/1.05	3.97/1.05
5	Possibility to express tacit knowledge	4.00/1.53	3.52/1.25
6	Possibility of reuse in other setting	3.81/1.52	3.11/1.32
7	We get a system view when combining our A3s	2.46/1.46	-
8	We know where doc. is stored	3.01/1.32	

4.3. Organization of documentation

Some participants comment that they would like to have added functional design to documentation and that often a systems view is missing. If CoA would put all A3s about one product together they would not get a systems view with dependencies (Q7). One participant recommends that *"A group of A3s should have one master document that presents and overview over the root causes and system references"*.

Another important point is to find the right information. *"Making the best documents does not help if there is no way to find and share them"* is another comment of a participant. Some respondents stated that they do not always know where the information they need is stored (Q8). Several respondents wish to have adequate searching functions and data bases.

Table 3. Statistical values; differences between leaders and non-leader

Q	Question topic	Leader [M/St.D]	Non-Leader [M/St.D]
10	A3 is an objective doc. Approach	5.00/1.27	3.81/1.33
11	A3 supports logical problem solving	5.70/0.68	4.45/1.00
12	A3 supports continuity in PD flow	5.10/0.98	3.74/1.52
13	I am used to create trade-off curves	3.18/1.72	1.95/0.95
14	We frequently talk about tolerances	5.50/0.67	4.77/1.43
15	We frequently talk about variation	4.58/0.90	3.53/1.59
16	I use much work time on tolerances	3.83/1.95	4.27/1.49

Both A3 and non-A3 users were asked if their (A3) documentation can be applied or reused across different problem settings, (Q6, p=0.060). It points out that A3 documentation is easier to reuse than other documentation. Nevertheless, standard deviation is high for both parties.

4.4. Tolerance engineering practice

Both companies rank the statement *"working with tolerances is a challenging activity for our organization"* relatively high (Q20), yet CoB holds both a significant higher (p=0.019) awareness and a stronger consensus with significantly lower St.D. than CoA. One reason for this can be traced back to CoA`s significant challenges with reoccurring problems (Q26; p=0.010). There is a difference in the attention and workload on TE activities between *leaders* and *non-leaders*. Leaders claim significantly to talk more about both tolerances (Q14, p=0.019) and variation (Q15, p=0.007) than the employees without leadership responsibility. On the contrary employees claimed to *"use much work time on technical tolerances*" (Q16) higher than leaders, yet not significant.

Table 4. Statistical values; differences between companies:

Q	Question topic	CoA [M/St.D]	CoB [M/St.D]
20	Tolerance work is challenging for the org.	4.28/1.43	5.08/0.78
21	We have a culture for knowledge sharing	4.19/1.38	
22	Culture for sharing tolerance knowledge	3.60/1.53	
23	We consult "lessons learned" when needed	2.95/1.14	
24	We have a system that stores "lessons learned"	3.16/2.00	
25	We know reasons for tolerance definitions	3.36/1.32	
26	Known failures reoccur	3.49/1.43	4.48/1.50

Overall, both companies rate their general culture for *"knowledge sharing"* relatively high (Q21). Still *"knowledge sharing on tolerances"* (Q22) seems to be more challenging with a more diverse practice (high St.D.). The articulated challenges on knowledge sharing on a detailed level (e.g. tolerances) can be seen in the relation to the overall low score on the statement *"we consult lessons learned or A3`s when faced with novel requirements"* (Q23) and a relatively low awareness on the existence of *"a system for storing lessons learned"* (Q24). The importance and benefit of capturing lessons learned through a good documentation practice was clearly articulated by a respondent stating *"Good documentation is actually a learning/training material. Very often some functionalities repeat from project to project. It is critical to track "challenges" experienced in other projects. If that is done, very often it is enough to check why things were done in such a way, and implement them again"*. As design often contains repeated elements, the quality of re-occurring TE considerations can be improved with accessible and trustworthy documentation. Several recommendations on how to improve the current TE practice were stated in the open questions. Based on the statement *"we sometimes choose design solutions requiring too tight tolerances",* possible countermeasures can be found in the statements *"we should* *consider manufacturing aspects to a larger extent when designing"* and the challenge of making the tolerance determination a collaborative activity by including other disciplines into the tolerancing decisions. One respondent claimed that tolerance considerations are *"an activity left to the designer/draftsman to a large extent"*. Differences in TE considerations between various engineering domains were indicated by one of the electronics engineer claiming *"As an electronics engineer I am more often given tolerances than I actively can specify. In my opinion, variations in electronics assemblies are rarely a pain"*.

4.5. Documentation supporting tolerance engineering

The comment *"I see that tolerance definitions always include a design rationale that should be documented"* supports the relatively low ranked (Q25) survey statement on the ability to find out *why* a certain tolerance is defined the way it is. Capturing the underlying assumptions behind a tolerance on a detail level, hence seems to be an area where good documentation practice can improve the quality of TE. Another area where good documentation practice can support TE is in internal and external communication. One comment on *"what tolerances you can expect from a manufacturing type/supplier"* proved the importance to access and reuse manufacturing knowledge such as capability data or others. This topic was generally ranked relatively low. Another respondent suggested *"to use a master document/sketch that gives the overview and "reason" behind the referencing and tolerancing"*. Tolerance considerations involve several activities and functional areas and consequently challenges in those issues. Hence, one respondent stated that the challenge is to *"increase the general competence level on tolerances and tolerancing, not primarily within the company, but rather towards suppliers and customers"*.

5. Discussion

CoA rates organizational as well as individual learning higher than CoB. The companies are of different nature with a different culture, so it can be difficult to compare them directly. However several KBD activities seem to be useful to both.

5.1. How do KBD professional perform (lean) documentation practice?

One fundamental precondition for a good KBD environment is a culture for knowledge sharing in the organization. Respondents of CoA rate their knowledge sharing culture higher than participants of CoB. Both companies state that they have very high trust in their colleagues, and use them as primary knowledge resource in case of a problem. CoA rates trust in written information and quality significantly (p=0.031) higher than CoB. Trust in people is also an important fundament for good LPD practices [13]. The trust in and contact with a leader is also considerably (p=0.002) higher in CoA, as well as collaboration between departments (p=0.037) and across different projects (p=0.044). This indicates that the acceptance of asking (right or wrong) questions is higher. Recent research [28] acknowledges the challenge of establishing and truly understanding design thinking among managers. Also in this area, CoA reports a significantly higher score on the statement *"it's natural for me to discuss technical details with my leader"*. The so far discussed aspects can be summarized under the topic "people", which is one of three important topics in successful LPD [13]; providing one important pillar for organizational and individual learning.

As a second pillar, "A3 activities" seem to have contributed positively to high score. Due to high variation in answers in this area, care should be taken in interpreting the results. The survey revealed that A3 shows better potential for knowledge reuse, subject for discussion, and individual learning, and avoiding to do the same mistake twice. It can also more effectively convert tacit knowledge into explicit knowledge. This is an essential need for a learning organization [29]. The implementation of A3 documentation requires training and experience, and especially the creation of trade-off curves show a lack of experience. The high discrepancy among A3 respondents in some areas indicated that A3 is well accepted among some respondents while it is not supported by others. Hence, individual opinions on A3 use are sometimes different. Consequently, there is a lack of common understanding of learning and documentation.

Even though some positive effects could be shown, there is much room for improvements in both companies. Especially on comprehensive understanding of systems and dependencies, a single A3 seems not appropriate. One possibility could be to link A3s that describe detailed problems on different levels of abstraction to the product architecture [10]. This can ensure structure and define clear dependencies between the knowledge elements [30].

5.2. How interlinked is documentation and tolerance engineering practice among KBD professionals?

Results reveal insufficient documentation practice as a potential for better organizational learning on tolerance engineering. A potential for improving the TE activities is seen in the interface between *talking about* and *working with* tolerances. Non-leaders work more and closer on the tolerancing topics, but leaders talk more about them in their work. One challenge is to exchange the knowledge about tolerances on a detailed level with the management insight on a system level. A3s can be a possibility to document tolerance dependencies as they support the description of one certain problem.

Challenges of interpreting the underlying assumptions (e.g. design rationale) are reported in literature [31], and are to some extent confirmed by this survey. It provides an ideal entry point for documenting the design rationale behind given tolerances. Since NPD design often evolves from an existing design basis, it is important to master the challenging task of identifying reusable knowledge [32]. Due to the fact that determination of tolerances is an integrated activity in PD, design engineers tend to not recognize it as a critical situation [33], and consequently it is not always documented. On the contrary, when the importance and consequences of these critical activities are understood, engineers might invest more time for creating and using the necessary documentation. According to [34] it requires the right organizational culture to support the knowledge creation process and some mandatory knowledge related process as defined in table 1. It seems that CoA has progressed further in these documentation activities, although not necessarily towards tolerancing topics. The importance is obvious for tolerances as they can easily be incorrectly reused in a similar design, which is based on underlying assumptions (interfaces, references etc.). In order to prevent unknowingly [6] suffering from substandard TE practice, it is recommended to improve the documentation practice at detailed level. Over time this change is expected to reduce the level of reoccurring failures reported in CoB.

6. Conclusions and Outlook

In this survey both companies appear to be good at learning. When comparing CoA and CoB, the possibilities of organizational and individual learning increase in a work environment that provides a better knowledge sharing culture, based on, among others, high-quality documentation, trust in people and documentation, and low hierarchy between employees. A3s provide several advantages such as increased individual learning, better reusability, or support of logical problem solving. A3 is an approach that is stronger supported by leaders than non-leaders, and the discrepancy among A3 opinions ranges from low trust in the A3 concept to strong support. Current A3s do not cover the system context well enough though.

TE is recognized as a challenging, yet important activity in both companies. Although learning by PD is a focus in both companies, the value of TE knowledge has not been a part of this. Hence, there are challenges in interpreting underlying assumptions for insufficiently documented TE. One of them is to exchange TE knowledge on a detail level with the management insight on a system level. Here, an A3 that provides a system view together with A3s that explain detailed TE knowledge may be an improvement possibility.

However, this research includes just a two companies; further research may include a broader sample selection to make findings more significant. Follow-up activities can be targeted towards better understanding how documentation can be performed effectively and precisely (e.g. A3) for TE. Including how detail and system knowledge can be related to create an engineering-friendly overview which ensures that the desired information is found throughout the product life cycle.

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