Industry 4.0 closed loop tolerance engineering maturity evaluation

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Closed Loop Tolerance Engineering (CLTE) is introduced as a model of information flow – feed forward and feedback- between functional requirements, tolerance selection, process capabilities and product performance. "Industry 4.0" and "Cyber physical manufacturing systems" opens new potentials for information and data exchange along variation management activities, when developing, producing and manufacturing products. This paper describes a method for evaluation of the maturity level of the CLTE data and information exchange. The method is based on and validated through empirical findings from field studies in a number of manufacturing companies.

Tolerancing, Quality Assurance, Digital Manufacturing System, Closed Loop Tolerance Engineering

1. Introduction

1.1. Tolerances and tolerance engineering

Tolerances are defined in order to limit components and products geometry and to ensure interchangeability, quality and function according to the customer demands. The selected tolerances will usually also impact manufacturing and inspection processes and thus manufacturing costs. In spite of the increasing ability to assess process capabilities and other data and the increasing number of design software; tolerances are still often determined with lacking insight. This may lead to inappropriate tolerances. Too tight tolerances "to be on the safe side" regarding assembly and product function and insufficient tolerance distribution are typical errors. Geometry features having an over-qualified manufacturing process are potentially more expensive than necessary. On the other hand, will under-qualified processes lead to problems to meet the quality requirements without sorting or other measures.

Literature reports many examples on this; Zhang (1997) [1] states that "*many parts and products are certainly over-toleranced or haphazardly toleranced, with predictable consequences*". Singh [2] point at the negative effects of inappropriate tolerances of increased cost and lacking product quality. Ali et al. [3] and Krogstie and Martinsen [4] point at the costs and efforts to change tolerances at a later stage. Adding to this is a seemingly lack of attention to tolerance engineering. As Watts [5] states; *"all industry is suffering, often unknowingly, of the lack of adequate academic attention on tolerances".* He claims tolerancing has *"gradually been removed from the curriculum at universities and has been replaced by other product development courses".*

Oddly enough have popular management paradigms that originates from quality and variation control such as TQM, Six Sigma and Lean a lacking attention to tolerancing. The focus is mainly on management [4]. "*Not only has tolerances low explicit attention within industry, academia and product development literature; managers are lacking tools to address tolerancing activities" [4].* Tolerancing has been "*kept in a high degree of technical focus*" with focus on norms and standards [6], [7].

There are many different product development methodologies and approaches where tolerances and variation management are addressed, such as Robust design [8] and Design for Manufacturing (or DfX) [9],[10]. A comprehensive listing of models and management control of product development shows, however, that tolerancing is not addressed in many other approaches. [11]-[14].

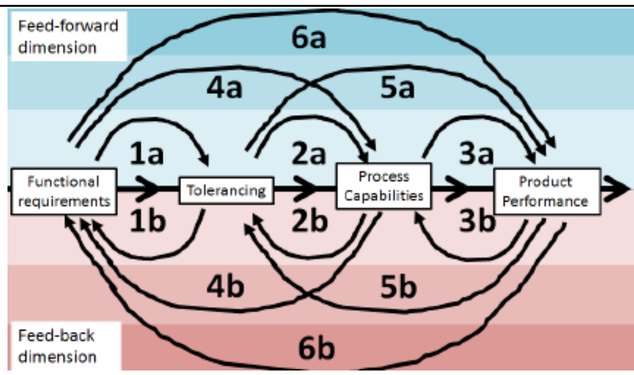

Figure 1. The CLTE-model [15]

1.2. Closed Loop Tolerance engineering

Krogstie and Martinsen have developed a conceptual model of Closed Loop Tolerance Engineering (CLTE) [15]. CLTE (Fig 1) is a model for *"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".* CLTE sees tolerancing as activities not limited to the traditional activities of tolerance-specification, allocation, modelling/optimization and synthesis, but also an organizational process, with information flow and ability to collect, use and reuse data. Prevent problems form occurring, attention to and understanding of tolerances in the whole value chain, fact based tolerance engineering are some benefits expected. Good tolerance engineering practice includes a collective ability to detect critical situations in the product development phase [16]. A critical situation is the decision-making between a desirable or negative consequence in the future. CLTE is distinguished from other approaches by representing the "*skilled knowledge-based collaboration with a specific focus on the importance of defining appropriate tolerances*". CLTE has been applied for analyzing tolerance engineering practices in different companies, including a high-precision aerospace company [17].

The CLTE - model has a "feed forward" and a feed-back" information flow dimension. It contains four interconnected activities: 1 - Defining functional requirements, 2 - Defining tolerances, 3 - Considering of production capabilities and 4 - Confirmation of functional performance. Furthermore, six pairs of closed loops of relations; 1a/b etc., see figure 1. The closed loop relations links activities together passing information forward in the project flow, as well as to the predecessors in the feed-back dimension. The ability to prepare and utilise information and data from both feed forward and feed-back dimension is the main key element. The need for cross-functional teams for product and process development is a well-known concept [18] and the proposed CLTE is a cross-functional.

2. Industry 4.0 CLTE

Industry 4.0 is a strategy for implementing the so called 4th industrial revolution, and a central concept is Cyber-Physical Manufacturing systems [19] where the physical and the virtual processes are providing simultaneous data-accessing and processing. Machine learning/Artificial intelligence, sensor based monitoring and control, multi-agent/holonic systems, (wireless) sensor networks, (big) data mining, virtual/ augmented reality etc. are some technologies that are mentioned. Better connectivity, productivity, efficiency, information flow, robustness, flexibility are some of the expectations to Industry 4.0.

There are a growing number of scientific articles on Tolerance Engineering in Industry 4.0. One example is Gianetti [21], who suggests a framework for process robustness, improving process robustness with quantification of uncertainties in Industry 4.0. She proposes to use big data analysis to find "*Likelihood Ratios*" for process capabilities used to set robust tolerance limits. Another is Söderberg et al. [22] discussing how a digital twin with "*geometry representation of the assembly, kinematic relations, FEA functionality, Monte Carlo simulation, material properties and link to inspection data base*". One might also argue that the vast number of articles on *Computer Aided Tolerancing* (including CIRPs own conference track) really are part of the essence of Industry 4.0- although the term "Industry 4.0" is newly "invented" [23]-[28].

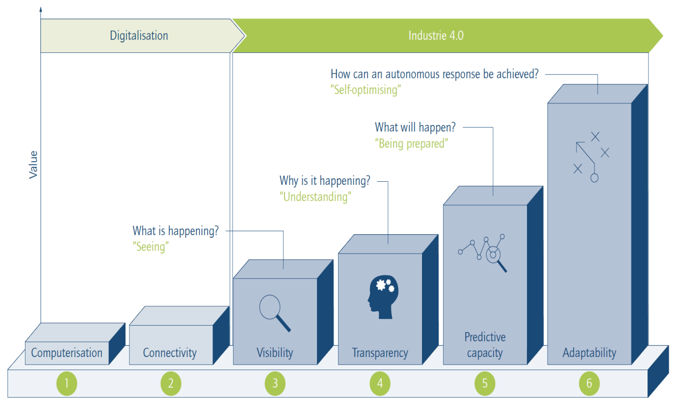

Figure 2. Actech Industrie 4.0 maturity index [20]

The Acatech study Industrie 4.0 Maturity Index [20] defines 6 steps from "*Digitalisation*" to "*Industrie 4.0*". Stage one and two are more or less current industry status. Stage three to six represent different steps from seeing, to understanding, to predicting what will happen and finally autonomous response. Collecting and displaying data, (*out of the "silos" and useful across the company*), up-to–date models at all times, simulations, optimisation, and ultimately autonomy (*response without human assistance*) are key competencies.

The Acatec steps of Industry 4.0, four last (*Industrie 4.0*) stages could mean the following for CLTE;

3. **Visibility** – what is happening; Instant and constant data collection and visualisation along the CLTE model. A "digital shadow" (or twin) across data silos with semantic linking of useful data for tolerancing (see also [22]).
4. **Transparency** –why is it happening; Ability to analyse and present data in a useful way for potential users along the CLTE
5. **Prediction** – what will happen; Ability to use the data for simulations and optimisations at all levels
6. **Adaptability** – Autonomous response –self-optimising CLTE without human intervention. The ultimate goal for CLTE would be to have an instant and autonomous flow of information and data across the CLTE chain "translating" information to adapt to the specific use and suggest decisions for the user. This level would mean that the product designer e.g. automatically gets relevant process capabilities and suggested optimised tolerance distribution and process path. as an automated relation in the CLTE model.

3. CLTE maturity assessment model

Based on the CLTE the author is here proposing a maturity assessment model CLTE. This maturity model was developed as a combination of literature study, discussion with industry partners, and case studies in selected Norwegian companies, mainly in the SFI Manufacturing research centre.

The CLTE maturity assessment can be used to evaluate and plan improvements in a company regarding their management of tolerancing and variations. The model consists of two parts; first part is assessing how well the company is performing in the 12 relation loops. Secondly how information flow in the relation loops and how data is stored, assessed and used. Both can be done as self-assessment by the company and by an external expert. It would be recommended to do both followed by a reflection workshop with discussions on actions to improve.

3.2. Performance assessment

The performance assessment is done by grading the company performance according to questions given regarding the performance on the CLTE relation loops (1a – 6a, 1b -6b). Grades are from (1) not applied, (2) poor, (3) medium, (4) good and (5) excellent. The list underneath is a simplified/ summary of the questions given.

1a How well are functional requirements transformed to tolerancing – by whom, in which form and which tools?

1b How well are the decision basis for selected tolerances stored and fed back to aid functional requirements description in following projects?

2a How well do the tolerances fit the manufacturing capabilities? How well are tolerance stack-up [29], critical tolerances and reference surfaces working?

2b How well are existing process capabilities used in tolerancing? How well are quality and productivity data on current products used in tolerancing of new products?

3a Are process capabilities and parameters and their effect on product performance and inspection well known?

3b Are sources of variation in product performance well understood? Is knowledge gained in product performance tests looped back to manufacturing? Can variation in product performance be traced back to variation in the manufacturing processes?

4a How are functional requirements information used in manufacturing? Are critical parameters known and manufacturing and inspection processes sufficiently attended?

4b How well are process capabilities fed back (and make an influence) on functional requirements?

5a How well are the relations between (critical) tolerances and the product performance understood? How are defined tolerances deciding product performance assessment?

5b How well are critical tolerances and their variation influence on the product performance understood?

6a How satisfactory is the product performance according to the functional requirements? How are functional requirements influencing the product performance assessment?

6b To what extent is existing product performance fed back to aid definition of functional requirements in following projects?

The results can be shown as spider diagrams comparing the company assessment, the expert(s) assessment and the wanted future scenario / goal.

3.3. Information and data exchange assessment

The second part of the maturity assessment is the information and data exchange assessment. For each relations loop (1a to 6a, and 1b to 6b) the company must agree on which stage they are (and wish to be):

Stage 1: No organised information exchanges.
Stage 2: Information exchange based on expert's subjective opinions. Cross-functional teams using semi-quantitative tools such as FMEA
Stage 3: Information exchange containing real data on ad-hoc basis. Time-consuming data processing and analysis using highly qualified personnel. Unknown or weak data quality with little to no meta data. Data mainly for internal use. Some use of computer-aided decision support.
Stage 4: Systemized (but manual) regular data and information exchange, analysis and computer-aided decision support. Data management with a broader use in mind. Meta data and cross-linked data, but still manual translation of information to adapt to the use. Generally good data quality and ability to assess and grade data quality.
Stage 5: Instant and autonomous data exchange. Automatic translation of data and information to adapt to the specific user. Automated data processing, simulation and optimisation and suggested decisions. Automated assessment, filtering and signal processing for maximum data quality.

3.4. Examples from industry case study

The charts underneath show the results from one industry case study. It is a global leading company in a specific niche as a Tier 1 automotive supplier. They own their own product patents and are developing, manufacturing and assembling a complete range of products within their niche. The assessment was made in two workshops separated by an expert mapping and analysis. The expert assessment is based on semi-structured interviews, observations and analyses of a few selected products.

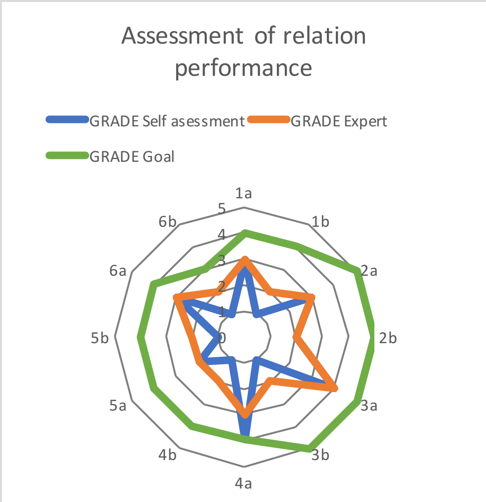

Figure 3. Relation Performance assessment

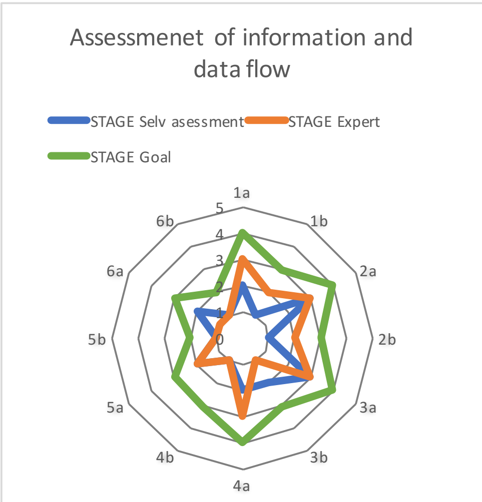

Figure 4. Information flow assessment

The charts show a typical picture where the feed forward (1a to 6a) are more advanced than the feed-back loops (1b to 6b). Similar results can be found in other companies. There are some deviations on the expert vs. company self-evaluation. This is not untypical; the companies are in some cases more "hard" on themselves on the self-assessment than the expert's assessment. The relation performance goals are in this case somewhat ambitious based on the current grade, but it is long-term goals where the company mean they have to be.

4. Discussions

4.1. Discussion on the CTLE maturity assessment model

The maturity assessment model is a semi-quantitative model useful as a tool to map a company and to point at possible improvements. This is not an exact numerical model and any comparisons between different companies should be done with care. The case companies are all measuring and storing large quantities of data in product tests, numerical models etc. in product development, productivity and capability/variability in manufacturing, product geometry in inspection processes and measurement of actual product performance. The data material is, however, usually stored for a specific use and to transfer the data and extract information for use by other departments is currently difficult. For example, are all data form statistical process control stored, but to translate these charts to process capabilities and make it easy usable for the product designers and tolerance definition is still not straight forward. This is one of the obstacles the Industry 4.0 paradigm should solve. Stage 5 in the information and data exchange assessment is currently not reachable for most companies. A key to this will be a seamless interconnection of Manufacturing Execution Systems (MES), Product Lifecycle Management (PLM), Computer Aided Engineering, including Computer Aided Tolerance Engineering software.

4.2. Shortcomings of the CTLE model – future extensions

The CLTE model is currently focusing on the process within one company. Future models must include tolerancing and variation management in the supplier vs. customer relations in the supply- and distribution chain. Furthermore; future CLTE models should include information and data exchange with product use phase and end-of-life and possibly remanufacturing of products. One of the current trends are the manufacturers liability of products after end-of-life (EOL) as well as the extension of the product to a product-service system. Products containing sensors opens for new business models, but the data collected could also be used for future CLTE activities, such as functional requirement definitions. Tolerance engineering and variation management will also be vital for a circular manufacturing with increasing remanufacturing of products and components rather than re-melting or disposal at the EOL.

5. Conclusions and further work

Industry 4.0 will most likely open new opportunities for information flow, data assessment and exchange for variation management and tolerancing engineering. This paper has suggested a maturity model that can be used to lift tolerancing on the agenda and point at improvement potentials for companies. This is a proposal for a management tool. Further work would see longitudinal results from industries using the tool with measured improvements.

6. Acknowledgements

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