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Procedia CIRP 21 (2014) 306 – 311

www.elsevier.com/locate/procedia

24th CIRP Design Conference

Variation Analysis in Collaborative Engineering; an Industrial Case Study of Rocket Motor Development

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Abstract

Considerably less research is found on tolerance specifications compared to research on tolerance analysis and synthesis. Where tolerance analysis and synthesis often can be completely understood based on technical input we argue that an extended research approach is needed to understand tolerance specification complexity. We have aimed to understand the Research Question (RQ) *"How does variation analysis support tolerance specification during collaborative Product Development (PD)"?* For this case study of the Product Development Process (PDP) of a rocket motor within the defense industry we have used interviews, observations, participation and secondary sources during data gathering. We found that collaborative gathering of input for the simulation generates useful knowledge for the project at an early stage. Further, that swiftly and precisely done variation analysis generates output supporting frequent and cross functional communication on tolerances. We see the enabled fact based decision making as an important factor to PD success.

Selection and peer-review under responsibility of the International Scientific Committee of "24th CIRP Design Conference" in the person of the Conference Chairs Giovanni Moroni and Tullio Tolio
Keywords: Tolerances, Variation, Analysis, Collaboration, Specification, CLTE

1. Introduction

Many readers will recognize the following true stories related to tolerances from their own product development context. Design engineer: *"You can't hold our tolerances"*. Manufacturing engineer: *"No. We don't. And the product works just fine"*. And other way round; Manufacturing engineer: *"Why did you make the tolerances so tight? We're scrapping most of the parts"*. Design engineer: *"We didn't think you would really try to hold the tolerances we actually need, so we tightened them"*. Few research contributions have aimed to understand the underlying reasons for this mismatch between departments on tolerances, and even less have provided practical solutions on this topic. We searched to understand this effect and followed the use of a variation analysis software tool throughout a collaborative product development project. In this process we applied the research model of Closed Loop Tolerance Engineering (CLTE).

2. Theoretical Background

It is stated by [1], there is *"probably no other design improvement effort which can yield greater benefit for less cost than the careful analysis and assignment of tolerances"*.

2.1. Traditional Tolerance Engineering

The comprehensive review on tolerancing research by [2] states that "*a tremendous number of research articles have been published over the last 30 years*". The seven categories of (i) schemes, (ii) modelling, (iii) specification, (iv) analysis, (v) synthesis, (vi) transfer and, (vii) evaluation organizes the tolerancing research. Schemes handle different approaches to represent and communicate limits of parameters. Including; not yet fully abandoned dimensional (+/-) tolerances [3], more precise and efficient Geometrical Dimensioning &

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doi:10.1016/j.procir.2014.03.157

Tolerancing (GD&T) [4] and more novel principles of Geometric Product Specification (GPS) [5] which is lately implemented in standards [6] and applied in recent research [7], [8]. Modelling seeks for efficient ways of defining and representing tolerance information typically within CAD or PDM systems. Challenges of communicating tolerancing information across different IT-systems are identified [9], attempts have been made to overcome them [10], and industrial needs are yet not fully fulfilled [11]. Analysis seeks to assure and confirm design functionality for a given variability of individual parts. Newer reviews [12] show few additional contributions compared to [2] which indicates a relatively low current research focus with some exceptions [13], [14]. Synthesis (aka allocation) is opposite to "Analysis" as it aims to optimize tolerance values often towards a function (i.e. cost) while the tolerance types are fixed. Both historical [2] and recent [15], [16] reviews report a rich set of applications. Finding a correct transfer function for optimizing complex industrial problems is frequently seen as a challenge [17]. Transfer aims to base tolerancing considerations on actual manufacturing knowledge. The ideas of early rigorous manual process charting methods [18] are now computerized in various commercial solutions [19] and even attempted to be linked to Key Characteristics of a product [20]. Several attempts on good practical implementation of tolerance transfer across the CAx-bandwidth (CAD/CAPP/CAM) are known [21] but still not completely solved [11]. An industrial breakthrough on tolerance transfer is long awaited and expected due to achievements within standardization [22] and novel principles of schemes [5]. Successful transfer is so dependent on other tolerancing activities as well. Evaluation deals with how geometrical deviations can be obtained from various measurement sources (i.e. Coordinate Measurement Machines (CMM)) with the purpose of discovering inspection inconsistencies and so to improve tolerancing. Linking metrology with tolerancing has over time occupied Computer Aided Tolerancing (CAT)-research, and been summarized [23], and lately been united with GPS-principles [24] in various applications [25].

2.2. Tolerances within PD literature

The complex task of PD which includes several participants and numerous activities has yielded a rich set of theories [26], models [27], and recommendations [28] which has been summarized in various reviews [29], [30], [31]. The classic book on PD [32] lists no less than 120 models, where only a few focus directly on tolerancing. The paradox of lacking direct addressing of tolerancing topics is seen in any products need for a clear manufacturing description which includes deliberately set tolerances. Recent PD-models are reviewed structurally by Horvàth [31], which sees an increasing focus on human relations in engineering design. Seeing PD as an integrated activity with participants from different disciplines is well known since [33] & [34].

A gap between two traditions in the PD literature appears; First, the "process and human oriented" branch represented by (but not limited to) [35], [36] focusing on development processes, innovation and collaboration but lacking a direct focus on tolerances. Important tolerance engineering activities are so "hidden" within the activities of embodiment design or detail design in the respective PD models [32]. Secondly, the "tools oriented" tolerancing literature which often sees tolerances as a communication language [37], object for optimization [38] or a topic for norms [39], hardly focusing on human aspects. Tolerances and participating engineers (the humans) are present in both branches of literature but are seldom addressed simultaneously and directly, but with some exceptions [40]. The gap between traditional tolerance - engineering literature and human oriented PD-literature provides a potential area to improve the understanding of tolerance specification activities.

2.3. Tolerance Specification

Described by [2] tolerance specification relate to *how to* specify tolerance types and values. It has long been a scarcely researched topic with limited attention in historical reviews [41], [42]. Contributions have focused on the use of tolerance standards and norms [43] and so scarcely covered the topic. Recent PD-research to a large extent has applied an extended set of research approaches of a descriptive nature [44] and so yielded another kind of insight into engineering behavior [36]. So we question whether sufficient aspects of tolerance specification currently are understood and communicated. Altogether tolerance specification follows several stages;

(a) From functional requirements to Tolerances; Any PDP starts with the definition of measurable or non-measurable requirements describing the qualities of the product. Distinguishing functional (must do`s) from non-functional requirements (qualities) [45] is one categorization. For this paper we let functional and measurable requirements gain focus. Those are defined by [46] to be *"an unambiguous agreement on what the team will attempt to achieve in order to satisfy customer needs"*. However; *"it is rarely possible"* for technology-intensive products. In the process of clarifying, understanding, and translating requirements to technical terms tolerances (see; (i), (ii) in [2]) are inevitabaly a valuable tool to transfer ambiguous requirements to measurable criteria.

(b) Linking tolerances with process capabilities. The normative nature of tolerances and the empirical values of process capabilities are closely interlinked. Measurements and quality conformance metrics (i.e. C_{pk}) express variation levels against control-limits [47] (see; (v) &(vi) in [2]).

(c) The link between Tolerances and Product Performance. Designing physical products for a desired product performance requires measurements on different technical scales (e.g. output, reliability, precision). Product performance will vary dependent on manufacturing process variation in a long cause-effect chain is often complex and challenging to follow. Critical Parameter Management (CPM) [48] is one technique to understand the relative contribution of different parameters to the overall variation in product performance. As the final product originates from several manufacturing processes (each varying), CPM supports understanding of interdependent variation of multiple parameters (see; (vi) & (vii) in [2]).