TOLERANCE CONSIDERATIONS IN WORK STRUCTURING

Colin Milberg[1]

ABSTRACT

Work structuring is the breakdown of both product and process into chunks, sequences and assignments to make work flow smoother and with less variability, in turn reducing waste and increasing value. Work-structuring decisions should include tolerance considerations. Tsao et al (2000) and Milberg et al (2001) illustrated how tolerance-related problems that interrupt workflow generate waste. Tolerance accumulation is often ignored in design, resulting in unanticipated tolerance problems. Tolerance accumulation is dependent not only on tolerance allocation but also on assembly sequence and interface (connection) design, which are functions of work-structuring decisions. This paper discusses tools and techniques used in evaluating tolerance accumulation and process capabilities during detailed design in order to make work-structuring decisions, as well as how tolerance management should be integrated into work structuring.

KEY WORDS

Lean construction, Work Structuring, Tolerances, Tolerance Management.

INTRODUCTION

A project begins with a customer's need for a product, and from the producer's perspective, a project ends when that product is delivered for use – not including activities such as gathering feedback on product performance. A production system is a system of organizations, processes, and materials that create the product to meet the customer need and deliver it to the customer for use. A production system encompasses project definition, product design, process design, supply chain management, fabrication, assembly, and turnover (Ballard 2001).

Work structuring is the design of that production system, i.e., how a product will be created and delivered to fit a customer's need. Put simply, work structuring determines how the work of a production system is structured in terms of how resources are organized down to the design of operations (Ballard 2001, and Tsao 2004). From a process standpoint, work structuring determines (Ballard 1999): 1) In what chunks work is assigned to specialists; 2) How those work chunks are sequenced; 3) When a work chunk will be done; 4) How work chunks are "released from one production unit to the next"; and 5) Where decoupling buffers are needed and how they are sized. Similarly, from a product perspective, work structuring determines in what chunks (subsystems, sub-assemblies, and components) the product is broken down. Work structuring should align the operations and process design, the product design, supply-chain structures, resource allocation, and design-for-assembly efforts (Ballard 2001). The goals of work structuring are to design the production system to maximize value and minimize waste while producing the product (Ballard 2001).

[1] Assistant Professor, Civil and Envir. Engrg. Department, 5500 Campanile Drive, San Diego State University, San Diego, CA 92181-1324, 619/594-8474, cmilberg@mail.sdsu.edu

Tolerances are essential to the communication between, and alignment of, product and process design, and are a necessary part of work structuring. Tolerance management involves assigning tolerances to product components and assemblies and ensuring that: product tolerance specifications are complete and follow tolerancing principles; product tolerances are consistent with the proposed process capabilities; the interacting component and assembly tolerances are consistent with each other; and the tolerances for design, construction and inspection are consistent with each other. The goals of tolerance management are to achieve proper performance and quality of the product (maximize value) and to ensure the product can be built without interruption in flow due to tolerance consideration and given the processes available (minimize waste).

Tolerances are simply another form of variability. Like with any form of variability, if tolerances are not properly managed within the production system, problems will arise during fabrication and construction. Tolerance related problems such as non-standard/ad hoc procedures, ad hoc connections/fillers, field modifications, non-standard parts, custom fabrication, misfits and failure to meet project specifications, all lead to poor quality, rework and large variations in work flow, i.e., reduced value and increased waste. Tsao et al (2000) and Milberg et al (2001) illustrated how waste can be generated by tolerance-related problems that interrupt workflow. Although practitioners sometimes consider and manage individual component or feature tolerances, tolerance accumulation is typically ignored resulting in unanticipated tolerance problems.

Over a five-year duration, the author investigated the application of tolerance management tools to three case studies, including: tolerancing principles, tolerance maps, vector modelling, and tolerance analysis. The objective was to determine the effectiveness of the tools to evaluate the tolerance specifications for each project production system and to improve those systems by generating alternative work structures. Although some tools showed promise for use as early as the conceptual design phase, the focus was tool application during detailed design. This paper will briefly introduce the tolerance tools and techniques used and convey how they can be utilized to direct and evaluate work-structuring decisions during the detailed design phase.

TOLERANCE MANAGEMENT

Tolerance management is based on theoretical principles regarding the specification and accumulation of tolerances within a product. Like with flow variability, in which variations in flow through the production system accumulate to determine the overall variation in the throughput of the production system, tolerances on components and features within an assembly accumulate to determine the overall variation in the geometry of the final assembly.

Unlike variations in activity durations, tolerance accumulation is non-linear because variations in the rotation of a component about three coordinate axes will impact the location of various features on that component in a non-linear fashion. Tolerance analysis evaluates the accumulation of tolerances within a product. The first step in all tolerance analysis is the determination of the assembly equation with the critical dimension as the dependent variable. The assembly equation is the expression of the critical dimension as a function of the geometry with toleranced features treated as independent random variables (Chase 1999, Gerth 1997, and Chase and Parkinson 1991).

For even simple two- and three-dimensional assemblies, determining the assembly equation in terms of the known feature variables without software can be difficult (Gerth

1997). The assembly equation is a function of the following (Soderberg et al. 1999, Gerth 1997, and Chase and Parkinson 1991): 1) the type of tolerance specifications for each feature; 2) the geometry of the system; 3) the datum selected; 4) the type of connections; 5) the order of feature fabrication; and 6) the order of assembly. All these factors are decisions made as part of work structuring.

TOLERANCE LOOPS AND CONSISTENCY

One concern of tolerance management is to ensure that variations in the geometry of the assembly due to the accumulation of the tolerances in the included components and their features do not compromise the constructability, functionality or quality of any assembly or sub-assembly within the production system. Tolerancing of a design, given multiple functions from different perspectives as well as manufacturing and inspection considerations, can result in over-specified or over-constrained designs (Davidson et al. 2004 and Tsai and Cutkosky 1997). Requirements for constructability, functionality and quality of the final and intermediate products are also sometimes specified by tolerances on the geometry. When a tolerance is given for an assembly dimension that is dependent on the accumulation of tolerances of the components and features, it is called the critical dimension, which over-constrains the geometry, forming a tolerance loop. In addition, when the variation due to the accumulations of the tolerances in the components and features exceeds the tolerance for the resulting assembly or critical dimension, the tolerances form an inconsistent loop.

The consistency of the loop depends on which tolerance constraint in the loop is the critical dimension. In an over-constrained loop, theoretically any tolerance constraint can be the critical dimension. If the fabrication or assembly process is given, the starting feature and the directions the loop is traversed are determined by the sequence of feature fabrication within a part or the sequence of assembly of parts (Tsai and Cutkosky 1997).

Inconsistent loops are particularly problematic because they can be unknowingly created and remain unnoticed until fabrication and assembly, causing failure to meet tolerances in the critical dimension resulting in poor quality and interruptions to work flow. Designs should be checked using variation analysis for inconsistent loops, and inconsistencies should be eliminated by changing the nominal geometry, the tolerance allocation for a given manufacturing or assembly sequence, or the sequence for a given allocation. Tolerance allocation is the inverse of tolerance analysis, i.e., the assignment of tolerances to individual parts and features based on the required assembly tolerance or limits on variation in the critical dimension.

PROCESS CAPABILITY

As mentioned, tolerances are communication links between product and process design. As such, tolerances are not based only on the function and quality of the product, but also on the process capabilities for producing a component. Process capability is a measure or description of the variations introduced in the parameters of a feature created by a particular process. Process capabilities are dependent on both the process used and the design of the component. Thus another important part of tolerance management is matching product tolerances with appropriate process capabilities.

TOLERANCING PRINCIPLES

In manufacturing, more advanced techniques and strategies for tolerance management are available, resulting in significant improvement in manufacturing efficiency and product quality. The most critical component of tolerance management in manufacturing is a well-established set of standards for tolerance notation and specification. These standards have associated rules for accumulation and principles to help minimize accumulation. Utilizing manufacturing concepts, the author identified a discrete set of tolerancing principles for application to AEC that represent the basis for tolerance management in civil systems. These principles are integrally tied to all the basic work-structuring decisions previously discussed, with the exception of when a chunk is done and how it is released. Tolerance maps, vector models and tolerance analysis support work-structuring decisions and the application of the principles.

Principle 1 & 2

Principles 1 and 2 deal with the clarity in the communication of tolerances (requirements of the product). Unclear communication of product requirements leads to poor work structuring, i.e., with garbage in, you get garbage out.

Principle 1: A feature or part should be completely toleranced. Nothing is made perfectly; plans and specifications should specify dimensional and geometrical tolerances needed to limit permissible variations of every characteristic (size, form, orientation, location) of every feature either directly or indirectly by a hierarchical relationship or relationship as a dependent variable (Davidson et al. 2004 and Henzold 1995 p. 179). Tolerances are a communication of design, manufacturing, and inspection intent. Therefore, tolerance specifications should also be complete in the sense that the intent is unambiguous (Tsai and Cutkosky 1997).

Principle 2: Every specified tolerance must be met independently unless one of the envelope relationships is specified (Henzold 1995 p. 182). Multiple tolerances are sometimes specified over the same or different characteristics of the same feature due to different functional considerations (Tsai and Cutkosky 1997). When this happens, the more restrictive tolerance can be missed or assumed to be an error, leading to poor work structuring, unless each tolerance is treated independently.

Principles 3, 4, & 5

Principles 3, 4 and 5 all strive to reduce tolerance accumulation through datum selection. Reducing accumulation reduces the potential for inconsistent tolerance loops and improves the quality of the product, typically without any additional costs. Preventing inconsistent loops helps avoid tolerance problems and interruptions to work flow, thus minimizing waste; improving quality helps maximize value. Options for datum selection are entirely dependent on how the product is broken down, what process or person is assigned to the fabrication and assembly of the feature or component, and the sequence of feature and component fabrication and assembly (discussed in principle 8).

Principle 3: Datum should be minimized within a tolerance loop. In general, using baseline dimensions, i.e., using the same datum for dimensioning tends to reduce the accumulation of tolerances in critical dimensions (Soderberg et al. 1999 and Gerth 1997).

Principle 4: Datum features with less variability (higher quality) should be selected where function permits. If a feature that is highly variable with respect to the assembly datum reference frame (DRF) is used as a datum for fabrication, then the feature toleranced from that datum will be even more variable with respect to the same DRF, resulting in more accumulation (Soderberg et al. 1999 and Gerth 1997).

Principle 5: Select more robust datum for a given critical where function permits. A set of datum is more robust if the critical dimension is less sensitive to variation in that set of datum than an alternative set of datum, as reflected by the partial derivatives in the respective assembly equations. Often different datum can be used to specify the location or orientation of a feature and capture the required function. The same principle of robustness can also apply to the selection of nominal values for the geometry. Robustness also serves to reduce accumulation.

Principle 6

Principle 6: Select connection types that eliminate large variations contributing to the critical dimension in the assembly equation. Sometimes variations in certain DOFs can be eliminated by selection of connections that are free to move in that DOF during assembly (Chase 1999). Often simply looking at the geometry before design parameters are fixed can determine the benefit of different connection types, allowing for application of principle 6 during the initial design iteration.

Principle 6 uses connections as decoupling buffers. Connections can be designed to absorb the geometric and dimensional variability due to tolerances and thus reduce the tolerance accumulation in the overall assembly. The information in the tolerance maps indicates where connections can be used as buffers and how the connection should be designed. Deciding which connections to use as buffers should take into account information from tolerance analysis regarding how much the connection can and needs to absorb as well as other work-structuring considerations, such as process work flow, quality and cost impacts of the alternative connection designs.

Principle 7

Tolerance analysis should be done to ensure variations in dependent critical variables are acceptable. If they are not, design should be modified until they are acceptable (Gerth 1997, Soderberg 1997 and Chase and Parkinson 1991). Similarly, analysis should be done to identify over-constrained loops and ensure that they are consistent (Tsai and Cutkosky 1997). If the loops are inconsistent, the design should be modified, or the loop should be clearly labelled as such. Again, inconsistent loops create tolerance problems during fabrication and assembly reducing quality and interrupting work flow.

Principle 8

Functional tolerances should be specified such that the implied sequence of fabrication, fabrication methods, and inspection methods are achievable and reasonable where possible (Thornton and Tata 2000, Soderberg et al. 1999, Gerth 1997, Tsai and Cutkosky 1997, and Chase and Parkinson 1991). It is often the case that the function of a part dictates that a feature be specified from a particular datum (Davidson et al. 2004, Gerth 1997, Tsai and Cutkosky 1997, and Henzold 1995). Sometimes due to the geometry of the part, the datum feature cannot be used to support, locate or orient the part for fabrication of the feature or be used to inspect a feature's deviation (Gerth 1997 p. 95 and Henzold 1995). Some examples include: when the datum is an internal feature of the part; when a feature is toleranced from a datum feature not yet fabricated due to practical limitations in the fabrication shop; and when the datum is too small to provide an accurate reference from which to measure. Where function permits, these situations should be avoided by selecting alternative datum from which to tolerance the feature (Gerth 1997, Tsai and Cutkosky 1997, and Henzold 1995). Similarly, every specified tolerance should preferably be directly controlled or inspected using reasonable fabrication and inspection processes (Gerth 1997 and Tsai and Cutkosky 1997). Preference for direct control should be given to the tolerances that have a greater impact on higher priority functions (Gerth 1997). The principle also implies that functional tolerance magnitude should have a basis in manufacturing process capability. The tolerance must be producible, i.e., there must be a process with sufficient process capability to meet the specified tolerance (Thornton and Tata 2000, Soderberg et al. 1999, Henzold 1995, and Chase and Parkinson 1991).

TOLERANCE TOOLS (MAPS, VECTOR MODES & ANALYSIS)

Tolerance maps are an adaptation of tolerance networks (Tsai and Cutkosky 1997) into a novel tool (Milberg and Tommelein 2005, 2004, 2003a, 2003b, and 2002). The purpose of the adaptation was to graphically represent information about the tolerance relationships to support more visual review of tolerance specifications. Multiple Tolerance Maps are generated from the design, construction, and inspection perspectives. Before beginning actual tolerance analysis, over-constrained loops must also be identified within the Tolerance Map. The author also used colours to designate which features are specified, fabricated, or assembled by the same organizational entity in order to help integrate other pertinent work-structuring information into the map, which can then be incorporated into design decisions based on tolerance considerations. Tolerance maps are the main tool for evaluating a given work structure. The other tools are used with the map to add necessary visualization and analysis not provide by the map itself.

Vector models are, like tolerance maps, a means to capture tolerance information about the assembly. A vector model uses vectors to represent the nominal geometry, while tolerances are then represented as variations in the length or direction of the vectors, but not shown graphically. The vector models are then used to conduct the tolerance analysis. The vector models, along with three dimensional CAD models of the assembly, aid in visualizing and translating the information in the tolerance maps into geometry, helping support the generation of alternatives work structures.

Finally, simulated tolerance analysis assesses whether a tolerance loop is inconsistent using a Monte Carlo simulation to find a sample critical dimension by sampling from appropriate distributions based on the specified tolerances or process capabilities, and the length and direction for the vectors in the assembly. The Monte Carlo simulation samples the assembly many times, creating a distribution for the critical dimension that can be expected in practice. Design tolerances should be used in the analysis, unless process capabilities are higher, in which case the process capabilities should be used instead. The resultant distribution for the critical dimension is then compared to the specified tolerance for that dimension to determine if the loop is consistent and by how much. This information is critical in directing where changes to the work structure will have the greatest impact on reducing tolerance accumulation and also how much reduction is required to make the loops consistent.

TOOL APPLICATION

These tools provide for the systematic review of a design for violations of tolerancing principles, and allows for the identification of solutions using alternative work structures that better follow tolerancing principles (Milberg 2006). Tolerance Maps should still be evaluated for the following: 1) Completeness. Check the Tolerance Map to ensure all potential component variations are specified. Include any missing tolerance specification, or determine that missing specifications don't impact function. 2) Datum selection. Check the Tolerance Map in combination with the vector and 3-D model to see if long chains of datum can be avoided by specifying one or more features from alternative datum to specify the same constraint, thus minimizing the datum in a loop. Also, check using the tolerance analysis which of any alternative datum for specifying a feature is the least variable with respect to the start of the loop. In addition, check if any alternatives are more robust in terms of the impact on the overall accumulation in the loop. Select datum that minimize datum numbers and variability and maximize robustness. To evaluate more robust datum requires additional tolerance sensitivity analysis using any alternative datum (Soderberg and Lindkvist 1999). 3) Process capabilities. Check to ensure the process capabilities in the construction Tolerance Map match the tolerances in the design Tolerance Map. Reconcile mismatched tolerances and process capabilities by increasing the design tolerances, using tolerance allocation, improving process capabilities, and/or selecting processes with more suitable capabilities. Remember that any critical dimension variations affected by the process capabilities or tolerances being changed must remain within tolerance. 4) Design, construction, and inspection consistency. Check all three Tolerance Maps to ensure that the datum used are the same, and reconcile them where possible. If the datum are different and cannot be made the same, then the three different Tolerance Maps should be combined because they may form additional inconsistent loops. 5) Check Tolerance Maps using tolerance analysis and make the loops consistent using tolerance allocation, design changes and process changes, as discussed below.

By identifying violations, the tools provide the necessary information to generate solutions. Tolerance allocation can be used when some of the tolerance requirements are governed by assembly concerns in a tolerance loop and some of the available process capabilities are tighter than the corresponding tolerance requirements. These conditions allow flexibility in adjusting the individual tolerance specifications. Design change leads to a different assembly equation by changing the critical dimension, nominal geometry, mating relationships (connection design), and/or datum priority, selection or sequence. Design changes are efforts to decouple some tolerance requirements or component variations from a tolerance loop. Looked at in this way, design changes can be used in a directed fashion to decouple from a loop either the largest contributor to loop inconsistency, or the specification with the mismatched process capability. Process changes involve process or inspection modifications focused on controlling the variation of individual components that enter the assembly. Examples of such strategies are to: improve process capability; inspect and reject components that do not meet tolerance requirements before their incorporation into the assembly or inspection; and match parts to the assembly. The goal of each strategy is to create revised tolerance requirements that accommodate both the individual component tolerances based on process capabilities or industry standards, and the requirements of the individual parts and the assembly.

Tolerance Maps can also be checked for work-structuring issues. The Tolerance Map colours indicate the different parties responsible for defining and controlling different tolerances and features. Tolerance Maps can also indicate when work on an assembly by one trade or one set of participants is continually interrupted due to the chosen datum sequence. In general, reducing the number of hand-offs on a project, and thus on a given assembly within a project, is preferable (Howell et al. 1993). Milberg and Tommelein (2004) provide an example of evaluating a map for work-structuring considerations.

ADVANTAGES FOR WORK STRUCTURING OVER CURRENT PRACTICE

Tolerance management could provide valuable information for work structuring, but is unfortunately currently un-utilized. One such example is a case study on hollow metal door frame installation in pre-cast cells (Tsao et al. 2004 and Tsao et al. 2000), which identified geometric dimensioning and tolerancing (GD&T) as a critical consideration for work-structuring decisions and an underlying source of waste generation. This case shows that tolerance problems are a subset of work-structuring problems. Similarly, tolerance information considerations and tools help in work-structuring decisions.

Without stating it as such, the case study actually conducts a one-dimensional tolerance analysis to identify the problem. The case evaluates different solutions to the tolerance problem. Several of the recommended solutions, though again not acknowledged as such, represented tolerance management strategies relating to the assembly function, including: connection selection, process re-sequencing, process capability improvement, and modification of nominal dimensions combined with filler materials. However, these solutions were arrived at using the "5 Whys", rather than tolerance tools. This paper introduces the application of tolerance management as a tool within work structuring to systematically identify solutions that employ tolerance strategies and that may otherwise be missed. In addition, tolerance management allows for evaluation of alternative work structures from a tolerance perspective to avoid selecting solutions that have other tolerance problems.

Although the hollow metal door case solutions represented tolerance strategies as mentioned above, they were not applied based on tolerance loop information. The difficulty with applying strategies without loop information is seen in the solution in which the door frame is cast directly into the pre-cast wall panel. Fortunately, during evaluation of the alternative, someone recognized that casting the panel in the door increased the tolerance requirement on the plumb erection of the panel to ensure proper operation of the door. Given the wall panel plumbness cannot be controlled as well as the door frame can be controlled when installed separately, and given the door frame may not be perfectly aligned with the wall panel when installed, the door will likely be more out-of-plumb and may hit the floor when opened, thereby preventing proper function. Using the tolerance management process described herein ensures that tolerance implications of an alternative work structure, such as the change in tolerance on the panel erection, are found in the tolerance analysis rather than relying on the experience of those included in the work-structuring evaluation. In the more general sense, using tolerance management incorporates tolerance considerations into decisions, improving those decisions and helping to achieve the goals of work structuring. For each alternative, all factors that contribute to the interrelationship between components, and thus impact various lifecycle considerations – including tolerances – need to be identified for better product and process design, as well as for a more efficient design process. Tolerance management tools offer a way to generate alternatives and provide for the systematic and thorough identification of geometric interrelationships between components.

CONCLUSION

To summarize the connection between tolerance management and work structuring, table 1 illustrates where tolerance management assists with the hierarchy of means for work structuring as detailed by Ballard (2001). In conclusion, tolerance management is not only important for maintaining a smooth work flow but is also important to the function and quality of the product. In addition, despite the many challenges in applying tolerance management to civil project production, tolerance management aids in all goals of work structuring and should therefore be included as an integral tool for work structuring.

Table 1: Tolerance management applications of TFV principles

Means	**Tolerance Management (TM) Application**
Increase Positive Iteration	Tolerance management tools should be integrated with detailed design and focus on revealing additional options for positive iteration.
Use set based strategy	The methodology for model evaluation and solutions generation is based on identifying multiple options for consideration, i.e., set based.
Design for full life-cycle	Tolerance maps are designed to take into consideration product quality, fabrication, construction, and inspection.
Inspect against purposes	Comparing inspection and design maps ensures inspection against purpose. Tolerance maps and standards aid in communication of intent. Tolerance map and specification rules help ensure complete specifications.
Focus control on complete system	Maps consider design, fabrication, construction, and inspection tolerancing perspectives and where possible incorporate additional perspectives on task assignment. Tolerance allocation is optimization of the whole system.
Reduce steps, parts, & linkages	Datum minimization, connection selection and analysis of the assembly equation are essentially the same principle.
Increase Transparency	Tolerance analysis and networks describe the interrelationships among parts, capturing intent and increasing transparency.
Reduce variability and latent product defects	Tolerances and process capabilities (PC) are a form of variability. So TM tools and strategies aid in identifying, describing, and reducing the geometric variability and tolerance related defects.
Get evidence of product compliance	One process strategy is inspection and rejection based on tolerance requirements.
Improve design for fab., construction, & installation	TM is designed for quality, fabrication, construction, and installation (QFCI). PC and tolerance comparisons represent a QFCI check. Allocation strategies employ QFCI considerations found in the tolerance maps.
Make inspections unnecessary	Tolerance management aids creation of designs based on actual process capabilities to eliminate the need for inspection.
Type, size, & locate buffers for variability	Connection design through map evaluation and tolerance analysis are all the sizing and locating of buffers for tolerances. Clearances and overlapping joints are the typical TM strategies for buffering

	tolerances.
Layout for flow	The colour in the map is designed to aid in layout for flow.
Minimize negative iteration	TM incorporates tolerance considerations into work-structuring decisions thus helping avoid negative iteration.
Redesign product for less processing time/cost	PC data helps identify tolerance allocations impacting process duration and cost. Tolerances are allocated among individual components to minimize processing time and cost for the assembly as a whole.
Act on causes of defective work	TM tools are designed to identify potential tolerance problems within a design and generate alternatives designs or processes to avoid them.
Assign tasks where best done	Tolerance allocation is based on this principle.
Reduce material scrap	Connection design helps avoid the need for field modifications to achieve custom fitted parts thus reducing scrap.
Design to intervals' upper ends	Tolerances are interval estimates. TM encourages design based on worst-case (upper end estimates) or statistical analysis.
Match load to capacity	Tolerance analysis ensures that individual tolerances meet assembly tolerances. Ensuring tolerances match process capability is same principle.

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