Chapter

15

Automating the Tolerancing Process

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15.1 Background Information

The steady increase of computing capability over the past several years has made powerful engineering analysis tools, such as Computer-Aided Design (CAD) and Finite Element Analysis, available to every engineer. Computer-Aided Tolerancing (CAT) systems that use the CAD geometry to derive mathematical tolerance models are now becoming available. These CAT systems hold great promise in automating tolerancing tasks that used to be performed by hand or with computer spreadsheets, outside of the CAD environment.

This chapter will introduce an automated tolerance analysis process and discuss the different component technologies available that can be used to automate the steps in the tolerancing process.

15.1.1 Benefits of Automation

In general, computer automation can provide great benefits. For tolerance analysis, automation can simplify the tolerance modeling and analysis process, increase the analysis accuracy, reduce analysis time, and reduce calculation errors. An automated tolerance analysis method can also be augmented to include tolerance optimization. Automation can be used to improve communication between design and manufacturing personnel. Furthermore, a CAT system that is integrated with a CAD system can keep the tolerance data synchronized with the CAD model.

15.1.2 Overview of the Tolerancing Process

The tolerancing process begins with two competing pieces of information: the design requirements that must be met to ensure performance and quality, and the manufacturing process capability that can be achieved with the tools available. As shown in Fig. 15-1, the tolerancing process is the means by which these competing requirements are balanced.

A tolerance model is constructed by first deriving design measurements from design requirements. A model function must then be defined to serve as a mathematical relationship between input variables and design measurements. Finally, the input variables must be derived from the manufacturing process capabilities.

Once constructed the tolerance model can be used to perform tolerance analysis or allocation. The terms "analysis" and "allocation" refer to moving through the tolerance model in opposite directions.

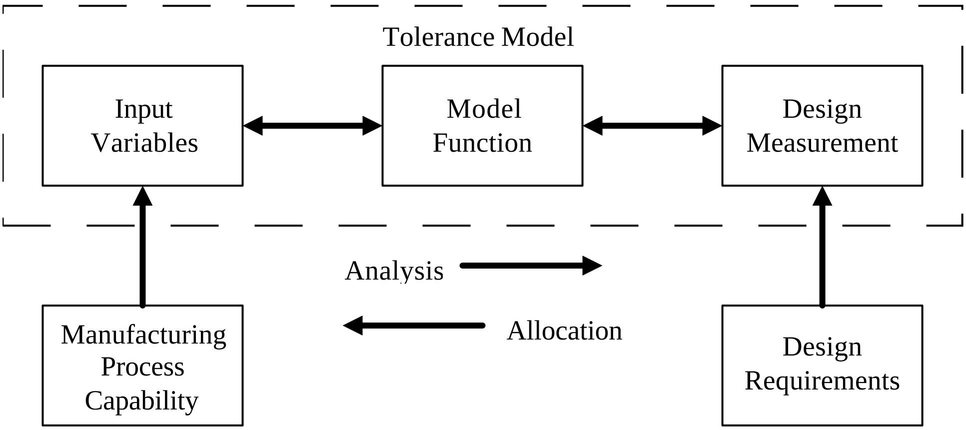

Figure 15-1 Tolerancing process

Tolerance analysis is the process of finding the output quality of a design measurement from the supplied input variables. Tolerance allocation, on the other hand, is the process of finding a set of values for the input variables that will give a desired quality for each design measurement. See Chapter 11 and Fig. 11-1.

The following three sections will discuss aspects of this tolerancing process including model creation, analysis, and optimization in more detail. They will focus on what considerations need to be made in deciding how to automate the various steps of the tolerancing process.

15.2 Automating the Creation of the Tolerance Model

15.2.1 Characterizing Critical Design Measurements

The first step in building a tolerance model is to define the critical design requirements that will be analyzed. Many design requirements are initially posed in qualitative form rather than quantitative form. For example, a design requirement that a circuit card must easily slide into a slot must be translated into insertion force and ultimately to clearance measurements. It is therefore a necessary step of any tolerance modeling process to characterize all qualitative design requirements as quantitative design measurements.

Automation of the characterization process requires the definition of a finite set of design measurements. This set must be general enough to mathematically characterize all the classes of design requirements that may exist. Typical types of design measurements include:

- Gap - Measurable distance between two features along a specified direction
- Angle - Measurable angle between two specified surfaces about a specified axis
- Position - Measurable deviation from a specified location within a specified plane

This set is general enough that most design requirements can be described with one or more of these design measurements.

With an automation tool the process by which a design measurement is defined is also important. This process must be intuitive and easy to use. In cases where a tolerance analysis tool is integrated with a CAD system, the process can be simplified by mapping the definition of the design measurement to physical features within the geometry. This gives associativity and context to the definition of the critical design measurement.

15.2.2 Characterizing the Model Function

The second step in the model creation process is to define the model function. The model function characterizes, in a mathematical form, all the behaviors and interactions that exist in real-world parts and assemblies. In order to properly define this function, all sources of variation and how they propagate must be understood. Understanding the form of the model function and the simplifying assumptions used to limit the scope of the tolerance model are also important.

15.2.2.1 Model Definition

Two significant classifications of variation are manufacturing process variation and assembly process variation. Manufacturing process variation describes all the variation that is introduced in the steps of the manufacturing process plan. These variations may be the result of machining error, setup error, tooling error, or tool wear.

Assembly process variation describes the variations that are introduced as parts are brought together to form assemblies. Assembly fixture error and fastening process error are two examples of assembly process variation.

The model function must take into account how these sources of variation will combine to affect the variation of critical features in the assembly. The features referenced during manufacturing setup determine how variation will accumulate within a part. Dimension chains or dimension paths are the terms typically used to refer to this accumulation. Automation of dimension path creation can greatly simplify the tolerance modeling process. The difficulty lies in trying to include the effects of the manufacturing and assembly process plan before the plan exists. When this plan does not exist the dimensioning scheme used for design may be used with some simple assumptions about tolerances and process capability.

At the assembly level, variation propagates either through small kinematic adjustments or through small part deformations. Small kinematic adjustments in the relative position of components occur as a

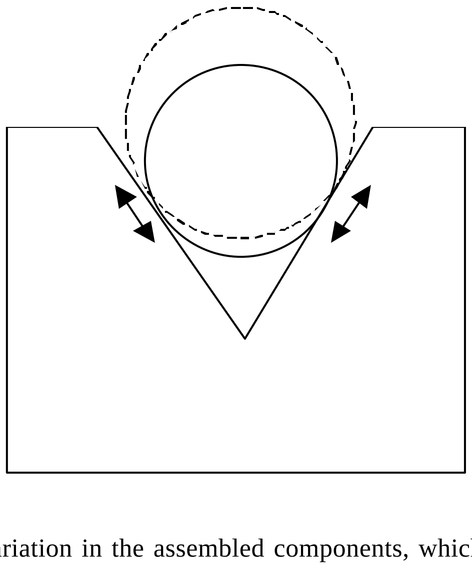

Figure 15-2 Small kinematic adjustments

result of variation in the assembled components, which are exactly constrained. For example, as the diameter of a cylinder in Fig. 15-2 increases, it will rest at a different location within an angled groove.

A complete model function must be able to account for these small kinematic adjustments. One way of characterizing these adjustments is to overlay the mating contacts within the assembly with a kinematic model. The kinematic model describes all mating contacts with kinematic joints and all parts as linkages.

The degrees of freedom are appropriately defined to correctly describe the nature of each contact. The kinematic model can then be solved to find the resulting position of the assembled components.

If the assembly is overconstrained so that parts cannot adjust their relative positions to account for variation, deformation of the components will occur. This is typically the case when sheetmetal parts are used. Sheetmetal parts are brought together by fixtures and rigidly fastened together. Once the fixtures are removed, the resulting assembly deforms to minimize its internal stress state. These deformation adjustments can be described by overlaying a finite element model of the components. This finite element model can then be solved to find the stresses and strains that will result from variation in the component parts and predict how the assembly will deform.

A comprehensive model function will include the effects of all these sources of variation and their corresponding methods of propagation.

15.2.2.2 Model Form

The model function must be captured in mathematical form for computer automation. It must be determined whether an exact or an approximation model will be used. Explicit equations $(y = f(x_1 \ldots x_n))$ rather than implicit equations $(y = f(y, x_1 \ldots x_n))$ are desired to perform tolerance analysis because analytical rather than brute force methods can be used. Exact models, however, can often only be expressed in implicit form for complex assembly models that include all sources of variation.

An alternative to an exact mathematical model is an approximation model. This approximation model can be of any order, but typically a first- or second-order approximation is used. The approximation model is defined by finding sensitivities of critical features to each input variable of interest. These sensitivities can be reasoned geometrically or calculated numerically. Once the sensitivity model is produced, it can be used as the basis for analytical algorithms of tolerance analysis and optimization.

One useful mathematical model of the assembly is the CAD model. A CAD model has a full mathematical definition of the assembly that can be interrogated through the CAD system's native or programmatic interface to extract valuable information. Critical features and dimensioning schemes can be identified from the CAD model. CAD systems that are parametric or variational geometry based can be perturbed to find sensitivities directly. Assembly based CAD systems that have meaningful assembly constraints can also provide definition for the assembly process variation. The CAD model is therefore a good starting point in defining the mathematical tolerance model.

15.2.2.3 Model Scope

The definition of an absolutely complete and correct model is often inefficient and unnecessary. By making simplifying assumptions, the complexity of the model can be reduced without losing significant accuracy. It is important, however, to understand the implications of these simplifying assumptions because making the wrong assumptions can lead to invalid results.

One of the most common assumptions is the simplification of 3-D problems to 1-D or 2-D stackups. The world is 3-D and the variations in an assembly interact three-dimensionally. Therefore, a truly accurate model will describe all the 3-D relationships that exist in an assembly. Historically, tolerance analyses have been simplified to 1-D stackups because many were performed by hand. One-D models ignore the effects of most assembly processes on a design measurement and include only the effects of linear variations along a single direction. This may be sufficient for assemblies that have only planar interfaces that are all at right angles to one another and do not involve complex assembly processes. Two-D models start to include the interdependencies that are introduced at the assembly level, but the variation is still restricted to a single plane. Reducing models to 1-D or 2-D may simplify a model function, but is not appropriate in all cases.

Another simplifying assumption is to reduce the number of parts and/or features included in the study. Not all features of all parts affect every design requirement. Ignoring irrelevant parts and features limits the complexity of the assembly function without losing accuracy. In addition to features that have no effect, there may be some features that have only minor effects on the variation in the assembly measurements. Cosmetic and manufacturabilty features such as fillets and rounds often fall into this category. Again, it is important to understand the effects of such simplifying assumptions on the accuracy of the model.

15.2.3 Characterizing Input Variables

The final step in the building of a tolerance model is the characterization of the input variables. The model function is the means of transforming how a change in the inputs will change the outputs. The input variables to the model function are assumed to vary based on variation in the different manufacturing and assembly processes. Tolerance ranges are also supplied for each variable as a limit of acceptable variation. The discussion of the analysis process in the next section will show that the type of analysis performed drives the type and form of the input data. Worst case analysis only requires tolerance limits while statistical analysis requires a defined distribution on the variation of each variable.

Input variable data can come from several sources. The variable definitions, along with some or all of the tolerance data, can be extracted from a CAD system. The statistical distribution information must come from manufacturing data, as will be discussed in section 15.5.

A complete tolerance model is therefore composed of quantitative design measurements, a comprehensive model function and characterized input variables. This comprehensive tolerance model becomes the basis from which tolerance analysis algorithms can be performed.

15.3 Automating Tolerance Analysis

While many tolerance analysis algorithms are simple enough to be applied without automation, there are great benefits in automating tolerance analysis calculations. Automating the analysis calculations can reduce effort and errors. Also, with automation, more advanced analysis methods can be implemented to provide greater accuracy than simple analysis methods.

The Worst Case and RSS methods discussed in Chapter 9, and the DRSS and SRSS methods discussed in Chapter 11 are all simple enough to be used without automation. For example, the RSS method is frequently used to solve simple 1-D tolerance stacks by hand. Very little data is required to use these four methods. The formulas for each of these methods only require tolerances, derivatives and, in some cases, Cpk values as inputs. Of course, these four methods are also easily automated by programming a computer spreadsheet or programming software code.

There are two advanced tolerance analysis methods that are not easily applied without some form of automation: the Method of System Moments and Monte Carlo Simulation. While both these methods are more complicated to implement and require more input data, both offer better accuracy and more capability than Worst Case, RSS, DRSS, or SRSS. Commercial CAT systems are generally based on one of these two methods. The next two sections will describe these advanced methods in detail.

15.3.1 Method of System Moments

The RSS, DRSS, and SRSS methods are all derived from a more general method, the Method of System Moments (MSM). MSM is a statistical method that estimates the first four statistical moments of a function of random variables. These four statistical moments are mean, variance, skewness, and kurtosis. MSM consists of four equations that relate to each of the four statistical moments. With the model function expressed in this form,

$$y = f(x_i), \quad i = 1, 2, 3 \ldots n$$

the four equations for MSM are:

$$m_1 = 0 \tag{15.1}$$

$$m_2 = \sum_{i=1}^{n} \left(\frac{\partial y}{\partial x_i} \right)^2 m_2(x_i) \tag{15.2}$$

$$m_3 = \sum_{i=1}^{n} \left(\frac{\partial y}{\partial x_i} \right)^3 m_3(x_i) \tag{15.3}$$

$$m_4 = \sum_{i=1}^{n} \left(\frac{\partial y}{\partial x_i} \right)^4 m_4(x_i) + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} 6 \left(\frac{\partial y}{\partial x_i} \right)^2 \left(\frac{\partial y}{\partial x_j} \right)^2 m_2(x_i) m_2(x_j) \tag{15.4}$$

where:

$\frac{\partial y}{\partial x_i}$ is the partial derivative of the function with respect to the *i*th variable,

$m_i(x_j)$ is the *i*th statistical moment of the *j*th variable, and

m_i is the *i*th raw statistical moment of the function.

Eqs. (15.1 through 15.4) are the four raw moments of the model function. These four raw moments can be easily converted to mean, variance, skewness and kurtosis. The first equation is the mean shift, the second equation is the variance, and the third and fourth equations are related to the skewness and kurtosis, respectively.

Eq. (15.1), the mean shift, is included because the mean shift is not zero for the second-order version of MSM. The four equations given above are based on a linear, or first-order, Taylor's Series approximation of the model function. The four MSM equations can also be developed using a second-order Taylor's Series approximation. A second-order approximation improves the accuracy of the approximation for nonlinear functions. The trade-off with the second-order formulation is that the four MSM equations become much more complex. The four second-order MSM equations can be found in Cox. (Reference 3)

The RSS, DRSS, and SRSS are first-order MSM methods derived from Eq. (15.2), the variance equation. Taking the square root of Eq. (15.2) yields the RSS formula, a formula for the standard deviation of the model function. (See Chapter 9 for another derivation of the RSS formula.) Unlike the RSS, DRSS, and SRSS methods, however, MSM allows the input variable to be characterized by any statistical distribution, including nonnormal distributions. Note that the four MSM equations include the first four statistical moments of the input variables. These four moments are calculated from the probability distributions of the input variables.

In summary, MSM is an advanced tolerance analysis method similar to RSS, but more general. MSM adds the capability of nonnormal input variables and a nonnormal estimate of the model function. Also, if a second-order approximation is used, MSM can provide a more accurate approximation for nonlinear model functions. The computation time for MSM is very small. In addition, once sensitivities are calculated, only the four MSM equations need to be re-evaluated whenever the distribution characteristics of the input variables change. This quality makes MSM very attractive for rapid design iteration.

15.3.2 Monte Carlo Simulation

Monte Carlo Simulation (MCS) is another advanced tolerance analysis method. MCS is a statistical technique based on random number generation. For the MCS method, each input variable is characterized by a statistical distribution. A random value is selected from each input variable distribution and then plugged into the model function. The resulting function value is then stored. To simulate manufacturing, the process of randomly selecting the input values and then storing the resultant function value is repeated many times. The stored function values can be plotted in a histogram, used to calculate the standard deviation of the model function or used to calculate other metrics. The sample size, the number of times the simulation is run, determines the accuracy of the analysis. The larger the sample size, the more accurate the analysis. A typical sample size is 5000 assemblies. Obviously, this type of method must be automated.

In contrast to MSM, MCS does not use an approximation of the model function. No derivatives are required for MCS. This can be useful if the model function happens to be discontinuous. However, since MCS evaluates the model function many times, the computation time of MCS can be significant, especially if high levels of accuracy are needed. Also, if any input variable's distribution is modified, the entire simulation must be re-run.

Tolerance analysis benchmarks have been performed which show the first-order MSM method to have about the same accuracy as MCS with a sample size of 30,000 assemblies. (Reference 5) These same benchmarks showed the second-order MSM to have about the same accuracy as MCS with a sample size of 100,000 assemblies. (Reference 6) The accuracy and speed of MSM makes it a good candidate for CAT systems.

Table 15-1 compares the features of the two advanced tolerance analysis methods. Selecting which analysis method to implement between MSM and MCS is mostly a matter of determining whether the function to be analyzed is continuous. If derivatives can be calculated, MSM provides a solution that is more suited to design iteration because of its fast analysis. Furthermore, the derivatives used by MSM can also be used to automate tolerance optimization.

Table 15-1 Advanced tolerance analysis methods: MSM versus MCS

	Method of System Moments	*Monte Carlo Simulation*
Fast Analysis	√	
Nonlinear Analysis	√*	√
Nonnormal Inputs	√	√
Nonnormal Output	√	√
Discontinuous Functions		√

**Using a second-order approximation*

15.3.3 Distribution Fitting

Distribution fitting is an important automation issue for the MSM and MCS tolerance analysis methods. A distribution must be fit to the output of both MSM and MCS in order for quality metrics such as sigma, PPM, DPU, etc., to be calculated. For the MSM method, the four statistical moments of the model function are fit with a distribution. For MCS, a distribution is fit to the histogram of the simulations. Distribution fitting is automated by using tabular data or numerical methods for known distribution types. The distribution types that are most commonly automated are the normal distribution, Lambda distribution, and the Pearson and Johnson families of distributions. (References 8 and 9)

In addition to fitting a distribution to the output of the MSM and MCS methods, the distribution types of the input variables must also be defined. Ideally, for the input variables, the designer can define specific distributions based on actual manufacturing data. If this data is not available, however, a distribution can be assumed from the tolerance value. For example, frequently it is assumed that variables are normally distributed, the mean is equal to the nominal, and the standard deviation is equal to one-third the tolerance value.

15.4 Automating Tolerance Optimization

One of the biggest benefits of automating the tolerance analysis algorithm is the opportunity to combine the automated analysis method with a tolerance optimization method. Tolerance optimization is the process of finding the optimal set of tolerances to meet certain design objectives. These design objectives might be assembly cost, assembly quality, and/or part quality. Tolerance optimization and allocation methods are presented in Chapter 11 and Chapter 14.

The analysis methods based on derivatives such as the Method of System Moments (MSM) have an advantage over Monte Carlo Simulation (MCS) with respect to optimization. These derivatives provide valuable information to optimization methods so that an optimal solution may be found quickly and efficiently. The MCS method has been successfully used with optimization methods, but in order to have reasonable computation time, sample sizes are usually set at 500 assemblies. Accuracy is sacrificed at sample sizes this small.

15.5 Automating Communication Between Design and Manufacturing

Automating the creation, analysis, and optimization of the tolerance model is the first part of the tolerance automation process. Automating the communication between design and manufacturing is the second part.

One of the main purposes of automating the tolerancing process is to reduce problems in the transition of a product from design to manufacturing. A major cause of transition problems is a lack of communication. Designers often don't understand manufacturing processes and capabilities. Manufacturing personnel may be unsure of the design intent and what is important to performance. These are the same issues addressed by concurrent engineering. Automating the communication between design and manufacturing is analogous to automating the application of concurrent engineering principles (Fig. 15-3).

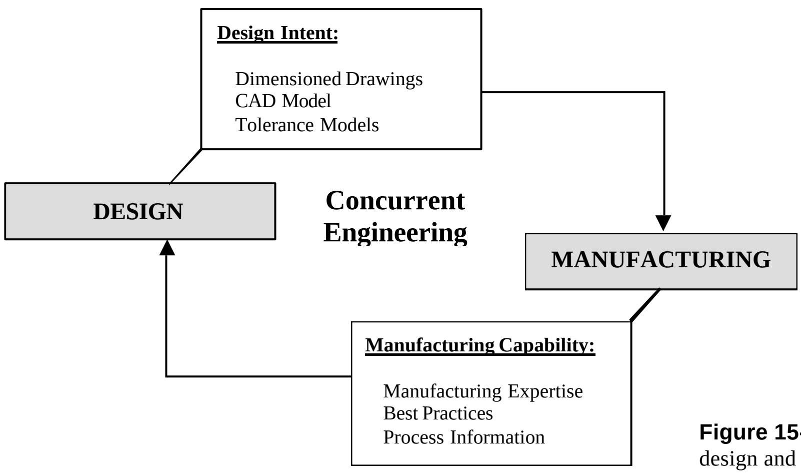

Figure 15-3 Communication between design and manufacturing

Improved communication between designers and manufacturing personnel can be defined in terms of deliverables from one group to the other. The deliverable from manufacturing to design is manufacturing process information. The deliverable from design to the manufacturing personnel is the product definition. The purpose of tolerance automation at this level is to simplify the delivery and use of these "deliverables."

15.5.1 Manufacturing Process Capabilities

A central tenet of concurrent engineering is that accounting for manufacturing capabilities early in the design cycle produces designs that are easier to build, less costly, and more robust. To accomplish concurrent engineering, designers need to understand what manufacturing processes will be used to produce the parts, along with the associated process capabilities. Giving the designers accurate process capability information allows them to predict approximate yields before production begins and to tailor their design to the available manufacturing processes.

Including manufacturing personnel in design teams is a common way to communicate process capabilities. (See Chapter 2, section 2.2.2.1.) Though effective, this is resource-intensive, often inconvenient to schedule, and may be overkill for some of the information needed by designers. Automation can simplify the transfer of some of the more common pieces of manufacturing information. One effective way to accomplish this is to provide the designers with a database of manufacturing process capabilities. (Reference 4)

15.5.1.1 Manufacturing Process Capability Database

Ideally, a database of manufacturing process capabilities should represent all the information necessary to make intelligent decisions about how to manufacture a design. It would include the types and capabilities of manufacturing processes used in-house. It would include the types and capabilities of manufacturing processes used by the vendors that supply the company with components. It would also include real-world application information, such as machine setup issues, fixturing, production cells, what machines can be used for various feature types, and rules of thumb related to manufacturing process planning.

As discussed in sections 15.2 and 15.3, performing statistical tolerance analysis requires characterizing the variation of the input variables of the tolerance model function as statistical distributions. By definition, a manufacturing process capability database would automate the characterization of the tolerance model input variable distributions.

Most companies do not have the resources to create a database of this caliber for their designers. However, it is realistic for most companies to characterize and catalogue, at a minimum, their manufacturing process capabilities and store them in a database. The knowledge of how to use that information to select manufacturing processes will still need to come from the manufacturing personnel. Once the manufacturing processes are selected, the designers will be able to use the manufacturing process capability information from the database to refine their design and check performance and producibility requirements.

To build a useful manufacturing process capability database, a company needs to look at its historical manufacturing process performance. Many companies have accumulated large amounts of process capability data through using SPC (Statistical Process Control) methods. Unfortunately, this data is usually not used effectively beyond the manufacturing floor. If process data is collected correctly, it can be used to form the basis of a process capability library. Proper gathering of data involves issues beyond the scope of this chapter. See Reference 7 and Chapter 17 for further details on collecting and developing process capability models.

15.5.1.2 Database Administration

The database form, organization, and location must be well planned to successfully automate the exchange of manufacturing process capabilities.

There are several formats that can be used to store the distribution information for each manufacturing process. The most direct is fitting a specific distribution to the process data and storing the distribution type and parameters. A second approach is to extract the first four moments from the process data and storing those values directly. This approach is especially appropriate if MSM analysis is performed. A third approach is to assume a distribution type and store a tolerance value and process capability index (Cp/Cpk). The distribution parameters are then derived from the tolerance and capability index values. Normal and uniform distributions are commonly used in this manner. Various combinations and modifications of these formats can also be used. The format selected may depend in part on what standard quality metrics the company uses. See Chapter 8 for methods of specifying statistical tolerances.

Manufacturing process capability data must be organized so that both designers and manufacturing can readily find the applicable manufacturing process information. For example, the data could be organized according to machine type, material type, feature type, feature size, and variation type (i.e., length or angular variation) for each manufacturing process. Additional organization factors might include vendor name, lead-time required, cost data, and surface finish capability.

Finally, the data must be placed in a location that is accessible to the designers. The most desirable setup would allow the designers to access the data from directly inside their tolerance analysis tool. This requires either that the tool itself provide an internal mechanism for storing a library of process information, or both the manufacturing process database and the tolerance analysis tool support a common database format. At the same time, the content of the data must be controlled so that it can only be updated by following a defined procedure.

15.5.2 Design Requirements and Assumptions

A second way to automate communication is for the designers to deliver a more complete definition of the design to manufacturing. Information frequently missing from the design definition is a tolerance model describing what design requirements are most important, and how those design requirements are affected by manufacturing variation. One of the products of the tolerancing process on a design should be a set of reusable tolerance models. The tolerance models and their results can then be delivered along with the rest of the design definition to manufacturing.

Providing tolerance models to manufacturing can help automate several critical production tasks. First, it helps automate troubleshooting manufacturing problems. The tolerance analysis model should identify both the design requirements and the driving dimensions (input variables). Each design requirement is driven by some critical subset of part dimensions. Not all part dimensions are relevant to a particular design requirement. When issues arise in meeting a design requirement, the tolerance model will provide visibility into what the primary variation contributors to the requirement are. This visibility helps automate finding the source of manufacturing problems.

Second, it helps automate predicting the impact of manufacturing process changes. The manufacturing processes used to produce a part may need to be changed in order to reduce costs, free up a specific machine tool for other production runs, or act as a substitute when the original machine breaks down. If manufacturing has access to the original tolerance models, they can pull up the relevant studies and change the assumptions to reflect the new process, and check conformance to the design requirements.

Third, it simplifies communicating design and manufacturing problems back to the designers. By using the same tolerance models, both design and manufacturing have a common frame of reference and can speak a common language when problems arise. The process of identifying the problem and finding a solution can be much quicker.

Fourth, it helps evaluate the usability of parts that are out of specification. For example, batches of parts may come in with mean shifts or excessive dimensional variations. With both manufacturing process capability data and a tolerance model accessible, the tolerance model can be updated to test the effect on the design requirements and see if the parts can be accepted.

15.6 CAT Automation Tools

Sections 15.2 through 15.5 discussed principles of automating the tolerancing process in terms of the creation, analysis, and optimization of tolerance analysis models, as well as methods of automating the transfer of information between design and manufacturing. The practical way these principles can be realized is by implementing them in a tolerance analysis tool.

There are a growing number of tolerance analysis tools marketed commercially, and even more that have been developed internally by various companies. Whether or not a specific tolerance analysis tool is suitable for a company's efforts to automate their tolerancing process is determined by the capability and usability of the tool.

15.6.1 Tool Capability

When selecting CAT tools, it's important to distinguish between specialized tools and general-purpose tools. Specialized tools are optimized for a specific type of tolerance analysis, such as optical lenses or electrical connector interfaces. General-purpose tools are generic enough to adapt to many common analysis situations — mechanisms, fixturing, assembly process variations, and others.

Defining the capability requirements of a tool requires understanding the common tolerance analysis situations seen in the company. Answering this requires conscientiously collecting information from a variety of designers and manufacturing personnel, and not simply relying on the judgment of one or two "experts" in the company. Individuals tend to develop tunnel vision about what types of tolerance analysis are important. It is important that a CAT tool comprehends the majority of the analysis situations and simplifies the current analysis methods.

While tool capability is very important, it is not the only criteria to consider when shopping for CAT tools. Several usability issues must be considered. In many ways, the usability issues eclipse the importance of tool capability. Sections 15.6.2 through 15.6.8 will discuss issues related to the usability of CAT tools.

15.6.2 Ease of Use

Ease of use is the single most important factor in determining the success of a CAT tool's deployment. If the tool is not easy to use, acceptance among designers and manufacturing personnel is unlikely. Defining what is easy to use is highly subjective, but several general characteristics should be considered.

- The user interface should have an intuitive layout. The information should be well organized with the most important data readily accessible.
- Model creation should follow a logical process that uses a clearly defined set of operations. The model creation process should be designed around a systematic approach that can be generically applied to a wide range of problem types.
- Model creation should be quick. Time is a scarce resource to designers. Few industries have the luxury of long tolerance analysis cycles. If the designers cannot quickly create a model, run the analysis, and get on to their next task, they are likely to use another means to analyze the tolerances or skip it altogether.

- The tool should have useful documentation. The tool's documentation is often the last place searched for answers to questions. However, when it is finally referred to, the user should find that the documentation is well organized and contains useful examples. The documentation should be available both on-line and as hard copy.

The importance of a CAT tool's ease of use cannot be overemphasized.

15.6.3 Training

The nature of tolerance analysis requires training. Tolerance analysis covers a wide range of specialized concepts: dimensioning, tolerancing, GD&T standards, optimization, statistics, mechanisms, kinematics, manufacturing, inspection, SPC, and others. The amount of training required is determined by the background of the trainee, the difficulty of the tool, the quality of the training program, and the complexity of the analyses to be performed. Purchased tools should provide training classes and materials. Companies that develop CAT tools in-house bear the burden of developing classes and materials to train its users.

15.6.4 Technical Support

The complexity of tolerance analysis guarantees that questions will arise about the use or behavior of a CAT tool. Extra assistance may be needed to understand problems in specific application situations. Software bugs will also occur. There must be resources available to answer the users' questions and assist in workarounds until fixes are available.

Commercially purchased tools should have a help line and a mechanism for distributing technical information (such as known bugs and workarounds). Help-line access usually requires a company to purchase a software maintenance package in addition to the tolerance analysis tool itself.

If tools are developed in-house, help-line resources must be budgeted yearly and skilled help-line personnel developed internally to support the users.

15.6.5 Data Management and CAD Integration

Computer-based tolerance analysis tools generate data files that must be maintained. Tolerance model files developed for a specific CAD model need to be stored with that CAD model. This may also be true of the analysis output files. To this end, the tolerance analysis files should integrate smoothly with the company's CM/PDM (Configuration Management/Product Data Management) system.

To help the designers achieve concurrent engineering, the CAT tool should work natively with the CAD system. The easier it is to keep the CAD model and the tolerance model in sync, the better. Having the CAT tool integrated with the CAD system also helps the manufacturing and quality control personnel find and use the tolerance models when they need them.

15.6.6 Reports and Records

Documenting a tolerance study and distributing the results should be quick and easy. The reports themselves should have a format that covers the important information. At a minimum, the reports should include:

- Output statistical/worst case variation plots
- Sensitivity/Percent contribution pareto of each performance or fit requirement to the part dimensions
- Part dimensions, manufacturing variations, and process capability metrics.

Reports need to be modifiable by the user. They should be output as straight text or another common format that can be easily read and edited by a word processor. Any graphic should also be output in a standard format that can be easily imported into a word processor.

15.6.7 Tool Enhancement and Development

It is unlikely that any existing tool on the market will meet all the requirements of a company. The CAT tool industry is still relatively immature and is changing rapidly. Therefore it's important to understand a CAT tool's future development path. Issues to understand include:

- What future enhancements are planned for the tool?
- Do future enhancements address all the outstanding issues (e.g., missing functionality) that the company has with the tool?
- Is there an effective mechanism for entering enhancement requests and bug reports?
- How rapidly is the tool being improved?
- If it is a commercial product, is the tool provider stable? If it is a tool developed in-house, does it have a stable funding source?

It is vital that the selected CAT tool is growing and the tool provider is reliable. If it is, the investment in a CAT tool has a far greater chance of delivering real returns to the company in terms of improved quality and reduced cost.

15.6.8 Deployment

The issue of deploying a CAT tool in a company is too large to address within the scope of this chapter. However, some questions that must be answered relative to deployment include:

- Who has responsibility for implementing the tool in the company?
- How much effort will be required internally to install and maintain the tool?
- Does the tool work on company-supported hardware and operating system versions?

In short, a deployment plan must comprehend all the infrastructure required to install and maintain the CAT tool.

15.7 Summary

Automation can provide great benefits to the tolerancing process. Through automation, tolerance model creation and analysis can be simplified and accuracy improved. The time it takes to develop an optimal dimension scheme for a design can be greatly reduced. Automation can also improve the communication between design and manufacturing and help develop a more concurrent engineering environment. Finally, careful consideration of the important capability and usability issues will enable the successful selection and deployment of tolerance automation tools.

15.8 References

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