EVALUATION OF VSA TOLERANCE ANALYASIS SOFTWARE PACKAGE AS A FUNCTIONAL DIMENSIONING AND TOLERANCING TOOL SUITABLE FOR A CONCURRENT ENGINEERING ENVIRONMENT

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Abstract Functional Dimensioning and Tolerancing (FD&T) is a concept used for specifying dimensions and tolerances of the component parts and sub-assemblies of a product according to their functional requirements. It is suggested that the Concurrent Engineering (CE) environment helps to solve FD&T problems. However, appropriate tools are needed for solving FD&T problems in a CE environment. In recent years a number of tolerance analysis software packages have been released and VSA claims to be the market leader. For this reason a VSA tolerance analysis software package was evaluated in order to test the state of commercially available tolerance analysis software packages currently available. In this paper this evaluation process is presented in detail with two solved examples. The findings of this evaluation draw attention to the shortcomings that are apparent in currently available commercial FD&T tools.

*Keywords**:** Functional Dimensioning and Tolerancing, Concurrent Engineering, Tolerance Analysis*

INTRODUCTION

Functional Dimensioning and Tolerancing (FD&T) is a concept used for specifying dimensions and tolerances of the component parts and sub-assemblies of a product according to their functional requirements. These functional requirements arise from all life cycle issues, such as manufacturing, assembly and inspection. *Concurrent Engineering (CE)* is an engineering and management philosophy, which also deals with life cycle issues of a product. CE is based on the idea of carrying out as many stages of product development concurrently as possible, rather than in a sequential order. It calls for the formation of a cross-functional product development team, which includes people from a wide range of departments, such as: product planning, design, manufacture, assembly, quality assurance, marketing, sales, finance, etc. CE has become the central theme of manufacturing, a necessary survival factor in today's global competitive environment [Szczerbicki, 1999].

It is suggested [Farmer, 1993, Wilhem and Lu 1992a] that the CE environment helps to solve FD&T problems but appropriate tools are needed for solving them in a CE environment. In recent years a number of tolerance analysis software packages have been released and VSA claims to be the market leader. For this reason a VSA tolerance analysis software package was evaluated in order to test the state of commercially available tolerance analysis software packages currently available.

This evaluation was performed from a Concurrent Engineering perspective. First the requirements of a FD&T suitable for a CE environment were formulated by considering various requirements for such a tool reported in the literature. Details of this establishment process can be found in [Islam, 1999].

REVIEW OF TOOLS AVAILABLE FOR SOLVING FD&T PROBLEMS

Initially, all tools for solving FD&T problems were manual. However, because FD&T is an iterative process and requires various calculations, with frequent references to engineering standards and process capability databases, performing these tasks manually is cumbersome and time consuming. Researchers have concentrated their efforts in developing computer-based tools to automate this process, and as a result, many prototypes have been built. Such as: *DATA SET* [Farmer and Gladman, 1986], *TOLTECH* (TOLerance TECHnology) [Bjørke, 1989], *ROSCAT* (Rule Oriented System for Computer Aided Tolerancing) [Maivannan et al., 1989], *CATC* (Computer Aided Tolerance Control)[Ahlwalia and Karolin, 1984], *CATC* (Computer Aided Tolerance Control) [Fainguelernt et al., 1986], *CAFT* (Computer Aided Functional

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Tolerancing) [Cheikh, 1990], and *CASCADE-T* (Concurrent, computer-Automated methods for the Synthesis of Competing Design Elements and geometric Tolerances) [Wilhetm and Lu, 1992b].

Computer-based tolerancing tools gained renewed emphasis with the advent of CAD systems because without tolerance specifications engineering drawings are not complete. Anticipating the market demand for computer-based tolerancing tools, companies are attempting to develop such tools on a commercial basis. The first commercially available three-dimensional tolerance analysis software package was introduced by Variation Systems Analysis Inc (*VSA*) in 1982 [VSA, 1997]. At present there are a number of other tolerance calculation software packages available in the market, such as *TI/TOL 3D+* from Texas Instruments [TI/TOL, 1996], *DCS* from Dimensional Control Systems [Dimensional, 2001], *Mechanical Advantage* from Cognition Corporation [Cognition, 2000], *Analytix* from Saltire Software [Saltire, 2000], and *VALISYS* from Tecnomatix [Tecnomatix, 2000].

BRIEF DESCRIPTION OF VSA TOLERANCE ANALYSIS SOFTWARE PACKAGE

VSA tolerance analysis software packages are available as modules within a number of leading CAD systems. The software package evaluated is the VSA package integrated into the *Pro/ENGINEER* CAD system, which works in a UNIX platform. This package consists of two modules: VSA-GDT/Pro and VSA-3D/Pro. *VSA-GDT/Pro* is the module used for making a Functional Feature Model (FFM) of a part in which FFM is the mathematical representation of a part necessary for performing variation simulations. *VSA-3D/Pro* is a module used for making a Functional Assembly Model (FAM) of the assembly built in *Pro/ASSEMBLY* (the assembly module within Pro/ENGINEER). FAM is the mathematical representation of the assembly, which contains all the information for representing the assembly.

VSA also developed a stand-alone software package, *VSA-SIM*, for performing Variation Simulation Analysis. It uses two types of simulation for tolerance analysis: (i) Monte Carlo Simulations and (ii) High-Low-Median Simulations.

Monte Carlo simulation is used to simulate the random nature of manufacturing variations that occur in input dimension. The combined effect of all the input variables is calculated and the result compared with the predefined specification limits. This process is repeated many times and the percentage of assemblies that will be out of specification is calculated. For the theoretical background of the Monte Carlo simulation and its application, refer to [Sharpiro and Gross, 1981]. VSA-SIM allows up to 100,000 simulations for an assembly, however the number required for a particular assembly depends on the complexity of the assembly. VSA-SIM can handle different types of distributions, such as: actual, normal and Pearson.

High-Low-Median (HLM) analysis is used to determine the main contributing input factors to the output variations. HLM employs a variance analysis technique where HLM simulations varies each input parameter to its high, low, and median values, one at a time, while holding all other inputs to their median values. For the HLM analysis, a considerably lesser numbers of simulations are required compared to Monte Carlo Simulations. More details on HLM simulation calculation procedures can be found in [VSA-SIM, 1997].

HOW VSA TOLEANCE ANALYSIS SOFTWARE PACKAGE WORKS

The application of VSA's tolerance analysis software package for solving a typical tolerance analysis problem includes the following tasks [VSA-GDT/Pro, 1997]:

- Define objectives (assembly requirements).
- Identify parts which are related to the defined assembly requirements.
- Create all these parts (Pro/ENGINEER).
- Apply plus/minus and geometric tolerances for these parts (Pro/ENGINEER).
- Create Functional Feature model (VSA-GDT/Pro).
- Check GD&T (VSA-GDT/Pro).
- Define assembly methods: sequence and constraints (Pro/ASSEMBLY).
- Verify assembly sequence and constraints (VSA-3D/Pro).
- Define assembly measurements (VSA-3D/Pro).
- Generate VSA-3D model (VSA-3D/Pro).
- Execute simulations (VSA-SIM).
- Generate and evaluate reports (VSA-SIM).
- Perform 'what-if' analysis based on results.

The most significant aspect of the VSA tolerance analysis software package is its ability to perform a 'what-if' analysis. Once the model is complete the user can easily change tolerances, probability distributions of the input variables, assembly measurements and assembly specifications, and analyse the effects of the changes to the assembly measurements.

SOLVED EXAMPLES

To test the effectiveness of the VSA tolerance analysis software package two examples were solved. The steps involved in solving these two examples are described below.

Example 1

First a typical 1D tolerancing problem illustrated in Fig. 1 was solved. The assembly consists of three parts; a small block, a big block and a U shaped part. The functional requirement is that when the small block and the big block are stacked within the U shaped part, the gap between the big block and U shaped part $(Z \pm z)$ should be (20.000 ± 0.03) mm. The functional dimensions were calculated based on Worst Case (WC) analysis:

$$Z = U - B - S \tag{1}$$

$$z = u + b + s \tag{2}$$

Selected values are:

$(S \pm s)$ = (20.000 ± 0.01) mm
$(B \pm b)$ = (40.000 ± 0.01) mm
$(U \pm u)$ = (80.000 ± 0.01) mm

The results of the Monte Carlo and HLM simulations are given in Fig. 2 and Fig. 3 respectively. The number of samples chosen for Monte Carlo simulations was 5000. The probability distribution for Monte Carlo Simulations was chosen as tested normal distribution. The results indicate a capability index (C_p) of 1.827213. This means that the tolerance bands can be shortened, because the specification limits were set according to Worst Case analysis. The results of HLM indicate that the three tolerances equally affect (33.33%) the assembly measurement, which is to be expected.

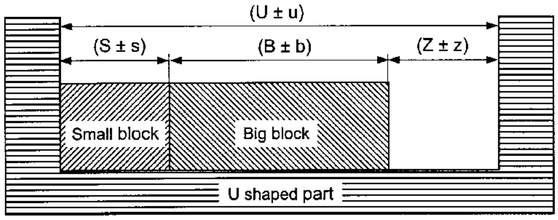


Fig. 1 A typical 1D tolerancing problem

Example 2

The next problem to be solved was a pulley assembly problem, shown in Fig. 4. The function requirements are:

- the fit between pulley and stud should be a running fit,
- the fit between stud and block should be a press fit, and
- the endways movement of pulley (Z ± z) should be (0.100 ± 0.050) mm.

This is taken from [Peck, 1968] who solved it as a 1D tolerancing problem and provided his solution in imperial units. The same problem was solved in metric units using the same methodology as applied by Peck. Peck selected the fits from B.S.1916: Part2: 1953 [British Standard, 1953] as: running fit between pulley and stud: ∅25.4H8f8 and the press fit between stud and block: ∅19H8s7. The dimensions and clearance condition for the fits were taken from the Limits and Fits Table. ∅25.4H8f8 given hole size 25.400 (-0/+0.034) mm and shaft size 25.380 (-0.034/+0) mm. ∅19H8s7 given hole size 19.000 (-0/+0.031) mm and shaft size 19.056 (-0.019/+0) mm. The length dimensions were calculated according to the Worst Case analysis:

$$Z = S - B - P \tag{3}$$

$$z = s + b + p \tag{4}$$

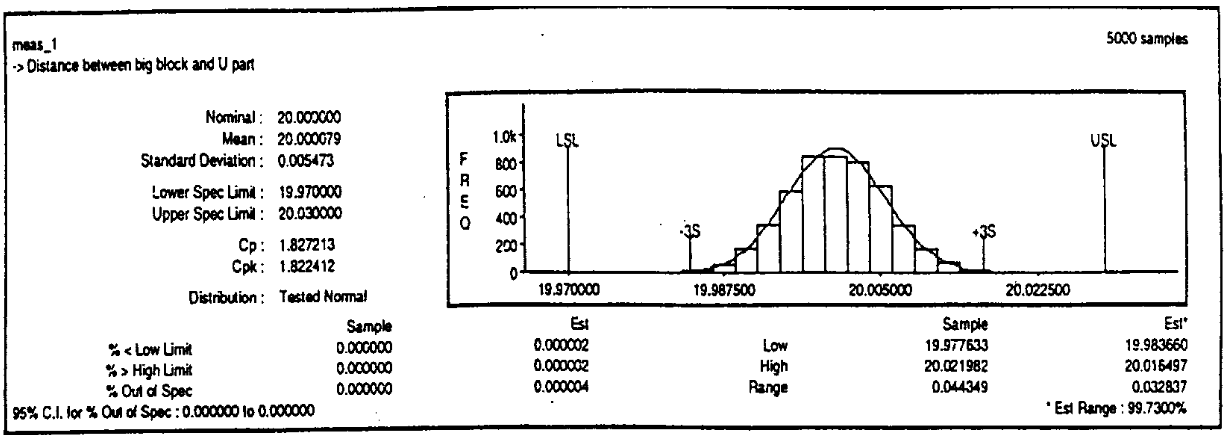
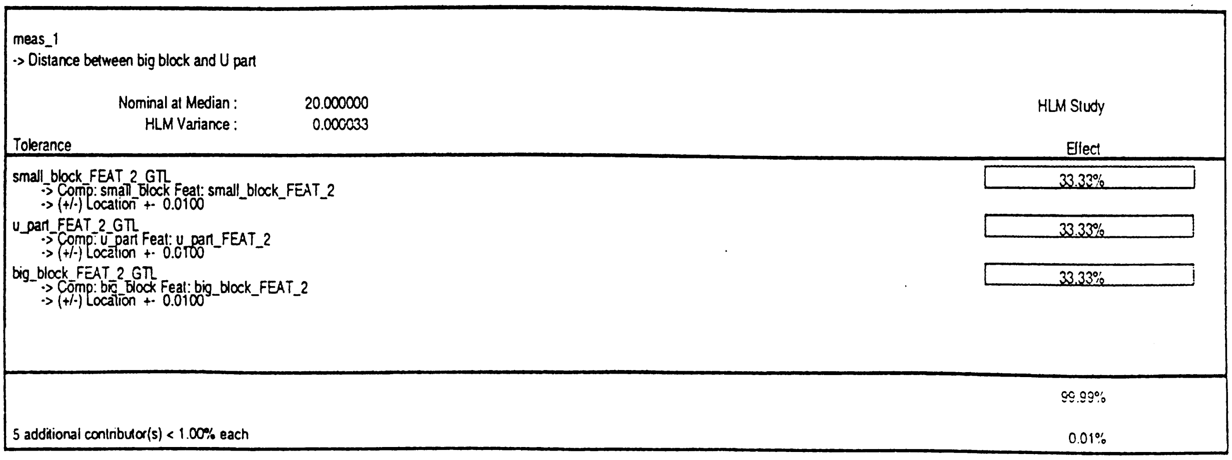


Fig. 2 Monte Carlo simulation results for Example 1


meas_1
-> Distance between big block and U part

Nominal at Median : 20.000000
HLM Variance : 0.000033

Tolerance	HLM Study Effect
small_block_FEAT_2_GTL -> Comp: small_block Feat: small_block_FEAT_2 -> (+/-) Location +- 0.0100	33.33%
u_part_FEAT_2_GTL -> Comp: u_part Feat: u_part_FEAT_2 -> (+/-) Location +- 0.0100	33.33%
big_block_FEAT_2_GTL -> Comp: big_block Feat: big_block_FEAT_2 -> (+/-) Location +- 0.0100	33.33%
	99.99%
5 additional contributor(s) < 1.00% each	0.01%

Fig. 3 HLM simulation results for Example 1

Selected values are:

$(S \pm s)$	=	(31.763 ± 0.013) mm
$(B \pm b)$	=	$(\ 6.250 \pm 0.024)$ mm
$(P \pm p)$	=	(25.413 ± 0.013) mm

The three parts to be used in the assembly were made in Pro/ENGINEER. The values of the geometric tolerances were set to be negligible to minimise their effects. The assembly measurement (endways movement of pulley) was defined as the distance between the inner face of the stud and the adjacent side face of the pulley.

The results of the Monte Carlo and HLM Simulations are given in Fig. 5 and Fig. 6, respectively. From the Monte Carlo Simulation results it can be seen that although the specifications were set according to Worst Case analysis, the capability index C_p is less than 1.0. This indicates that the specified tolerances will produce an unacceptable portion of assemblies out of specifications. This is contrary to usual expectations because when specifications are set according to WC analysis, the C_p is expected to be greater than 1.0. In the HLM Contributor Report it can be seen that there are three major contributors to the variations. The second contributor will explain why the C_p was less than 1.0 despite the selection of specifications according to the WC analysis. VSA-3D/Pro detected a float (clearance) between the stud and pulley. Peck solved this as a 1D problem. As such, it was assumed that when the endways movement of the pulley takes place, the axis of the stud and the axis of the pulley remain aligned; all the dimensional vectors were collinear.

HLM Contributor Report provides information about potential changes. On the basis of this a ‘what if’ analysis can be performed. As the block feature tolerance (*b*) has the greatest effect on the assembly measurement, the easiest way to reduce rejects is to reduce the block feature tolerance (*b*). The tolerance value of the block feature (*b*) was reduced to ±0.013mm from ±0.024mm and another set of Monte Carlo Simulation and HLM Simulations were performed (Table 1). In this case the capability index was increased to 0.78644, but this was still considered to be unacceptable. The design team will have a target C_p value in mind which could be $C_p \geq 1.0$. The HLM Contribution Report showed that the clearance between stud and pulley had the greatest effect (58.99%) on the assembly measurement. Therefore, the next step to increase C_p was to reduce the clearance between stud and pulley, however, this is a fitting condition which comes from another functional requirement and as a result the clearance cannot be reduced arbitrarily. B.S.1916 [British Standard, 1953] was referred to again and another fit was chosen for the stud and pulley: ∅25.4H6f6. The new hole size was 25.400 (-0/+0.013) mm and the new shaft 25.38 (-0.013/+0) mm. Another set of Monte Carlo and HLM Simulations were performed. The Monte Carlo Simulation results show that the target capability index of $C_p \geq 1.0$ was achieved (Table 1).

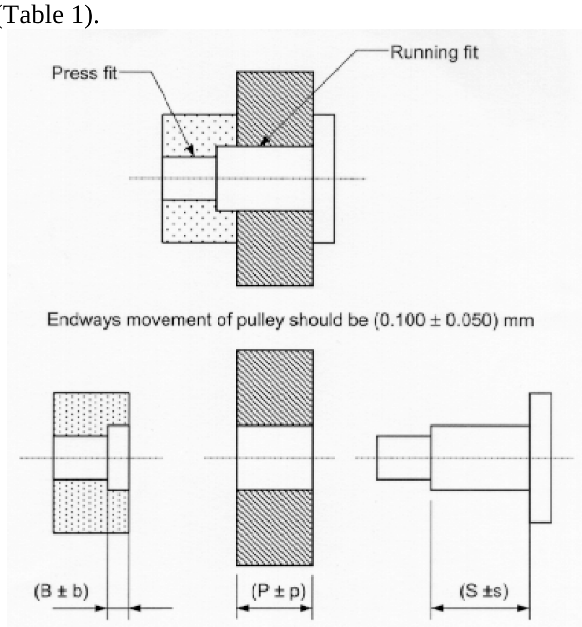


Fig. 4 Pulley assembly (Modified from [Peck, 1968])

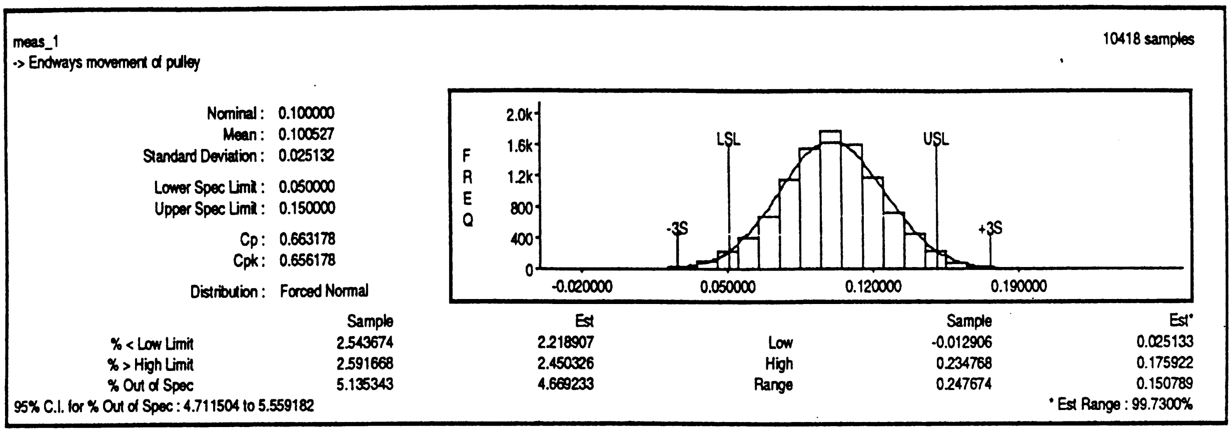


Fig. 5 Monte Carlo simulation results for Example 2

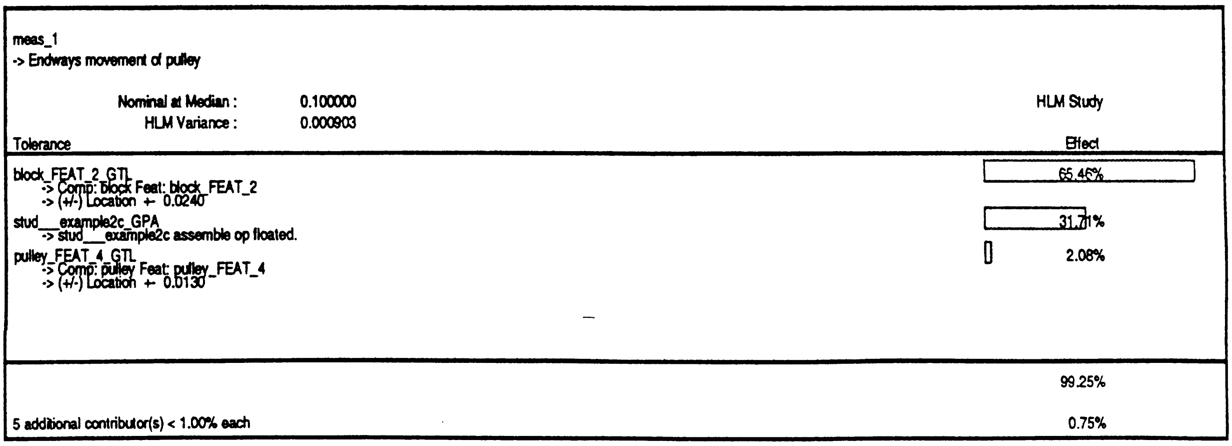


Fig. 6 HLM simulation results for Example 2

Table-1: 'What-if' analysis results for Example 2

Action	Tolerance Values				Process Cap.	Tolerance Values			
	s	*b*	*p*	*Float**	*Cp*	*s*	*b*	*p*	*Float*
Initial values	0.013	0.024	0.013	0.086	0.663178		66.46%	2.08%	31.71%
Reduce *b*	0.013	0.013	0.013	0.086	0.786440	1.38%	35.74%	3.87%	58.99%
Reduce *Float*	0.013	0.013	0.013	0.046	1.027921	2.17%	55.94%	6.05%	35.81%

*Note: *Float* is between pulley hole and stud. The illustrated values are the maximum clearance values.

DIFFICULTIES ENCOUNTERED

The Functional Feature Model built into VSA-GDT/Pro depends heavily on the application of Geometric Dimensioning and Tolerancing (GD&T) as a consequence it was found that VSA-3D does not work properly without the application of GD&T. So, even if the user is not interested in geometric variation s/he is forced to use GD&T. One way to try and overcome this is by including geometric tolerances with very small magnitudes. Setting tolerances to zero in some cases produces a division by zero and stops the software from running.

The greatest difficulty encountered using the VSA tolerance analysis software package was the making of a FFM. This was because to build a FFM a great deal of manual interaction was necessary between the model and the user. Surprisingly, the VSA User Manuals did not outline in detail the procedure for making a FFM. The solved example, which comes with the software package assumes that the FFMs are already built, denying the user any chance to gain any hands on experience.

When making the FFM for the parts involved in Example 1 a problem associated with defining size tolerance was encountered. In VSA-GDT/Pro a size tolerance can be defined in two ways: (i) as size tolerance and (ii) as a location tolerance. Initially the length dimensions were defined as size tolerances. When parts were assembled together the VSA-3D/Pro could not map the assembly move. The reason for this is that when a length was defined as size tolerance, for example, length *(S ± s)* of the small block (Fig. 1), the two of the opposite surfaces formed a complex feature. The surfaces used in defining assembly conditions must be basic features otherwise VSA-3D/Pro cannot map the move. Subsequently when the length *(S ± s)* was defined as distance between two basic features, considering one surface as a datum and defining the other with the help of a location tolerance, the problem was rectified.

The most alarming aspect of the VSA-3D/Pro is that, even though it is unable to interpret assembly constraints, the simulations proceed ignoring these variations relating to unmapped move(s) and as a result it produces incorrect results. The software should give a warning about the inadequacies of the FFM and the possible inappropriate results of the simulation for the requirement being investigated.

In general VSA-3D/Pro is difficult to use because in the process of using it many things might go wrong and at the end, when simulation results are obtained, the user cannot be sure of the validity of the model. When asked how they verify the model, the VSA Technical Support Department provided a list of 20 steps to follow for verification [Technical Support, 1997]. This is an indication of the difficulty involved in making a model. It is noted that many of the checks could be done by the software itself and that it could provide the user with its assessment.

FINDINGS

There is no doubt that VSA-3D/Pro is a powerful tool which can be used for solving FD&T problems. As noted in the case of the pulley assembly example, VSA-3D/Pro provides the opportunity for 3D variation analysis, which would not be possible otherwise. However, FD&T is more than variation analysis. For example, in solving the second example (pulley assembly), before embarking on the variation analysis, the CE team members have to make a number of decisions such as: whether any standard part could be used; whether to produce parts in-house or to purchase the parts; if the parts are to be produced in-house then: decide what design sizes to be used and whether any preferred size can be used; decide which fit to select; decide the magnitude of tolerances whether the selected tolerances could be produced cost effectively.

After making these decisions the CE team will be able to check the selected tolerance values with the help of the VSA tolerance analysis software package. If necessary the CE team could perform a ‘what if’ analysis with the help of the VSA-SIM. However, in changing the initial values the CE team has to reconsider some or all of the above mentioned points. The tolerance values should not be changed on the basis of simulation results, which only analyses the assembly requirements, whereas tolerancing involves fulfilment of a number of other requirements, such as manufacturing and inspection.

The problem is more complicated when there are many coupled functional requirements, ie the requirements have one or more common variables. In the case of coupled functional requirements, a strategy is required to determine which requirement is to be satisfied first and in what order the remaining requirements are to be satisfied. In a real life problem the number of requirements and the number of variables will be high and a way of storing and managing all this information is required. Any FD&T tool suitable for the CE environment should provide all of these facilities.

When using the VSA-3D/Pro the user should be careful about the assumptions made for the simulations because of their implications on subsequent analysis. For example, for HLM simulations it is assumed that interactive effects between input variables are not present. This may not be true in many cases, especially when the same manufacturing process is used. For HLM simulations it is also assumed that the variations of each input variable is distributed normally, although in reality this may not be true.

For Monte Carlo simulations, the distribution data of all input variables have to be provided by the user. At the design stage however, only a normal simulation is feasible due to the lack of statistical data, viz. skewness and kurtosis are essential for non-normal simulations. Data on mean and standard deviation for the manufacturing processes to be used could be obtained from previous quality control records or from machining handbooks. The assumption that all input variables are normally distributed will produce less variation in the assembly measurements, which might produce higher assembly yields.

Another problem with the VSA tolerance analysis package is the difficulty in comparing the predicted assembly yields with the assembly yields achieved in practice. There are no publicly available data at present although a number of industry-sponsored works have been performed by VSA customers: which they do not wish to share with their competitors [Iannuzzi, 1997]. Further research is needed to investigate the correlation between the VSA simulation results and the assembly yields achieved in practice.

The evaluation results of VSA tolerance analysis package as a FD&T tool for a CE environment is illustrated in Table 2. Brief explanations are provided in subsequent paragraphs.

Table-2: Evaluation summary of VSA package as a FD&T tool for a CE environment.

Req. No	Requirements	Source	Findings
R1	It should help the user to describe and quantify the functional requirements of the design.	[Farmer and Gladman, 1986]	No
R2	It should help the user to develop functional equations.	[Farmer and Gladman, 1986]	Yes
R3	It should provide an economic solution to the functional equations.	[Farmer and Gladman, 1986]	No
R4	It should consider manufacturing, assembly, and inspection requirements in tolerance selection.	[Farmer and Gladman, 1986] [Sohlenius, 1992]	No*
R5	It should help in decision making in multiple stages of product development.	[Sohlenius, 1992]	No
R6	It should suitable for team members with different technical background.	[Farmer and Gladman, 1986] [Sohlenius, 1992]	No
R7	It should be interactive.	[Farmer and Gladman, 1986]	Yes
R8	It should run on a platform that is easily accessible.	[Tool, 1992]	No
R9	It should be easy to learn.	[Tool, 1992]	No
R10	It should be based on structured methodology.	[Tool, 1992]	No
R11	It should be applicable to a wide range of products.	[Tool, 1992]	Yes§
R12	It should provide credible results.	[Tool, 1992]	Yes‡

***Considers assembly requirements only, § But cannot solve multiple functional requirements, ‡ If not applied with care, may lead to incorrect results**

R1: VSA does not help the user to describe or quantify the functional requirements of the design. The user has to identify the functional requirements from conceptual design drawings.

R2: VSA has an in-built facility to generate functional equations. However, the model is difficult to develop and in the process of model development many things might go wrong.

R3: VSA does not provide any economic solution. It has no cost minimization strategy.

R4: VSA considers assembly requirements only. It does not provide any facility to match the manufacturing processes with selected tolerance values.

R5: VSA helps in decision-making only at the design stage.

R6: VSA is difficult to use and requires a high technical background to understand and to use the package.

R7: VSA is interactive and it can be used for a 'what if' analysis.

R8: The package was evaluated on an UNIX platform.

R9: It is difficult to learn.

R10: It has no structured methodology for solving FD&T problems.

R11: It is a 3D package and thus it can handle all types of tolerancing problems. However, like other packages, such as TI/TOL or DCS, it does not provide any module for solving simple 1D problems. It has no strategy for solving multiple functional requirements either.

R12: The results seem credible, however, if not applied with care it may lead to incorrect results.

CONCLUDING REMARKS

The above findings draw attention to the shortcomings that are apparent in currently available commercial FD&T tools. They are:

- Difficult to use and generally not suitable for use in a CE environment.
- Simplified assumptions are made. If not applied with care, they may lead to incorrect results.

- The statistical data used is not usually available at the early design stage.
- There is no optimisation strategy. The results only take into account the assembly constraints.
- Cannot solve coupled functional requirements.

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