Parametric Technology Corporation

Pro/ENGINEER® Wildfire® 4.0
Tolerance Analysis Extension
Powered by CETOL™ Technology
Reference Guide

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Introduction

Pro/ENGINEER Tolerance Analysis Extension powered by CETOL Technology is a tolerance analysis application that is integrated with Pro/ENGINEER Wildfire 4.0. With Tolerance Analysis Extension, you can quickly perform 1-D tolerance stackup analysis that is associative to the Pro/ENGINEER part dimensions.

Background

Tolerance Analysis Methods

In performing a tolerance analysis, Tolerance Analysis Extension provides two fundamentally different analysis tools for predicting assembly measurement variation: worst-case analysis and statistical analysis.

Worst-Case Tolerance Analysis

Worst-case tolerance analysis is the traditional type of tolerance stackup calculation (Figure 1). The individual dimensions are set at their tolerance limits to make the stackup measurement as large or as small as possible.

The worst-case model does not consider the statistical distribution of the individual dimensions, but rather that those dimensions do not exceed their respective specified tolerance limits. Mathematically, the model assumes that all the tolerance dimensions will equal one of their limit values, which yields an extreme stackup condition. In other words, this model predicts the maximum expected variation of the measurement.

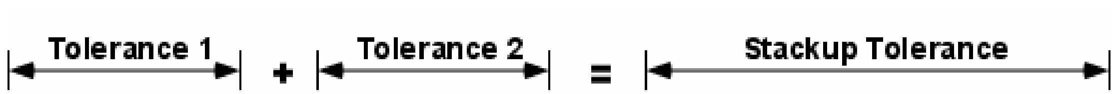

Figure 1: Worst-case stackup variation

Designing to worst-case tolerance requirements guarantees 100 percent of the parts will assemble and function properly, regardless of the actual component dimensional variation and stackup combination. The major drawback is that the worst-case model often requires very tight individual component tolerances. The obvious result is expensive manufacturing and inspection processes and/or high scrap rates.

Worst-case tolerancing is often required for critical mechanical interfaces and spare part replacement interfaces. When worst-case tolerancing is not a contract requirement, properly applied statistical tolerancing can ensure acceptable assembly yields with increased component tolerances and lower fabrication costs.

Statistical Variation Analysis

The statistical variation analysis model takes advantage of the principles of statistics to relax the component tolerances without sacrificing quality. Each component's variation is modeled as a statistical distribution (Figure 2) and these distributions are summed to predict the distribution of the assembly measurement. Thus, statistical variation analysis predicts a distribution that describes the assembly measurement variation, not the extreme values of that variation. This analysis model provides increased design flexibility by allowing the designer to design to any quality level, not just 100 percent.

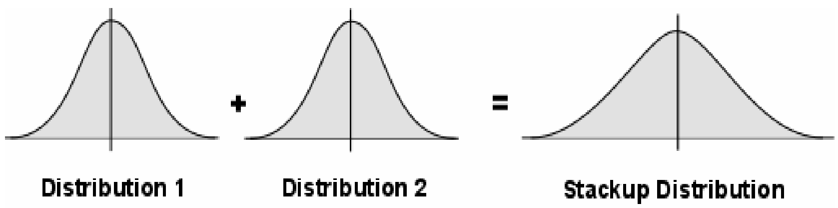

Figure 2: Statistical stackup variation

Statistical Distributions

Pro/ENGINEER Tolerance Analysis Extension powered by CETOL Technology represents all distributions in terms of scaled moments. The moments used are mean, standard deviation, skewness, and kurtosis. Scaled moments are calculated from the central moments (moments about the mean) of the statistical distribution.

Mean

The distribution mean represents the average (or expected) value of the population.

= distribution mean

Standard Deviation

Standard deviation ( ) is a measure of the spread of a distribution. It is the square root of the second central moment (variance):

$$\sigma = (\mu_2)^{1/2}$$

where:

$_2$ = second central moment, variance

Skewness

Skewness is a measure of the symmetry of a distribution. A skewness of 0 indicates a perfectly symmetric distribution. It is related to the third central moment. Since all distributions in Tolerance Analysis Extension are assumed to be symmetric, the value for skewness is always zero.

$$B1 = \frac{\mu_3}{c^{\ 3}}$$

where:

$_3$ = third central moment

Kurtosis

Kurtosis is a measure of the peakedness of a distribution or, conversely, the weight of the distribution tails. It is related to the fourth central moment. Kurtosis is labeled B2 (Beta 2) in Pro/ENGINEER Tolerance Analysis Extension powered by CETOL Technology.

$$B2 = \frac{\mu_4}{\sigma^4}$$

where:

$_4$ = fourth central moment

For convenience, Pro/ENGINEER Tolerance Analysis Extension powered by CETOL Technology provides three distribution types for the analysis: Normal (Gaussian), Uniform, and Lambda.

Distribution Types

Statistical variation is represented in Pro/ENGINEER Tolerance Analysis Extension powered by CETOL Technology with one of the following three distribution types.

Normal (Gaussian) Distribution

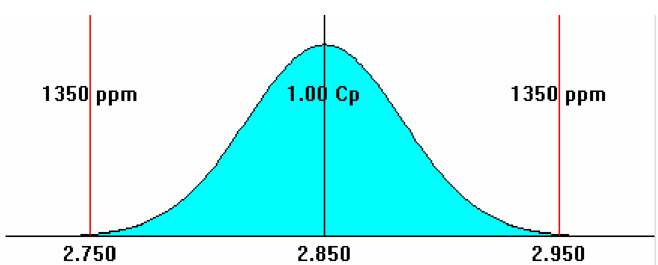

Figure 3: Normal distribution

A normal distribution (Figure 3) can be completely defined in terms of two parameters: mean and standard deviation. In Tolerance Analysis Extension, the distribution for all part dimensions is assumed to be normal.

Uniform Distribution

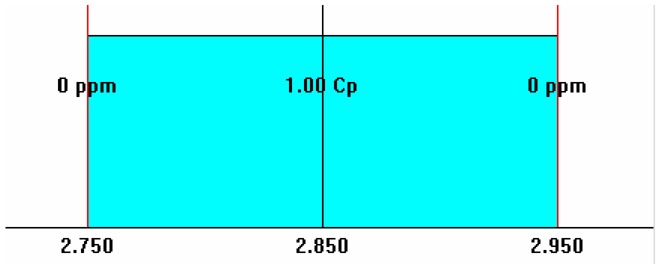

Figure 4: Uniform distribution

A uniform distribution (Figure 4) can be completely defined in terms of two parameters: min and max. In Tolerance Analysis Extension, the distribution for the clearance for floating interfaces is assumed to be uniform.

Lambda Distribution

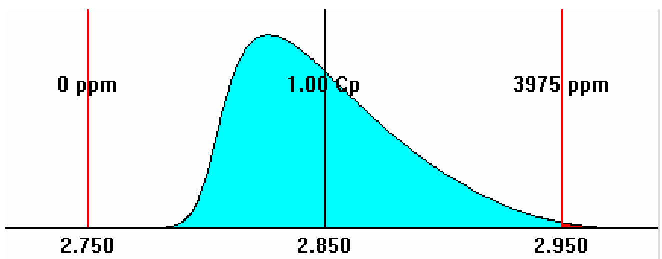

Figure 5: Lambda distribution

The lambda distribution is a statistical distribution defined in terms of four lambda parameters. The Standard Moments Lambda (Lambda) distribution (Figure 5) is a very flexible generic distribution defined in terms of four lambda parameters but specified using mean, standard deviation, skewness and kurtosis.

An analysis may result in a lambda distribution if you have any floating interfaces in the measurement definition. Otherwise, the results will always have a normal distribution.

Creating a Tolerance Analysis Measurement

To initiate the creation of a tolerance analysis measurement, select **Analysis > Tolerance Study** from the Pro/ENGINEER menu.

The Tolerance Analysis Manager

When you select **Tolerance Study** from the **Analysis** menu, the **Tolerance Analysis Manager** dialog box opens, listing all of the tolerance analysis measurements that have been defined in the model. You can add, edit, or delete tolerance analysis measurements in this dialog box.

To define a new tolerance analysis measurement, click **Add** in the **Tolerance Analysis Manager** dialog box. This starts the **Tolerance Analysis Extension Powered by CETOL Technology** interface. You will be prompted to select the measurement references from the Pro/ENGINEER model.

Defining the Measurement References

The geometry that you select must result in a valid 1-dimensional measurement. That is, you must define a measurement that results in an unambiguous result. For example, you cannot select nonparallel planes because the distance between planes is ambiguous (the distance depends on the point at which you are measuring to on each plane).

Table 1 shows the combinations of geometry references that are valid for defining a 1-dimensional tolerance analysis measurement.

1st Feature: 2nd Feature	**Planar Surface or Datum Plane**	**Linear Edge or Datum Axis**	**Vertex or Datum Point**
Planar Surface or Datum Plane	Must be parallel	Must be parallel	OK
Linear Edge or Datum Axis	Must be parallel	OK	OK
Vertex or Datum Point	OK	OK	OK

Table 1: Valid Combinations of Geometry References

Once you have selected the measurement references, the application may prompt you to select a measurement direction feature. If you select a planar surface or a datum plane, the measurement direction is normal to the selected plane. If you select a linear edge or datum axis, the direction is along the selected edge or axis. When the direction of the measurement can be derived from the measurement references (for example, one or both references are planes), you do not need to select a separate direction feature.

Selecting Dimensions

Once the measurement references have been selected, you must select dimensions from the Pro/ENGINEER model that define the dimension loop. The dimensions that you select must be parallel with the measurement direction and define a 1-dimensional loop from the first measurement reference to the second.

To aid in the selection process, the candidate dimensions are automatically displayed in Pro/ENGINEER. Starting with the first measurement reference, the dimensions belonging to that part that are parallel to the measurement direction and whose endpoints are aligned with the measurement reference are displayed. When you select a dimension, the next set of candidate dimensions are displayed (dimensions that are parallel to the measurement direction and whose endpoint is aligned with the endpoint of the previously selected dimension).

Once you have selected all of the pertinent dimensions of the first part, click the next part in the loop. The candidate dimensions for that part are displayed. You continue this process until you have completed the dimension loop. Once you have selected a dimension whose endpoint is aligned with the second measurement reference, the loop is complete and the selection process ends.

The following dimension types are supported:

- Standard linear dimensions
- Basic linear dimensions
- Size dimensions (such as diameter or radius)
- GD&T of the following types:
    - Position
    - Profile of a surface

When selecting dimensions, you can select parametric dimensions, annotation dimensions, or GD&T.

As you are defining the dimension loop, if there are size features that should be included, you must make sure that you select the size dimension that is centered on the current dimension loop endpoint. When you select a size dimension, you will be prompted to specify whether the related geometry is a hole or a pin.

Pro/ENGINEER Tolerance Analysis Extension Powered by CETOL Technology Interface

The Pro/ENGINEER **Tolerance Analysis Extension powered by CETOL Technology** interface is comprised of three views: **Measurement Table**, **Dimension Loop Diagram**, and **Analysis Results** (Figure 6).

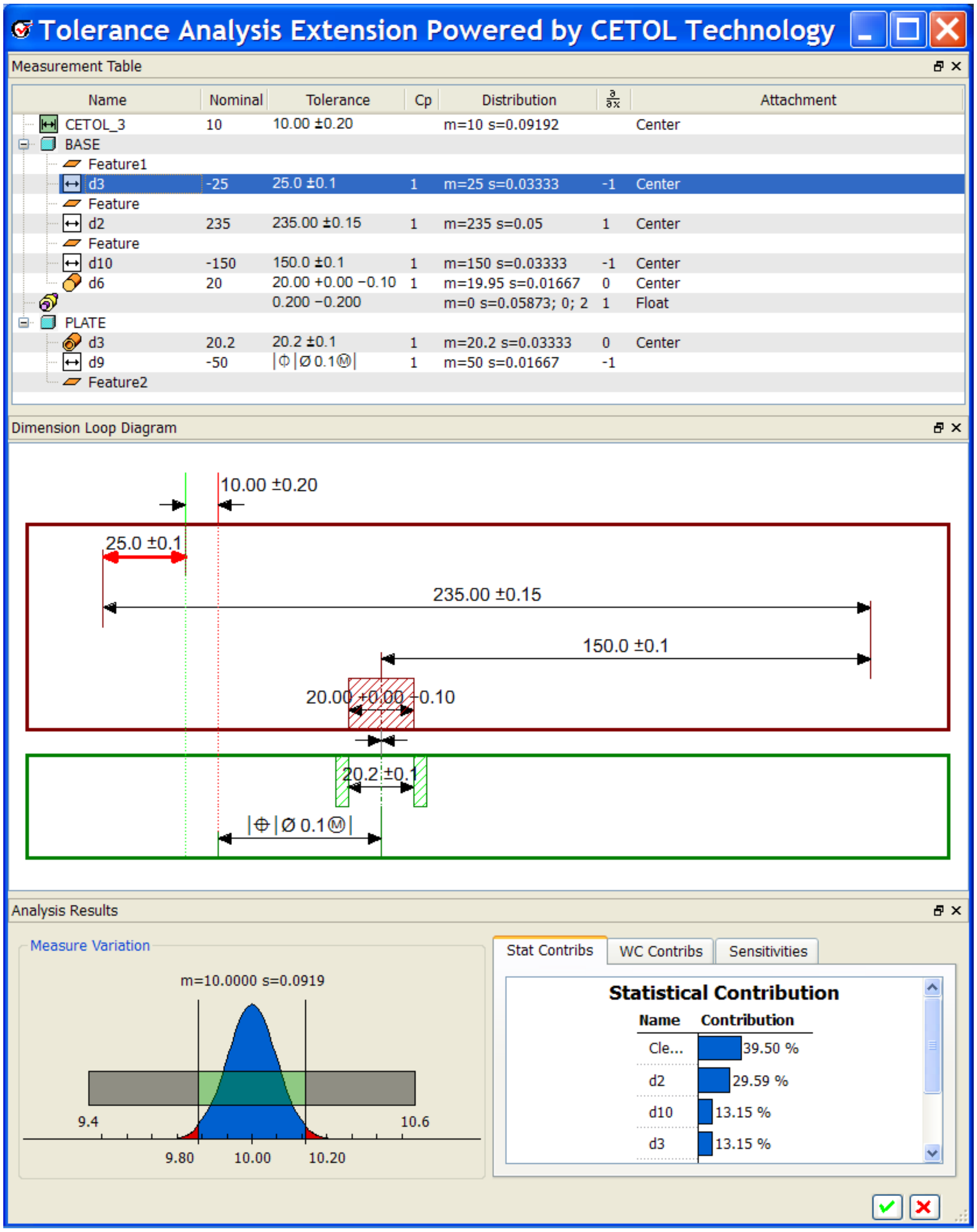

Figure 6: Three views in the interface

These three views can be rearranged to suit your needs. To rearrange the interface, you can click the title bar of one of the views and drag the view to a new location within the interface to dock it to a new location. If you drop the view on top of one of the other views, they will share the same screen space with named tabs. You can toggle to the desired view by clicking the appropriate tab. If you drag and drop a view outside of the interface, it will be displayed as a floating window. Double-clicking a view title bar will toggle the view between its docked and floating states.

You can also toggle the view on or off. If you right-click one of the title bars, a shortcut menu appears. Select a view name to toggle that view's visibility.

Measurement Table View

The **Measurement Table** view provides spreadsheet-style view of the tolerance analysis measurement. Each row in the table represents an object in the tolerance analysis measurement. Each column represents a property for the objects.

Object types

A tolerance analysis measurement contains the following object types.

Measurement—A linear measurement between the selected features.

Part—A part from the Pro/ENGINEER model that is involved in the measurement variation.

Feature—A feature represents the geometry at the ends of the dimensions in the dimension loop. Features of size (pins, holes, etc.) include a size dimension.

Dimension—A linear dimension from the Pro/ENGINEER model. For standard dimensions, the variation of the measurement is based on the tolerance properties of the dimension in Pro/ENGINEER. For basic dimensions, the variation of the dimension is based on the related GD&T selected from Pro/ENGINEER.

Interface—In between each pair of parts in the Measurement Table, you will see an interface object that represents the assembly interface between the adjacent parts. The properties of the interface object depend on the last feature of the preceding part and the first feature of the next part. For example, when the preceding last feature is a pin and the next first feature is a hole, the interface object represents the pin/hole assembly interface. The drop-down menu in the attachment column allows you to specify the attachment option for the interface. For pin/hole interfaces, you specify whether the pin is centered in the hole, tangent to the right or left (based on the orientation shown in the dimension loop diagram), or floating.

When you select the floating option, an additional variable is introduced into the model that represents the random variation of the pin in the hole. The distribution of the float variable is calculated based on the distributions of the pin and hole diameters, assuming a uniform distribution of the clearance.

Object Properties

A tolerance analysis measurement contains the following object types.

- **Name**—The name for parts and dimensions are initialized to the name of the related part or dimension in Pro/ENGINEER. However, you can modify the names in the Measurement Table. Changing the name of a part or dimension within a tolerance analysis measurement will not affect the names of those objects in Pro/ENGINEER.
- **Nominal**—For dimensions, this value corresponds to the nominal value of the dimension in Pro/ENGINEER. For measurements, this is the nominal value for the measurement based on the dimension loop. Note that this may differ from the value for a corresponding measurement in Pro/E, depending on the attachment of any pin/hole interfaces in the measurement. You cannot modify any of the values in this column.
- **Tolerance**—This column shows the tolerance properties of the dimension based. The tolerance properties are initialized from the dimension properties in Pro/ENGINEER. You can edit the tolerance properties of the measurement or a dimension by double-clicking the appropriate cell in the table.
- **Cp**—This value represents the capability index that is assumed for the dimension. The default value for Cp is defined in the application options, but you can modify the value for each dimension (0>Cp>2).
- **Distribution**—This column shows the statistical distribution parameters for the measurement and the dimensions. All dimensions are assumed to have a normal distribution. The mean (m) and the standard deviation (s) are calculated as follows:

  $$m = \frac{UTL - LTL}{2}$$

  $$s = \frac{UTL - LTL}{6 \cdot C_p}$$

  Generally, the distribution for the measurement results will be normal. However, if you have included float for any pin/hole interfaces, the float variation introduces some non-normal effects that may result in a lambda distribution, which has four distribution moments. You cannot modify any of the values in this column.
- $\frac{\partial}{\partial x}$—This column shows the sensitivity of the measurement to each dimension. For example, a sensitivity value of -1.0 means that increasing a

dimensional value by .1 would decrease measurement value by -0.1. The application automatically calculates the sensitivity for each dimension. You cannot modify any of the values in this column.

- **Attachment**—An attachment is indicated for each dimension and each feature of size. Left or Right attachments are with respect to the orientation of the model as shown in the dimension loop diagram.

  For dimensions, this setting indicates the attachment location of the dimension to the previous feature. For features of size, it indicates the attachment of the feature to the previous dimension.

  For interfaces, the attachment defines the location where the related features of size are aligned.

Measurement Table Shortcut Menu

When you right-click in the **Measurement Table** view, a shortcut menu appears that may contain the following commands:

- **Restart Measure**—Clears all of the data from the current measurement definition and restarts the tolerance analysis measurement creation process.
- **Remove Last**—Removes the last selected dimension from the dimension loop.
- **Resume Selection**—Reactivates the dimension selection process, if you have an incomplete dimension loop.
- **Create Report**—Generates an HTML report for the tolerance analysis measurement.
- **Toggle Hole/Pin**—Toggles the state of a feature of size.
- **Toggle Controlled Feature**—When there is a position tolerance with a material condition modifier, it must be associated with the appropriate feature of size so that bonus tolerance can be calculated correctly. The position tolerance should be associated with either the feature immediately before or immediately after it in the measurement table. An arrow immediately preceding the position tolerance indicates the controlled feature.
- **Expand All**—Fully expands the data in the **Measurement Table** view.
- **Collapse All**—Fully collapses the data in the **Measurement Table** view.
- **View Options**—Opens the **Options** dialog box for setting application options. These options are permanently stored in the Windows registry so that they apply to any tolerance analysis measurement in any assembly that you define.

You can modify the value of any tolerance value and other values in the **Measurement Table** view by double-clicking in the appropriate field and entering the desired value. Analysis results are automatically updated any time you make a change to a value that affects the results. When you change the value of a tolerance, that tolerance value is updated in the Pro/ENGINEER model.

For features of size, you have the option of defining the feature as a pin or a hole. By default, all features of size are assumed to be holes. To get the correct interface options, you should modify the type for the features of size to correspond to CAD geometry.

If you click a row in the measurement table (except for standard features), the corresponding object is highlighted in the **Dimension Loop Diagram** and in the Pro/ENGINEER model.

Dimension Loop Diagram View

The **Dimension Loop Diagram** shows a 1-D loop diagram for the measurement. All of the dimensions and features of size are shown to scale in this diagram.

The measurement is shown at the top of the diagram. The location of the first measurement reference feature is represented by a vertical green line, and the location of the second reference feature is represented by a vertical red line.

Each part involved in the dimension loop is represented by a box in the dimension loop diagram. All of the features and dimensions that are related to a part are shown within the part box. The vertical line segments at the ends of the dimensions represent the standard features.

Interfaces are represented between the part boxes. For Pin/Hole interfaces, a Float attachment is shown with a double arrow, as shown in Figure 7. For the other attachment options, a vertical line shows the location for the attachment, such as, Left, Right, or Center.

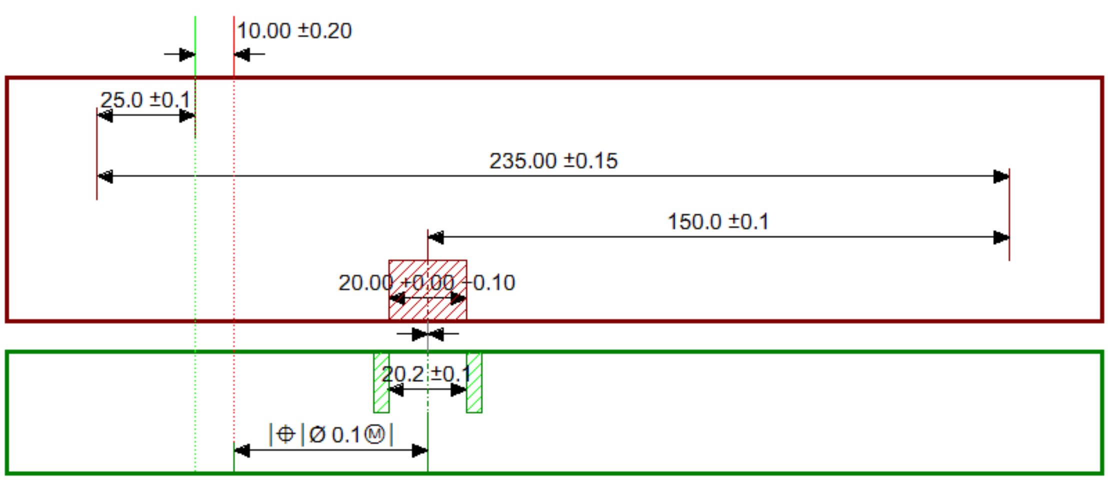

Figure 7: The Dimension Loop Diagram

If you click a part box, a dimension line, or the measurement, the corresponding object is highlighted in the **Measurement Table** and in the Pro/ENGINEER model.

Dimension Loop Diagram Shortcut Menu

When you right-click in the **Dimension Loop Diagram** view, you will see a shortcut menu that contains the following menu options:

- **Zoom In**—Incrementally increases the scale of the dimension loop diagram.
- **Zoom Out**—Incrementally decreases the scale of the dimension loop diagram.
- **Fit to Window**—Changes the horizontal scale of the dimension loop diagram to fit in the window.
- **Copy**—Copies the dimension loop diagram image to the Windows clipboard.
- **Save**—Saves the dimension loop diagram image to a file.

Analysis Results View

The **Analysis Results** view has two display regions. The left region shows a variation plot for the measurement. The variation plot shows the statistical variation plot and the worst-case range for the measurement based on the specified tolerances for the dimensions in the dimension loop.

Analysis Results Shortcut Menu

When you right-click a contribution or sensitivity plot in the **Analysis Results** view, you will see a shortcut menu that contains the following menu option:

- **Copy—**Copies the plot image to the Windows clipboard.

Tolerance Analysis Results

Once a tolerance analysis measurement has been completely defined (that is, the dimension loop from the first measurement reference to the second is complete), Pro/ENGINEER Tolerance Analysis Extension powered by CETOL Technology automatically performs a worst-case tolerance and a statistical variation analysis. The results of these analyses are reported in the **Analysis Results** view.

The Variation Plot

The variation plot shows the worst-case range and statistical distribution for the measurement.

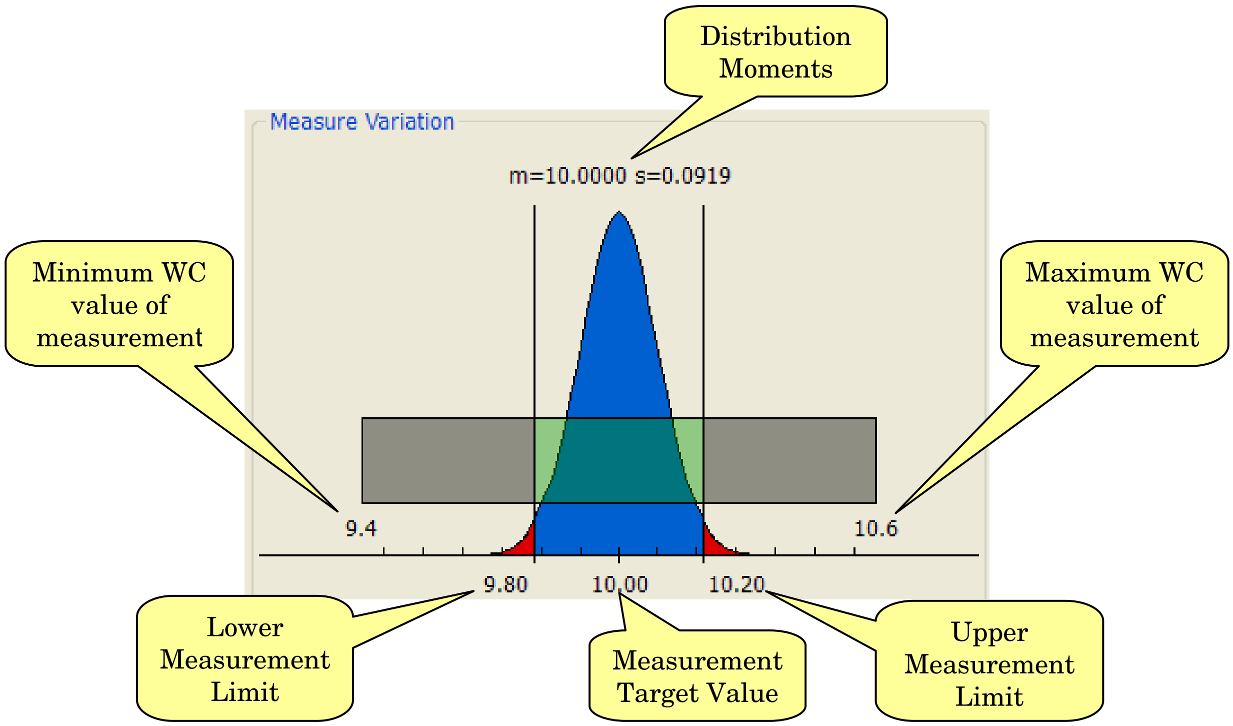

Figure 7: A variation plot

The measurement specification limits and the target value are user-specified values. These define the design requirements for the measurement. The statistical variation is represented by a statistical distribution. Pro/ENGINEER Tolerance Analysis Extension powered by CETOL Technology supports three distribution types: Normal, Uniform, and Lambda. The distribution moments depend on the distribution type, which is determined based on best-fit criteria. For most real-life problems, the **Analysis Results** will be represented by either a normal or lambda distribution.

Sensitivity Plot

The sensitivity plot shows the sensitivity of the measurement to each of the tolerances. A sensitivity value indicates the mathematical relationship between a measurement and a tolerance. A sensitivity of 1.0 indicates that for a unit change in the value of the dimension associated with the tolerance, you will see the same amount of change in the value of the measurement. Thus, the higher the value of the sensitivity (absolute value), the more critical a dimension is for a particular measurement. In a 1-dimensional tolerance analysis, most dimensions have sensitivities of either 1.0 or -1.0, except for diameter dimensions that sometimes have sensitivities of 0.5 or -0.5.

Contributions

Percent contributions combine the sensitivity information with the part dimension variation information to show how much of the measurement variation is caused by each part dimension. The percent contribution of a dimension depends on the analysis type.

Statistical Contributions

The first-order statistical percent contribution formula is:

$$Contribution_{x_i} = \frac{\left(\frac{\partial U}{\partial x_i} \cdot \sigma_{x_i}\right)^2}{\sigma_U{}^2} \times 100$$

Where,

x_i= ith part dimension in stackup

U = measurement

$_{x_i}$= standard deviation of x_i

$_U$ = standard deviation of U

Worst-case Contributions

The first-order worst-case percent contribution formula is:

$$Contribution_{x_i} = \frac{\left|\frac{\partial U}{\partial x_i} \cdot \left(UTL_{x_i} - LTL_{x_i}\right)\right|}{UTL_U - LTL_u} \times 100$$

Where,

x_i= ith part dimension in stackup

U = measurement

UTL_{x_i} = upper tolerance limit of x_i

LTL_{x_i} = lower tolerance limit of x_i

UTL_U = upper tolerance limit of U

LTL_U = lower tolerance limit of U

Data Management and User Interface Issues

Since the tolerance analysis measurement references Pro/ENGINEER dimensions, the measurement results update automatically if any of the referenced dimensions or tolerances is modified in Pro/ENGINEER.

You can view or modify the tolerance analysis measurement by selecting the tolerance analysis measurement from the list in the **Tolerance Analysis Manager** dialog box and then clicking **Edit**.

Note that when you select a dimension in Pro/ENGINEER Tolerance Analysis Extension powered by CETOL Technology, that dimension is shown in Pro/ENGINEER with its original properties. If you have made a change to that dimension, the properties in Tolerance Analysis Extension may differ from the properties of the dimension in Pro/ENGINEER. When you click in the lower-right corner of the dialog box to accept the changes to the tolerance analysis measurement, the tolerance analysis is saved to the assembly model. If you have made changes to any of the dimension properties, those changes are written back to Pro/ENGINEER.

Since Tolerance Analysis Extension is not native Pro/ENGINEER functionality, the interaction with the application differs from Pro/ENGINEER standard behavior in a few ways:

- The tolerance analysis data is always stored in the top-level component, regardless of which component is the active component.
- While Tolerance Analysis Extension is running, most Pro/ENGINEER functions are disabled.
- A middle-click of the mouse in Pro/ENGINEER dialog boxes is equivalent to clicking **OK** but has no effect in the Tolerance Analysis Extension dialog boxes.