Proceedings of ICAD2002
Second International Conference on Axiomatic Design
Cambridge, MA – June 10&11, 2002
ICAD 024

Geometrical Coupling Analysis in Assembly Design

Rikard Söderberg, Ph. D. and Lars Lindkvist, Ph. D.
Dept. of Machine and Vehicle Design
Chalmers University of Technology
412 96 Göteborg, Sweden
Tel: +46 31 7728617, e-mail: riso@mvd.chalmers.se

Abstract

This paper describes a methodology and a software tool that allow assemblies to be evaluated and analyzed with respect to degree of geometrical coupling and robustness on any hierarchical level of the assembly s tructure.

Based on mating conditions and specified geometrical constraints, geometrical couplings between sub-systems, components and individual features are detected and presented in stability matrices. The analysis tools assist in the iterative work of concept improvement and decomposition of top-level geometrical constraints (tolerances on critical product dimensions) into bottom level feature constraints (tolerances on individual surfaces).

The analysis tools utilize the basic ideas in robust design and axiomatic design (the independence axiom) and can be used to compare and evaluate assembly concept solutions including different assembly fixturing solutions. The similarities between uncoupled robust assembly design and uncoupled robust tolerancing of individual parts are discussed and illustrated.

Three examples are used to describe the methodology and the software tool.

Keywords: Tolerancing, Robust Design, Axiomatic Design

1 INTRODUCTION

Product design and manufacture is a complex activity where a product specification is to be translated to, or fulfilled by, a set of subsystems, components and manufacturing processes. The functionality of the product is in the end realized by a number of geometrical features, produced by a set of manufacturing processes.

In the axiomatic design [1], the design world consists of four distinct domains: a *customer* domain with customer attributes (CA:s), a *functional* domain with functional requirements (FR:s), a *physical* domain with design parameters (DP:s) and a *process* domain with process variables (PV:s), see figure 1. The design process involves mapping between these four domains.

Geometry-related quality problems (tolerance problems) generated in the functional and physical domain are often discovered during the assembly process when different parts, manufactured using different processes, are assembled using some kind of assembly strategy. A substantial amount of all quality problems that arise during assembly can be referred to the geometrical concept of the product, i.e. the way parts are designed and located to each other. Quite often in real applications, the FR/DP in-dependency is maintained by the concept but the DP/PV relation becomes coupled as result of the manufacturing processes used.

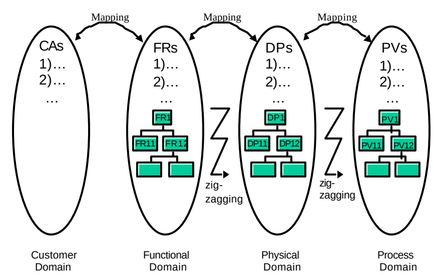

Figure 1: The Axiomatic Design domains

Early avoidance of tolerance problems brings product modeling and tolerance design closer together. In [2] a method to specify interactions between sub-systems on the same hierarchical level in a product hierarchy is described. Characterization of functional couplings was treated in [3]. Identification of potential tolerance chains during configuration and concept design is treated in [4], [5], [6], [7] and [8]. In [9], a "datum flow chain" is used to relate the datum logic explicitly to the product's key characteristics (KC:s). In [10], screw theory is used to detect conflicts between key characteristics in complex mechanical products. The use of KC:s and KC hierarchies to systematically describe all parameters that significantly affect a product's performance, function and form is treated in [11] and [12].

This work

From a geometric and tolerancing point of view, the *product requirements* are stated in the customer or in the functional domain, the *geometric model* is created in the physical domain and the *available processes* are found in the process domain. During early concept phases, designers and production engineers together must decide how parts are to be assembled and located to each other. Different assembly and locating concepts need different detail solutions and lead to different amounts of variation in critical product dimensions. Ideally, tolerances are allocated to compensate for assembly sensitivity and, finally, processes are selected to meet tolerance constraints on part features. We will in this paper describe tools for *robust concept design* and *process selection*. Chapter X describes the locating scheme stability analysis used to assist robust uncoupled design in early phases. In chapter X we describe a matrix-based tool for product/process sensitivity analysis, used to support designers and production planners in selecting processes to meet the overall product constraints.

2 STABILITY ANALYSIS

Axiomatic and Robust Design

Generally, a robust design is a design that is insensitive to variation or disturbance. The important performance characteristics of the product are insensitive to manufacturing variation, temperature, wear etc, see [13]. Figures 2 and 3 show an example of a non-linear relation between an input parameter, x, and an output characteristic, y. By shifting the nominal value, x_0, to the right, the sensitivity Dy/Dx is decreased.

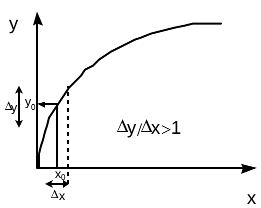

Figure 2: Sensitive design

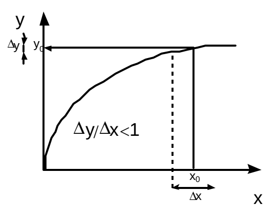

Figure 3: Robust design

The main source of variation considered in this paper is the manufacturing variation, affecting the geometry of parts and assemblies. By decreasing the sensitivity of the design, wider tolerances on input parameters, i.e. geometry features, may be used. For many cases, this results in a lower manufacturing cost.

To illustrate the use of axiomatic design (the independence axiom), and robust design on geometry problems we will use a beam with two supports, DP_1 and DP_2, see figure 4. The vertical position of the two end points of the beam is critical for the over all function. The two functional requirements, "position of left end of beam" and "position of right end of beam", FR_1 and FR_2, are satisfied by the two supports, DP_1 and DP_2. Geometrical variation applied to the two supports, DP_1 and DP_2, result in position variation in the two end points, FR_1 and FR_2.

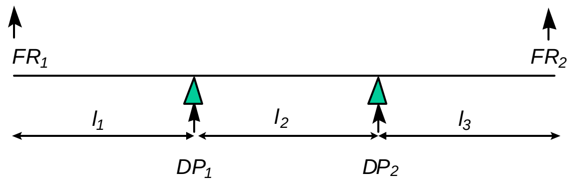

Figure 4: Supported beam

The relation between the input parameters, DP_1 and DP_2, and the output parameters, FR_1 and FR_2, may be described by the design equation:

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix} \quad (1)$$

For this case, the matrix elements, a_{ij}, representing the partial derivatives, dFR_i/dDP_j, may be written as:

$$a_{11} = \frac{\Delta FR_1}{\Delta DP_1} = \frac{l_1 + l_2}{l_2} \quad (2)$$

$$a_{12} = \frac{\Delta FR_1}{\Delta DP_2} = \frac{l_1}{l_2} \quad (3)$$

$$a_{21} = \frac{\Delta FR_2}{\Delta DP_1} = \frac{l_3}{l_2} \quad (4)$$

$$a_{22} = \frac{\Delta FR_2}{\Delta DP_2} = \frac{l_2 + l_3}{l_2} \quad (5)$$

Initially, the position of the supports were chosen such that $l_1 = l_2 = l_3$, resulting in the design equation:

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix} \quad (6)$$

This solution is a coupled solution since the non-diagonal elements are ¹ 0. It can also be noted that, since the diagonal elements are > 1, this solution <u>amplifies</u> the input variation, which is characteristic of a sensitive design.

Generally, in order to increase the robustness of the design and to make it uncoupled, a diagonal matrix with the diagonal elements < 1 is preferable. In this case, the design is improved by choosing $l_1 = l_3 = 0$, i.e. moving the supports to the ends of the beam. This results in a fully diagonal matrix with the diagonal elements equal to 1, which is the best possible solution in this case. To improve the design further, the supports, DP_1 and DP_2, must be placed outside FR_1 and FR_2. This may be accomplished either by extending the beam or by moving FR_1 and FR_2 inside DP_1 and DP_2.

In early concept phases, decisions about how parts are to be located to each other are made. Depending on the assembly sensitivity, different fixturing concepts may be evaluated, as may different embodiment solutions. Finally, tolerances on individual part features are selected on the basis of assembly sensitivity.

Robustness and *variation* represent two important characteristics of an assembly product. Robustness is here defined as "the ability to suppress geometrical

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input variation”. The variation is the actual variation in a particular surface or geometrical feature of the design. The relations and dependencies between variation, robustness, locators and tolerances can be formulated as:

$$\begin{bmatrix} robustness \\ variation \end{bmatrix} = \begin{bmatrix} x & 0 \\ x & x \end{bmatrix} \begin{bmatrix} locators \\ tolerances \end{bmatrix}$$

The equation indicates a coupled behavior where final variation is controlled by both the locators and the tolerances. The robustness, controlled only by the locators, should therefore be treated first. This stage is supported by the *stability analysis* that will be described later in this chapter.

The 3-2-1 Locating scheme

In the beam example, only 2D translation effects due to rotation around one axis were discussed. In a 3D reality, each part in an assembly has six degrees of freedom, three translations and three rotations. During positioning, these degrees of freedom are locked by locating points. Figure 5 shows the six-point locating scheme, frequently used in the automotive industry and often referred to as the 3-2-1 locating scheme. Six theoretical locating points are used to lock six degrees of freedom for a part. The locating points are represented in reality by physical locators such as planes, holes and slots.

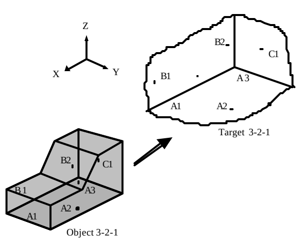
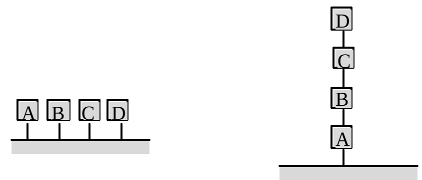


Figure 5: The 3-2-1 locating scheme (P-frame)

Assembly Robustness Evaluation

In an assembly, each part is positioned by its locating scheme. Formulated according to axiomatic design, the FR is “position part” whereas the DP is “locating scheme” or positioning frame (P-frame). The locating scheme *stability matrix* describes the influence of each part locating scheme on the position of each part in an assembly when a small disturbance is applied to each locating point in its locating direction. Figure 6 shows two types of assemblies and their *stability matrices*. In the parallel assembly, the position of each part is controlled by its own locating scheme (P-frame) only, which represents an *uncoupled design*, easy to adjust and tune. The serial assembly represents a coupled design, which is more difficult and time-consuming to adjust and tune. A triangular stability matrix may however be adjusted if done in the correct order, starting with A, then B and so on. Real assemblies are often a mix of the parallel and the serial case, involving assembly fixtures as well.



$$\begin{bmatrix} PositionA \\ PositionB \\ PositionC \\ PositionD \end{bmatrix} = \begin{bmatrix} x & 0 & 0 & 0 \\ 0 & x & 0 & 0 \\ 0 & 0 & x & 0 \\ 0 & 0 & 0 & x \end{bmatrix} \begin{bmatrix} P-frame\ A \\ P-frame\ B \\ P-frame\ C \\ P-frame\ D \end{bmatrix} \qquad \begin{bmatrix} PositionA \\ PositionB \\ PositionC \\ PositionD \end{bmatrix} = \begin{bmatrix} x & 0 & 0 & 0 \\ x & x & 0 & 0 \\ x & x & x & 0 \\ x & x & x & x \end{bmatrix} \begin{bmatrix} P-frame\ A \\ P-frame\ B \\ P-frame\ C \\ P-frame\ D \end{bmatrix}$$

Parallel Assembly **Serial Assembly**

Figure 6: Uncoupled and coupled assembly.

By studying the stability matrix, two positioning aspects may be judged: the *degree of coupling* and the *robustness*. Here, a fully uncoupled design is represented by a diagonal matrix. The robustness is judged by studying the values of the matrix elements. A value higher than one means that variation is amplified by the P-frame, whereas a value below one means that the input variation (variation in the contact points) is suppressed by the P-frame. A value equal to zero indicates no coupling at all between input and output.

Locating scheme stability analysis

By varying each locating point with a small increment, *Dinput*, one at a time, *Doutput/Dinput* may be determined in the X, Y and Z directions separately for a number of output points, *n*, representing the geometry. The *RMS* values for all points, corresponding to variation in each of the six locating points, *i*, are determined as:

$$RMS_{x,i} = \sqrt{\frac{1}{n}\sum_{1}^{n}\left(\frac{(x - x_{nom})}{\Delta input}\right)^2} \qquad (7)$$

$$RMS_{y,i} = \sqrt{\frac{1}{n}\sum_{1}^{n}\left(\frac{(y - y_{nom})}{\Delta input}\right)^2} \qquad (8)$$

$$RMS_{z,i} = \sqrt{\frac{1}{n}\sum_{1}^{n}\left(\frac{(z - z_{nom})}{\Delta input}\right)^2} \qquad (9)$$

The total *RSS* influence of all six locating points, *i*, is calculated in each direction as:

$$RSS_x = \sqrt{\sum_{i=1}^{6} RMS_{x,i}^2} \qquad (10)$$

$$RSS_y = \sqrt{\sum_{i=1}^{6} RMS_{y,i}^2} \qquad (11)$$

$$RSS_z = \sqrt{\sum_{i=1}^{6} RMS_{z,i}^2} \qquad (12)$$

The total *RSS* magnitude is calculated as:

$$RSS_{x,y,z} = \sqrt{\sum_{i=1}^{6} RMS_{x,i}^2 + RMS_{y,i}^2 + RMS_{z,i}^2} \qquad (13)$$

The *RSS* sensitivity value shows how well a certain locating scheme controls the position stability of a certain part. In an assembly consisting of a number of parts with individual locating schemes, the individual *RSS* values are presented in the *stability matrix*.

3. EXAMPLES

In the following sub-sections, three examples will be presented to illustrate the use of the stability analysis.

Door example

Figure 7 shows a door assembly consisting of four parts: body, door, top hinge and bottom hinge. In the initial solution, the hinges are mounted on the door with their corresponding *P-frames*. A sub-assembly is created. The door sub-assembly is then mounted on the body with a compound *P-frame* consisting of positioning features from the hinges and from the door (or actually the lock). The result of a stability analysis for this solution is shown in figure 7. As can be seen, the design is highly coupled since there are a number of non-diagonal matrix elements, on both sides of the diagonal, that are not equal to zero. The position of the door is controlled by the *P-frame* of the door itself as well as by the *P-frames* of the body and the two hinges. This means that, in order to adjust or control the position of the door, a number of parameters may have to be adjusted. During production set up, this may be very time consuming and during production the concept is quite sensitive to disturbance.

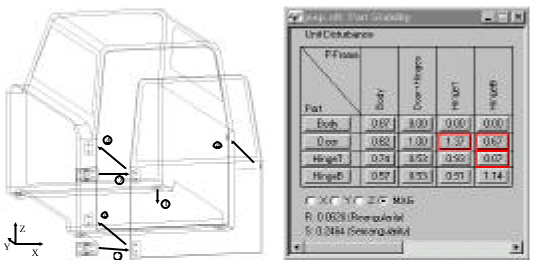


Figure 7: Initial assembly case

To improve the robustness of the product/process concept, an assembly fixture may be used. By locating the door in the correct position with a fixture and then mounting the hinges, the tolerance chain from the body to the door is broken and several geometrical couplings are dissolved. Figure 8 describes such a change.

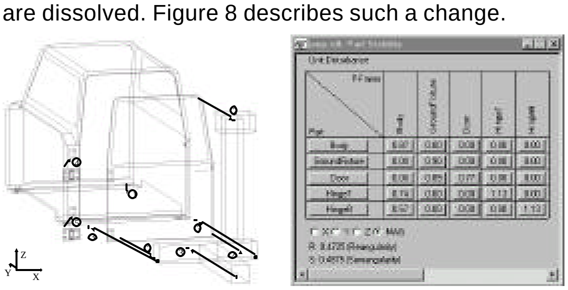


Figure 8: Modified assembly case

As can be seen, the position of the door is now controlled entirely by its own *P-frame* and its locating fixture. The improvement has resulted in a significant increase in *R* and *S* values. In a real life situation, the fixture variation is probably about ten to twenty percent of the part variation, why this contribution will be less than indicated in the stability matrix. Fixturing cost and related quality level has to be compared to the cost for allowing longer tolerance chains with tighter tolerances on individual part features. Trade-off analysis between quality and manufacturing cost related to geometrical variation is discussed in [14], [15], [16], [17].

Multi-level Stability Analysis

The stability analysis is performed by varying the locating points (P-frame points) of a sub-assembly, part or feature and studying the effect on the position of all the other sub-assemblies, parts or features that are involved in the analysis as indicated by figure 9.

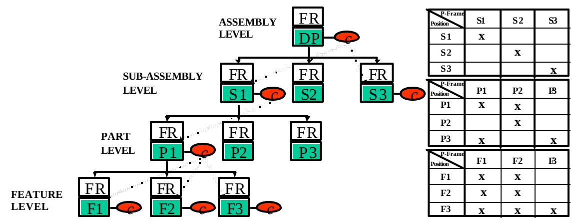


Figure 9: Multi-Level Stability Analysis

The stability analysis performed on the sub-assembly level to analyze geometrical couplings between sub-assemblies can assist in the work of finding the best modular architecture for the whole product or assembly. In most cases, functional or geometrical couplings between modules are not desired.

On the part level, the analysis can be used to detect geometrical couplings between parts in the way described by figure 9. This analysis can be carried out for parts within a sub-assembly or for parts belonging to different subassemblies.

In the hierarchical decomposition of a product, the individual part features are treated in the same way as the components or sub-assemblies. Each feature is positioned in the part by its P-frame, locking its six degrees of freedom in space. This is the same philosophy as used by the GD&T standard, where a three dimensional tolerance zone (for instance surface profile tolerance) is locked in space by its datum frame (A, B and C). On the feature level, the analysis shows the internal geometrical couplings between features within a part or between features belonging to different parts or subassemblies. For individual parts, this analysis can be used to find the best (uncoupled) solution for tolerancing a part. Internal couplings and tolerance chains between part features may be analyzed and removed by changing datum schemes and individual datums for feature tolerances. For instance, using one common datum frame (an A, B, C or 3-2-1 datum scheme) for positioning the part and for constraining (tolerancing) all features of the part is a good way to make a part internally uncoupled.

Floor example

Figure 10a and b show two different vehicle floor concepts where the critical dimension is the total width of the floor. In the first concept (figure 10a), the tunnel is positioned in space using a fixture. The left and the right parts of the floor are then attached to the tunnel part with vertical flanges, allowing variation to propagate in the same direction as the direction of the critical dimension. In the second concept (figure 10b), the tunnel and the left and right parts of the floor are positioned in space by the fixture. This is because the horizontal sliding contacts between the tunnel and the right and left parts do not allow for variation to propagate in the horizontal direction of the assembly.

In the example, all part features are modeled in the same way as the parts in the assembly, i.e. they are attached and constrained to each other using positioning/locating schemes. The purpose of this is to capture the effect of individual feature variation. It also allows for tolerancing in a similar way as in the GD&T standard, i.e. where feature variation is separated from the nominal dimension, which facilitates tolerance chain and coupling analysis *within* a part.

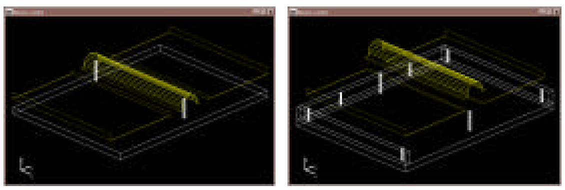


Figure 10a and b: Three Parts Floor Assembly (two different concepts)

Figure 11 shows the part level sensitivity analysis for the width of the floor for the two concepts. The percentage number of each box indicates the statistical part (or feature) contribution to variation in the critical dimension when all contact points are given a variation of the same magnitude. The number shown with the chain segments indicates the contribution in that particular relation between the two mating objects (parts or features). Comparing the total contribution with the chain segment contribution gives an idea as to which chain is affected most by a particular part or feature variation.

Assemblies often contain several interrelated tolerance chains. The total contribution of each chain is determined as the sum of the individual contributions within the chain. Since one part or feature may contribute in several chains, the sum of the chain contributions may exceed 100%. The analysis result may be shown for all chains or for one chain at a time. Often, one chain stands for the majority of the critical dimension variation, and thus the focus should be on that chain. In the examples in figure 6a and b, only one major chain exists.

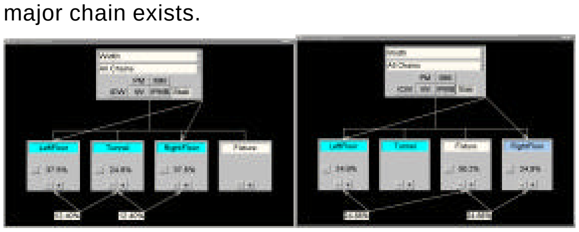


Figure 11a and b: Part Level Chain Analysis

Figure 12 and 13 show the main contribution feature chains for the two floor concepts. As can be seen, the first concept has a very clear tolerance chain between all features of all parts in the assembly. In this concept, the critical assembly dimension is fully controlled by the quality of the individual parts of the assembly.

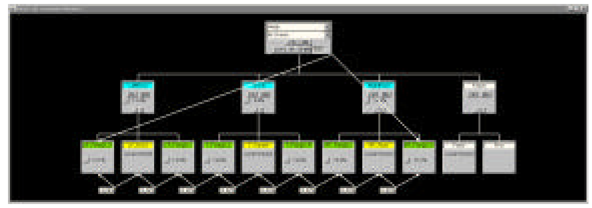


Figure 12: Tolerance Chain Analysis – First Concept – Feature level

In the second concept (figure 13), the tolerance chain is moved to the process equipment, i.e. the assembly fixture. The position of the vertical end flanges of the floor parts is now totally controlled by the fixture. Moving the tolerance chain from the product to the process decreases the importance of individual part variation. The final assembly quality level is now controlled by the process, which is easier to tune to the proper quality level during production start-up and to monitor and adjust during production.

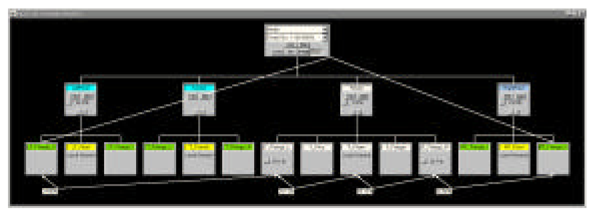


Figure 13: Tolerance Chain Analysis – Second Concept – Feature level

The sensitivity analysis described is done with equal variation automatically applied to all physical features (contact points) in their surface normal direction to detect tolerance chains (variation propagation loops) and to give information about geometrical sensitivity. Early detection of geometrically sensitive concepts or areas allow concepts to be changed and improved before any tools are designed and ordered. A concept that can not be improved can then be "compensated for" by assigning tight tolerances to sensitive areas and wider tolerances where the importance is not as great. The same sensitivity analysis as is described may also be carried out with real tolerance values (process distributions) assigned to the geometry features of the assembly.

Figure 14a and b shows the part stability matrixes for the two concepts, indicating the influence of each locating scheme on all parts of the assembly.

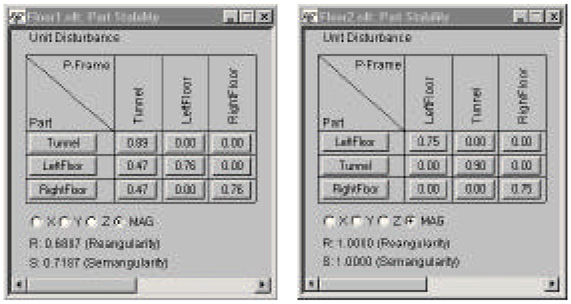


Figure 14a and b: Stability Analysis – Part Level

As can be seen, a change from the first to the second concept solution decreases the degree of coupling, which makes the concept easier to adjust and control. In the first concept (figure 14a), all parts are influenced by the locating scheme for the tunnel. In the second concept (figure 14b), each part is controlled by its own locating scheme only.

The stability analysis is performed by applying variation to the master location scheme of each part and studying the effect on the rest of the parts. Since the fixture is fixed in space relative to the rest of the parts, it does not appear in the matrix. The fixture variation (variation in the contacts with the parts) is shown in the matrix as an influence of each part location scheme. This is based on the philosophy that part design precedes fixture design and that fixtures are designed to support parts in their locating points. The analysis shows how well the individual part location schemes are chosen. In the RD&T software, the relative importance of each location point within a location scheme is presented by clicking on a matrix element.

The part stability analysis gives a hint about the general degree of coupling (number of non-zero elements) and the robustness (element value) in an assembly when no consideration is taken to any particular critical assembly dimensions. The same analysis can also be performed for the defined critical assembly dimensions, see [6].

4 KEY PROCESS IDENTIFICATION

The zig-zagging process between different domains of the design space, as indicated by figure 1, implies a one-to-one mapping between a functional requirement (FR) in the functional domain, a design parameter (DP) in the physical domain and a process variable (PV) in the process domain. In geometry assurance, when trying to control the way geometry variation propagates through assemblies and affects the critical dimensions, the design solutions often become coupled as result of the manufacturing processes used. A typical situation is that independence is maintained between the FR and the DP domain but that the DP/PV relation becomes coupled since the same manufacturing process is used for a number of physical surfaces, on a number of parts in the assembly.

Key process identification for in-house production

Figure 15 shows the stability analysis for a door assembly consisting of a body, an outer door and an inner door. The inner door is located to the body, and the outer door is located to the inner door, as shown by the locator symbols. The stability matrix shows that, with this assembly concept, the position of the inner door is controlled only by its own locating scheme to the body.

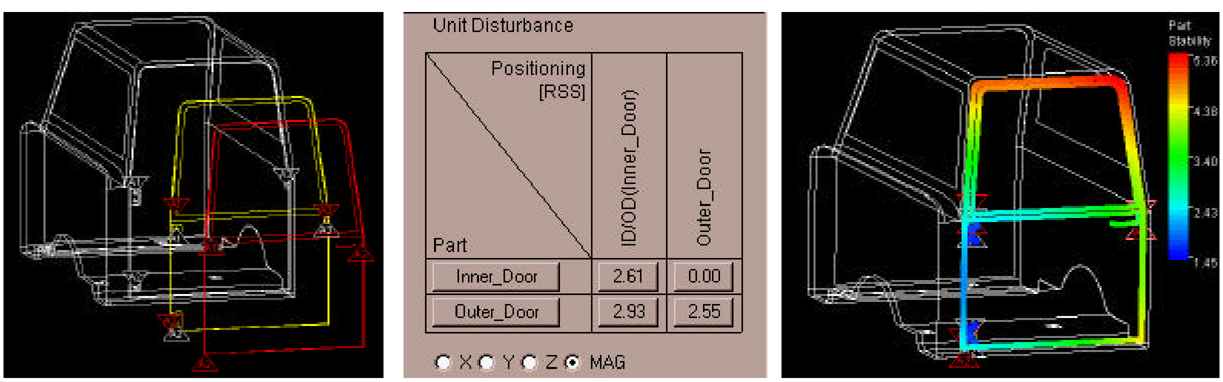


Figure 15: Stability analysis for door assembly: a) Locating schemes, b) Stability matrix, c) Color coded variation result

The outer door is controlled both by its own locating scheme to the inner door, and by the locating scheme for the inner door to the body. The matrix elements are buttons that may be clicked on to show the sensitivity coefficient for each locating point of the locating scheme. The stability analysis also provides color coding of variation result which enables quick identification of critical areas. The analysis is used for early concept evaluation to support concept refinement and to identify areas where tight tolerances may be necessary and areas where wider tolerances can be accepted.

From an axiomatic design perspective, this analysis corresponds to Axiom 1. The idea is to uncouple the concept as much as possible, to avoid unnecessary long tolerance chains and time-consuming process adjustments later on during production.

Contribution Analysis

Contribution analysis, often used in tolerance analysis, is a type of sensitivity analysis that also takes the magnitude (tolerance value) of the input parameter into consideration. The variation contribution of each of a number of input parameters on a critical output parameter is calculated as:

$$contribution_i = \frac{\Delta output_i^2}{\sum_{i=1}^{n} \Delta output^2} \cdot 100\,\% \qquad (14)$$

where $\Delta output$ is the output variation caused by variation in input parameter *i* and *n* is the total number of input parameters.

Normally during tolerance analysis, the contribution to variation of each part feature (or point) to the total variation in a critical assembly dimension is determined. However, since a number of features of a number of parts may be manufactured using the same manufacturing process, see figure 16, the situation often becomes quite coupled and complex. To be able to directly see the consequences of the process on the product, the process contribution to the variation in critical assembly dimensions is key information during detail design and process planning.

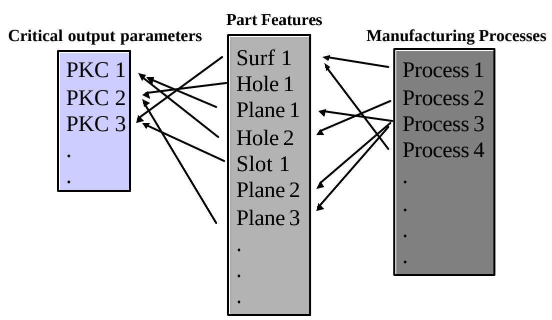


Figure 16: Couplings between output parameters, part features and manufacturing processes

The process contribution to the variation in a critical assembly dimension can be determined as:

$$contribution_{process\ j} = \frac{\Delta output_j^2}{\sum_{i=1}^{n} \Delta output^2} \cdot 100\% \qquad (15)$$

where $\Delta output_j = \sum_{i=1}^{k} \Delta output_i^2$ and *k* represents all features (or points) using process *j*.

Figure 17 shows the process contribution analysis for the door assembly example. The matrix shows the influence of each process on the critical assembly dimensions (the two measures). The ID_Body_Z reflects the gap between the inner door and the body measured between the top of the inner door and the roof of the body. This dimension is critical for the sealing of the door to the body. The OD_Body_Z reflects the gap between the outer door and the body measured between the top of the outer door and the roof of the body. This dimension is critical for the visual appearance of the vehicle.

Two matrixes are shown: the unit disturbance matrix and the real tolerance matrix. The unit disturbance matrix is a contribution matrix showing the relative importance of each process when the same disturbance (distribution) is used for all processes. This information is used for early identification of key processes, i.e. processes owing to the concept sensitivity will require small variation. This analysis is used in early stages when overall manufacturing alternatives (process types) are evaluated.

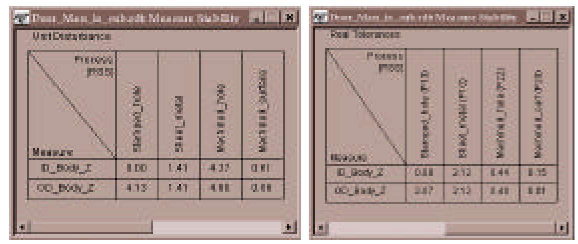


Figure 17: Process contribution analys of each process is evaluated with respect to its variation (distribution).

Here the result of each set of individual processes may be evaluated with respect to variation in critical assembly dimensions, which is an analysis that can assist the production planner in his work. As can be seen from figure 17, where unit disturbance is applied, the process type “Machined_hole” is a key process for both critical dimensions of the assembly. This means that the process type will have a major impact on the quality of the assembly. The real tolerance matrix shows the total contribution of each selected process. This means that processes (machines) of the selected process types are chosen and that contribution analysis is made with respect to real process (machine) variation.

As can be seen, the selection of P22 as the manufacturing process for machining a hole compensates for the Measure/Process sensitivity of the concept. The reason for that is that the variation in P22 is relatively low as compared with other processes.

5 SUMMARY

In this paper we have shown three different tools that can assist *robust concept design*, *tolerance analysis* and *process selection*.

Based on a 3D CAD assembly model containing information about all mating conditions (locating schemes) and critical dimensions in the assembly, tolerance chains are automatically detected, weighted and presented. Geometrical couplings between sub-systems, parts or features are detected and presented in stability matrixes. The tolerance chain and stability analysis presented are based on sensitivity analysis, where variation of equal magnitude (but different variation direction) is applied to the locating points of all part of an assembly. The *key process identification*, based on contribution analysis, supports designers and production planners in selecting manufacturing processes to meet the overall constraints of the product specification.

Three examples are presented to show the usability of the tool. In the first example, two different strategies for locating a door to a body is us ed to present the stability analysis. In the second example, two different vehicle floor assembly concepts are analyzed. The analysis shows how critical dimensions are controlled either by the product, i.e. variation in individual parts or by the process, i.e. the fixture variation. By moving a tolerance chain from the product to the process, two major advantages are achieved: 1) the design becomes less sensitive for part variation and 2) the tolerance chain can be adjusted once and for all and checked periodically during production. The third example uses another door example to describe product/process sensitivity, used to assist designers and production planners in meeting the overall product constraints.

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