INTERNATIONAL DESIGN CONFERENCE - DESIGN 2006
Dubrovnik - Croatia, May 15 - 18, 2006.

DESIGN 2006

FORM DIVISION IN AUTOMOTIVE BODY DESIGN - LINKING DESIGN AND MANUFACTURABILITY

A. Dagman, R. Söderberg and L. Lindkvist

Keywords: form division, geometrical robustness, tolerance analysis, and split-line

1. Introduction

The spatial relations between the individual parts in an assembled product can be critical for the functional and aesthetic quality of a product. These relations are the result of a form division [Tjalve 1989]. From the beginning in the Product Development (PD) process, the geometry of a product is or can be seen as a non-divided form. Take an automobile body, for example. The original form can be divided based on several reasons, like safety reasons, aesthetical reasons, manufacturability reasons, etc. The automobile form, in this case, needs to be divided into doors, hood, trunk, etc. to fulfil the functional reasons. The design of the individual parts will belong to or contribute to the overall design language of the product. However, in the mean time, the design of them will also affect the manufacturability. The contours of the individual geometries create a spatial relation, here defined as a *split-line* (See Figure 1).

Figure 1. A number of examples of split–lines

Variation within a split-line, caused by part and assembly variation, influences the output variation, which is what the customer sees and judges. In the long run, it also influences the sales of the product. In the automotive industry, the relation between doors, fender, hoods, and the like are important nowadays for the quality characteristics, the Visual Quality Appearance (VQA) defined as the impression a product visually conveys to a customer when the customer observes it [*Dagman et al. 2004*]. The VQA is affected by visual sensitivity, geometrical sensitivity and tolerances (variation) in the design. Part and assembly variation can influence the split-lines in such negative way that the user interprets the product as badly fitted individual parts. Lacking geometrical quality in a product originates from the design of the geometry and the position of the locating schemes during production and assembly. The locating scheme describes in what way the part is positioned in the world and in the assembly itself. The placement of the locating schemes is today a result of the design of the geometry or sometimes done when the geometry are set. In the meantime, the platform concept is more and more spread in the companies, which, in many cases, provide an inheriting of the locating schemes between models and sometimes even brands. This means that the locating schemes for many

parts are already known at the beginning of the PD process. Being able to analyse the geometries regarding manufacturing aspects at the early stages of the PD process is of high value from the aspects of both time and money. In these stages, the problem issues are difficult to find but easy to fix. However, the longer the PD process proceeds the relation between finding and fixing will be contrariwise. Changes at this stage can, without a huge increase in cost, involve modifications of the geometry and the design. A slight change in the original design could prevent production problems due to the shape of the geometry. Working concurrently is essential in order to meet these types of problems. The shape of the individual parts caused by the form division will be differently geometrically robust. According to Ulrich and Eppinger [2004.], the manufacturing cost can be reduced, particularly when Industrial Design (ID) works closely with the manufacturing engineering. Continuous collaboration between ID and ED is required to ensure that the requirements of appearance are met while still allowing the technical function [Pahl and Beitz 1996].
Tools and methods have been presented in order to support decision-making regarding geometrical variation and design aspects for design solutions (See [Maxfield et al. 2000] and[Wickman 2005]). To be able to involve manufacturing and styling aspects in the same phase, an analysis tool should be formed in a way that allows analysis of the manufacturing and styling aspects simultaneously to realise synergy effects.

1.1 Scope of the paper

According to Ullman [2003], the evaluation of product performance must support three factors: 1) the evaluation should result in numerical values that can be compared with the stated requirements; 2) the evaluation should also provide some identification of which features to modify in order to bring the performance to target; and 3) the evaluation procedure must include variation due to manufacturing, etc. This paper presents a tool for form division from a geometrical robustness point of view in the early phases of the PD process, where the geometry is not set, that will try to support all three of these steps. CAID (Computer Aided Industrial Design) software has been linked to CAT (Computer Aided Tolerancing) software representing the two areas that are supposed to cooperate. The user of the tool will be able to analyse the geometrical robustness of the form division and have the possibility to make design changes in order to solve the issues. The aesthetical aspects of the geometries are presumed to be taken care of by the user. We only provide a tool that enables changes of aesthetical nature. This is alternative to the traditional approach in the area of geometrical robustness, where the locator positions are changed or the tolerances are tightened in order to meet problems with high output variation in split-lines.

2. Tolerance management

In the automotive industry, two main measuring directions are of special interest when evaluating variation in spatial relations: gap and flush. Gap is defined as the distance perpendicular to the normal surface between two parts, while flush as the distance on the axis of the normal surface between two parts (See Figure 2).

Figure 2. The gap and flush measuring directions

Variation in critical product dimensions, in this case in flush and gap directions, has its roots in three areas. They are component variation, assembly variation and the robustness of the concept (See Figure 3). These characteristics can be seen as Product Key Characteristics (PKC). PKC *are a set of product features that are highly constrained or for which minute deviations from nominal specifications, regardless of manufacturing capability, have a significant impact on the product's performance, function, and form at each product assembly level. PKC are permanent for a given product design decomposition and set of requirements [Lee and Thornton 1996].*

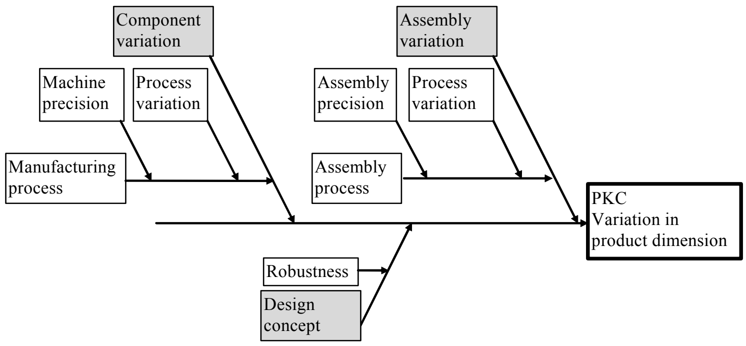

Figure 3. Geometrical PKC variation contributors

The usual procedure is that suppliers control the component variation, and the assembly variation is taken care of in-house by the assembly process. The final variation is dependent on the geometrical robustness of the concept. In a sensitive design, component and assembly variation is amplified, whereas in a robust design the variation is suppressed. Since the robustness of a concept is controlled by the placement of the locators, it is important to achieve geometrical robustness already in the concept phase. The relation between robustness and variation can be explained using a beam and a support (See Figure 4).

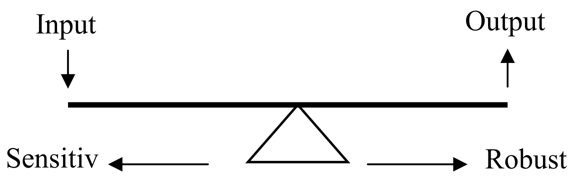

Figure 4. Robustness and variation explained using a beam and a support

Depending on the placement of the support, the input variation will either increase or decrease the output variation. If the support is moved to the left, the input variation will lead to an amplified output variation. If the support is moved to the right, the output variation will not be as affected as in the first example and the robustness will increase. This indicates that input and output variations depend on each other and on the placement of the support. The relation between input and output thus controls design robustness.
The 3-2-1 scheme is commonly used in the automobile industry (See Figure 5). Theoretically, the locators are points used to lock all degrees of freedom for a part to be able to position it.

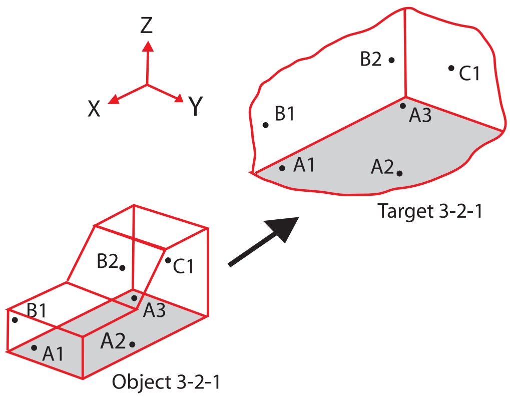

Figure 5. The locating scheme

Physically, geometrical features like holes, planes and slots represent the locator points. A part has six degrees of freedom, three translations and three rotations. The first three points, which form a plane, lock one translation and two rotations. The next two points, which form a line, lock one translation and one rotation. The sixth point locks the remaining translation. The 3-point scheme is similar to the 3-2-1 scheme, with the difference that only three points are used. The first point locates the part in three directions, the second in two and the third in one direction.

2.1 Stability analysis

The stability analysis, first described in [Söderberg and Lindkvist 1999], enables analysis of the geometrical robustness of an assembled product. By varying each locating point by a small increment, *Δinput*, one at a time, *Δoutput/Δinput* may be determined in the X, Y and Z directions separately for a number of output points, *n*, representing the geometry. The *RSS* values for all points, representing the sum of variation in each point caused by variation in the six locating points, can be determined. The result can be presented numerically but also with help of colour coding. The colour coding assigns different colours depending on the level of variation in the measure. If the variation in a measure is wide, it will be assigned a red colour. If there is a low variation, there will be a blue colour.

2.2 Seam Function

The seam variation analysis was first introduced by [Söderberg and Lindkvist 2002]. It calculates gap and flush variation along a relation between two parts, a seam, based on tolerances on parts and fixtures. The seam variation analysis creates multiple measures along the split-line. The seam is defined as the relation between parts over a specified distance. It also describes the most frequently used quality characteristics for the evaluation of geometrical variation in automobile design. The results are presented with distributions and colour coding. The seam's variation analysis can be evaluated both individually and as a group.

3. Form division analysis

Most commonly, the functional analysis is made when the geometries are set. The intention with the tool presented in this paper is to make it possible to analyse the geometrical robustness before the geometries have been set. The user will then be able to analyse and prevent geometrical sensitivity of an assembled product by changing the form division of the original design. The tool links CAID software, in this case Alias AutoStudio, and CAT software, in this case RD&T (Robust Design & Tolerancing). This direct linking allows the industrial designer or the person responsible for the form division to manipulate the design and simultaneously be able to analyse the design regarding the geometrical robustness. It could also be used as a basis for discussions regarding tolerancing issues with multiple competences present. When manipulating the geometry in the CAID software, the geometries and analysis results are updated in the CAT software automatically. The link between the software's has been created using the Application Programmer's Interface (API), a C++ based language with predefined classes, for AutoStudio. The usual procedure when working with CAID is that the design intentions are drawn up in CAID software and then exported into a CAD environment to produce solid geometries, drawings and production information, etc. Most of the functional analyses are made at the stage where the design has been digitally embodied.

The analysis starts with the creation of the intended design of the product and the modelling of it in the CAID software. At this stage, only the outer shell of the product is needed. In order to perform the analysis, the product geometry has to be exported, using stl-format, into the CAT software for preparation. In the CAT software, the positioning of the locating schemes for the individual parts that the geometry shall be divided into is carried through. A three point system has been used for the individual parts in this case, illustrated in Figure 6. At this stage of the PD-process, the real tolerances are not known and cannot be specified. Instead, unit tolerances are used in order to analyse the geometrical robustness of the concept. The intended relation between the individual parts, where the seams will be present, is defined in order to be able to analyse it in the CAT software. Someone familiar with the production plant and the locating scheme configuration performs the CAT preparation.

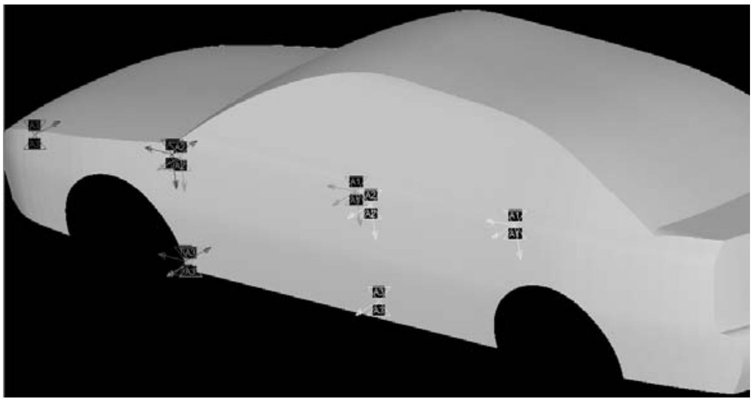

Figure 6. The locating schemes for the individual parts, i.e. the front fender and both doors

It is now time to define the shape of the individual parts. The lines creating the contours of the individual parts, i.e. the split-lines, are exported from the CAID setting into the CAT software. The actual line is not exported but multiple points running along the split-line are, with equal distance between them. The measuring directions gap and flush are also incorporated in the data exported from the CAID software. In the CAT software, multiple measures are created using the exported points and the seam variation function. The measures used are point-point measures, measuring from a point on one part in the relation to the other part in the relation. The analysis of these measures makes it possible to analyse the robustness of the division of the geometry by use of the stability analysis. The results are presented both as numerical values of the sensitivity but also as colour-coded arrows describing the level of sensitivity (See Figure 7).

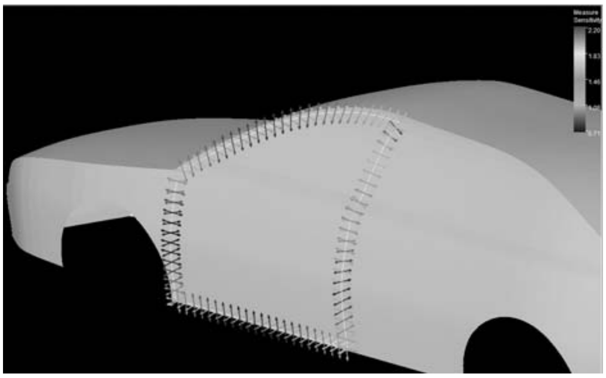

Figure 7. The colour coding of a seam

Coloured arrows will show the sensitivity in both gap and flush direction in each measuring point. A red arrow indicates high sensitivity and a blue low sensitivity. Since both flush and gap results are presented at the same time, one measuring point can contain both a red and a blue arrow. The direction of the arrows will indicate if the sensitivity will be in gap or flush direction. That is why there are two arrows in each point when analysing both flush and gap simultaneously. The colour coding of the analysis results will increase the ability to interpret the results independent of the interpreter's earlier knowledge in the area. If the analysis result indicates sensitive areas, these shall be treated in order to increase the robustness of the concept and the manufacturability of the product. Manipulating the split-line geometries in the CAID software does this. The software's are now linked so every little design change is updated both geometrically and analytically in the CAT software. This will give the designer the possibility to match the design of the individual parts and the geometrical robustness of the concept. The motivation to achieve high robustness shall not be seen as superior to the overall design intent, but of equal importance.

4. Analysis example

This section will present an example of how to use the presented tool in order to analyse an intended design. An automobile geometry shall, in this case, be divided. The intended split-lines or the division of the geometry is shown in the lower right part of Figure 8 as lines on the geometry; the image is from the CAID software.

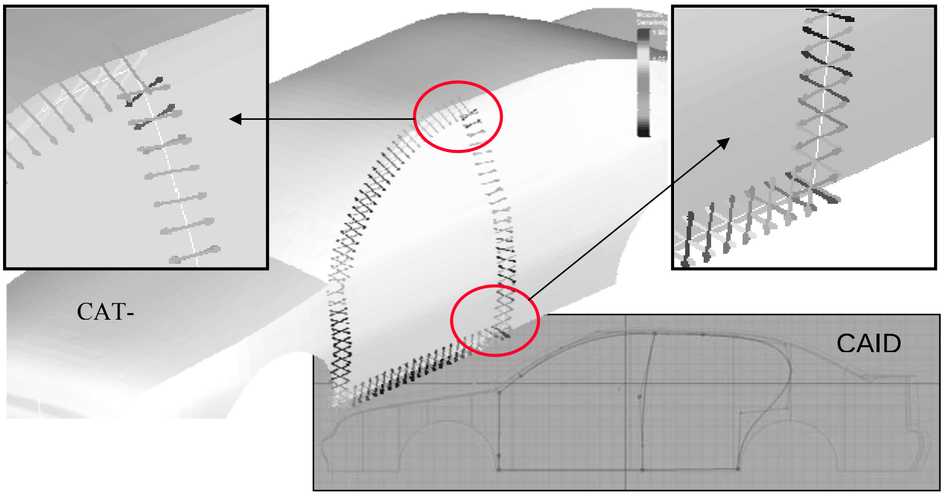

Figure 8. Analysis results of the original form division

The analysis result is presented in the CAT software in the upper left hand corner of Figure 8. The non-divided geometry is exported into the CAT tool. Location schemes for the individual parts are assigned to the geometry. The relations to be analysed are specified, e.g. door-fender, door-door, etc. When the designer is pleased with the shape of the individual parts, the lines defining the individual parts (i.e. the split-lines) are exported into the CAT software as multiple points, with the gap and flush directions defined.

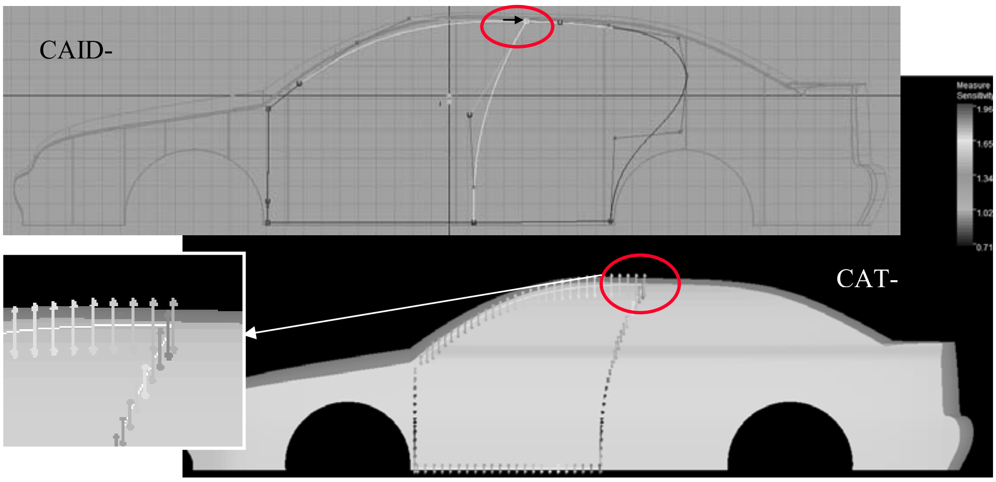

Figure 9. Analysis result after moving the upper part of the split-line slightly

The exported points are used in the seam function analysis as measuring points. The analysis result is colour-coded with the arrows describing both gap and flush directions. Sensitive areas are discovered in both the upper and lower part of the door-door relation, marked with circles in Figure 8. The red (dark) arrows indicate high sensitivity. The flush direction is the more sensitive direction in this example. It will therefore be presented alone here, without the gap direction. In this case, there are two alternatives. The first is to keep the original design and try to specify low tolerances or change the locator schemes to meet the variation in the sensitive area. The other alternative is to change the design of the form division to meet the production requirements. In this case, the designer can allow a slight change in the sensitive areas by moving the split-lines between the two geometries slightly. The intended design language is still preserved. The upper sensitive area is dealt with first, moving the split-line slightly to the right. This lowers the sensitivity of the area (See Figure 9). The designer moves the lower part of the split-line slightly to the left, and the geometrical robustness is increased in that area, too. This can be iterated several times until a satisfactory result have been achieved. The changes shown in this example might not be enough to meet the production requirements while producing, but the geometrical robustness has increased compared to the original design. This is the intended way of working with the tool. By changing the design slightly at this stage of the PU processes, the inherited locator schemes can probably be used with preserved design intent and better manufacturability (See Figure 10).

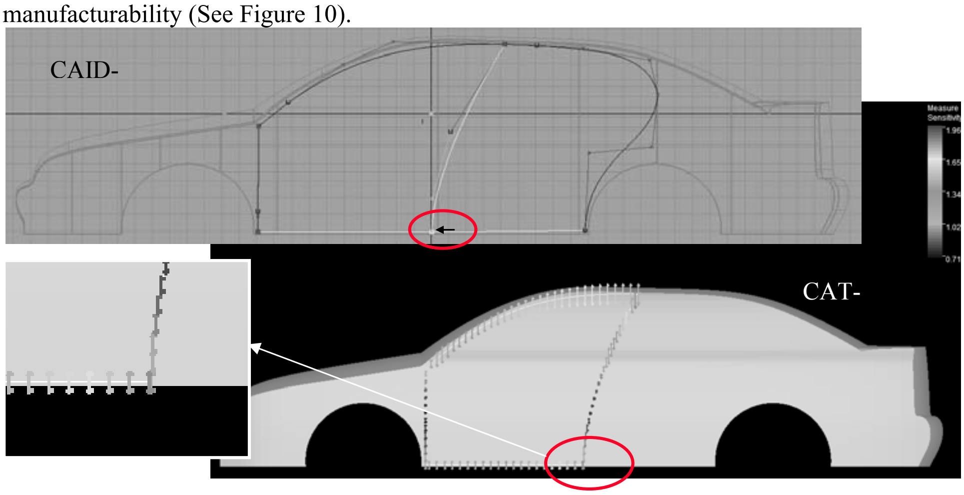

Figure 10. Analysis result after moving the lower part of the split-line slightly

5. Discussion and conclusions

At the early stages of the PD process, problem issues are often difficult to find but easy to fix. Conversely, the problem issues are rather difficult to fix but easy to find in the end. This fact prescribes a work approach that enables problem detection as early in the process as possible. When dividing the original form, it will be divided into several individual geometries. At the same time the shape of these geometries are set, a number of manufacturing issues are set as well, caused by the selected form of the geometries. For that reason, there should be some kind of support when the division is carried through. There are more than functional requirements involved: there are aesthetical ones also. The support must therefore incorporate both aspects. One has to be aware that in good design both form and function are incorporated with each other in harmony. An aesthetically well-designed product that is costly and hard to manufacture is not a good design, and vice versa. In this work, we have proposed a tool that enables analysis of the geometrical robustness during the form division stage before the geometries are set. The tool incorporates both aesthetical and geometrical robustness aspects. It is of importance to note that the analysis result presented shows geometrical sensitivity and not the actual output variation. Linking CAID and CAT software has created the tool. It may be seen as a shortcoming that the tool does not describe in what way the geometries shall be changed in order to increase geometrical robustness. But that was intentional in order to preserve the creativity of the user. In Dagman [2005], a tool for creating the optimal split-line is presented solving this issue.

The presented tool could be a step closer for working concurrently with both aesthetic and manufacturing aspects. A theoretical way of working with the tool has been presented. It can be seen as a complement to the more classical working procedure, in the area of tolerancing, decreasing the tolerances and changing the locator schemes in order to meet the requirements. A production environment where the locator systems are inherited from earlier or similar models, will hopefully be improved by the presented way of working. Future work will hopefully include the task of making a user test in a company dealing with form division issues.

Acknowledgement

The authors would like to acknowledge The Swedish Foundation for Strategic Research, through the research program ProViking, for its financial support.

References

Dagman, A., "Incerased Visual Quality through Robust Split-Line Design", Product and Production Development, Göteborg, Sweden, 2005.

Dagman, A., Wickman, C. and Söderberg, R., "A Study of Customers' and the Automotive Industry's Attitude Regarding Visual Quality Appearance of Split-Lines", 4th International Conference on Advanced Engineering Design, 5-8 September, Glasgow, Scotland, AED, 2004.

Lee, D. J. and Thornton, A. C., "The Identification and Use of Key Characteristics in the Product Development Process", The 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference, August 18-22, Irvine, California, USA, American Society of Mechanical Engineers, 1996.

Maxfield, J., Dew, P. M., Zhao, J., Juster, N. P., Taylor, S., Fitchie, M., Ion, W. J. and Thompson, M., "Predicting Product Cosmetic Quality Using Virtual Environment", ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 10-13 September, Baltimore Maryland, American Society of Mechanical Engineers, 2000.

Pahl, G. and Beitz, W., "Engineering Design: A Systematic Approach", "Springer", Berlin, Germany, 1996.

Söderberg, R. and Lindkvist, L., "Computer Aided Assembly Robustness Evaluation", Journal of Engineering Design, 10(2),1999, pp. 165-181.

Söderberg, R. and Lindkvist, L., "Stability and Seam Variation Analysis for Automotive Body Design", Journal of Engineering Design, 13(2),2002, pp. 173-187.

Tjalve, E., "Systematisk udformning af industriprodukter : vaerktjer for konstruktren / af Eskild Tjalve", "Akademisk forlag", Köbenhavn, 1989.

Ullman, D. G., "The Mechanical Design Process", "McGraw-Hill", New York, USA, 2003.

Ulrich, K. T. and Eppinger, S. D., "Product Design and Development", "McGraw-Hill", Boston, USA, 2004.

Wickman, C., "Visualising the Effect of Geometrical Variation in Assembled Products. Predicting Visual Quality Appearance", Department of Product and Production Development, Göteborg, Sweden, 2005.

Andreas Dagman, Lic. Eng, Ph D Candidate
Chalmers University of Technology, Department of Product and Production Development
SE-412 96, Göteborg, Sweden
Tel.: +46 (0) 31 772 1472
Email: dagman@chalmers.se
URL: http://www.ppd.chalmers.se