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Geometrical robustness analysis considering manual assembly complexity

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Abstract

The manufacturing industry is focused on geometry assurance. Much of the virtual geometry assurance is done in Computer Aided Tolerancing (CAT) tools. Earlier research shows that assembly complexity influences the product quality but is not considered when geometry systems (locators and tolerances) are defined. Further previous research shows CAT simulations do not predict all the variation and therefore additional factors need to be included to improve accuracy. In this study, a robustness value for a geometry system solution based both on geometrical sensitivity and manual assembly complexity has been introduced. Calculation methods have been tested and implemented in a CAT tool using a real industrial case.

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Keywords: Assembly; Complexity; Robust Design

1. Introduction

1.1. Introduction to subject

In the manufacturing industry much effort is directed towards quality assurance and one important piece of this is geometry assurance. Focus is both on the esthetics of the products [1,2,3,4] and functional properties [5]. Automotive companies usually have specific roles in the company that are responsible for creating the geometry system solutions; defining locators, balancing tolerances, doing stack up analysis in 3D, measuring and verifying geometrical demands etc. This work is done virtually using different types of CAT-tools (Computer Aided Tolerancing) [6,7,8]. In previous research it has been shown, for manual assembly parts, that assembly complexity influences the product quality [9,10]. Previous studies [11] also show that assembly factors, such as complexity, are not included when the geometry systems are defined. A recent study [12] shows low correlation between CAT simulations and actual outcome in production. This study also shows that there is significant correlation between the fact that geometry engineers use their own individual judgment or experience instead of actual assembly assessment parameters and assembly problems. Further it is [12] shown that only 12% of the CAT simulations contained some sort of process tolerances assuming that the operator that assembles the part doesn't add any variation at all. Because of this, assumptions and experience are often used as input and as a result the CAT tool has not been fully utilized. A model for early assessment of assembly complexity [10] has been developed and this is suitable for usage in co-operation with CAT simulations. But further research is required in order to find out how assembly complexity can be included in early virtual geometry assurance work with CAT as a base.

1.2. Nomenclature

- CAT: Computer Aided Tolerancing, 3D tolerance chain stack up analysis
- Stability analysis: analyzes geometrical robustness of a part with respect to the locators used i.e. the sensitivity to variation

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- Geometry system solution: Locating scheme, tolerances, fasteners etc. for a part
- Geometry Engineer: Responsible for virtual verification of geometric requirement, performs CAT simulations

- Geometry assurance: engineering activities with the purpose to secure that all geometrical requirements are fulfilled on the product

1.3. Related work

Complexity can be defined as being difficult to understand, describe, predict or control something [13]. Several methods to assess complexity in assembly have been developed such as;

Entropic measurement [14], using production data to calculate the probability of a state

Manufacturing Complexity Index [15], evaluates risk of different alternatives in a design stage

Operator Choice Complexity [16], evaluates risk of incorrect choices in production, for example choosing tools

Complexity Index [17], uses a questionnaire to find problem areas at station level

None of these methods focus on capturing potential problems very early in product development, instead they are mostly methods to fix problems when they occur in production or assess a design when it is already finished.

Assembly issues, such as incorrect assembly, have been shown to highly contribute to costs of poor quality [18]. In addition to this it is further shown that poor quality costs can be 10-40% of a company´s total turnover [19,20,21]. The financial return if these quality costs that can be reduced, is significant.

In 1986 Taguchi introduced the ideas behind robust design and quality improvement together with the concept of insensitivity to variation which has become the most important principle in geometry assurance [22].

These principles of robust design were then implemented into a CAT software, developed by Söderberg and Lindkvist [22] called RD&T (Robust Design & Toleracing) [23] which is the CAT tool used in this study. Other CAT tools can be seen in [24,25,26].

In the research field of robust design connected to geometry assurance much research has been done to further explore the field.

For example optimizing locator positions to maximize robustness in critical measures [8], a statistical approach with focus on optimizing spot welds and simulation accuracy [27], robustness in aerospace [28], geometric robustness for plastic components [29] etc. None of these research efforts have however tried to combine robust design, geometry assurance and assembly complexity, this paper aims to do this.

2. Geometry Assurance

2.1. Early Geometry Assurance

Regardless of what type of manufacturing and assembly process that is used it will be subjected to geometrical variation. This affects the final product and could lead to problems with quality, both esthetic and functional, for example un-parallel gaps or parts that don't fit. The focus of this study will therefore be the early concept phase of product and production development where the most important geometry assurance activities are performed: definition of the geometry system solution. This means that the geometry engineer will define the position and function of the locators (often the same as the fasteners) and one way of doing this is by using a CAT tool and Stability Analysis. This does not only define the geometry system solution but also defines many parameters of the assembly operation. It is also already in this phase of development that consideration to manual assembly needs to be incorporated.

2.2. CAT software RD&T

RD&T is a Monte Carlo-based CAT simulation software used for geometry assurance during the entire geometry assurance process. All CAT simulations in this study are done in RD&T. For more information about RD&T see [23]. In this study the analysis used will be the Stability Analysis. RD&T will also be the tool that the proposed method is implemented in as a demonstrator.

2.3. Locating Schemes

In the automotive industry datums and locators are used to control the stability of a system, which has a great impact on how variation propagates through the system and the total geometrical robustness of the product. This will affect most product key characteristics. Selection of locators should aim at minimizing the effect of variation enabling a high geometrical robustness. The location scheme also locks all six degrees of freedom for a part or an assembly and locates it in the coordinate system. The names of locating schemes are often ABC or XYZ.

Figure 1 shows the base type of locating scheme called 3-2-1. Six discrete points are used to represent the locating scheme and they lock the six degrees of freedom: translations in A, B and C directions (TA, TB and TC) and rotations around the A, B and C axis (RA, RB and RC).

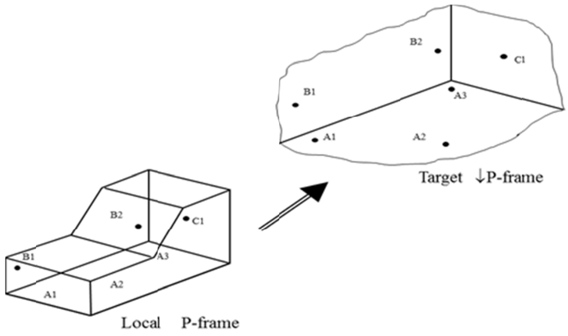

Fig. 1. 3-2-1 locating scheme

In reality physical locators are realized with features such as small planes, holes and slots.

2.4. Stability Analysis

The analysis evaluates the locator sensitivity by varying each locator a small increment one at a time. By calculating the quota between input variation and the output deviation in all points of the geometry the sensitivity to variation is found. This is then Root Sum Squared for each point on the geometry to find the total sensitivity. An example of the result can be found in Figure 2. The result is used to determine where the locators should be placed on the part for maximum robustness. (For more information about the stability analysis see [30]).

This analysis is a pure sensitivity analysis and does not evaluate if it easy or difficult to assemble the part so that all locators are in contact (all degrees of freedom locked) which is a must for the simulation results to be valid. This means that a large responsibility is transferred to the operator. Investigations have however shown that in many cases the operator does not manage to use the locating schemes as intended. This is due to lack of knowledge about the intention or complex assembly situation.

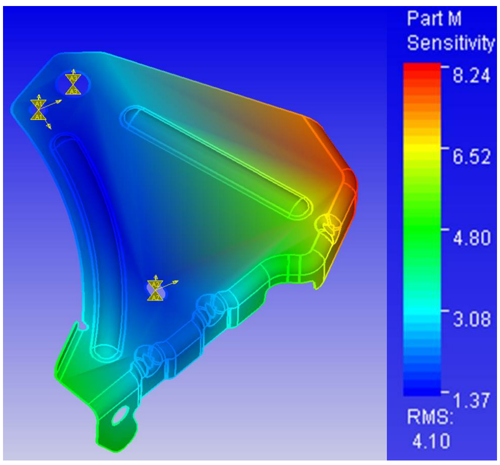

Fig. 2. Stability Analysis

3. Methods

3.1. Objectives

The objective of this study was to develop and explore a new method to take manual assembly complexity into consideration in early product development and merge this with geometry assurance in CAT.

The study aims at suggesting a new way of working with early product development and introducing a new method integrated in an existing CAT tool.

The final purpose is to test the results with an actual industrial case.

3.2. Normalization of the complexity Method

The complexity method is fully described in [10], only a brief description will be included in this study. The base for assessment of an assembly operation is 16 High Complexity (HC) criteria and depending on how many of these that are fulfilled, the operation can be categorized in 5 levels of complexity from high to low. The criteria can be seen below.

Criteria (n=16) for high assembly complexity (HC) tasks considered as “tricky and demanding” operations:

- Many different ways of doing the task
- Many individual details and part operations
- Time demanding operations
- No clear mounting position of parts and components
- Poor accessibility
- Hidden operations
- Poor ergonomics conditions implying risk of harmful impact on operators
- Operator dependent operations which require experience/knowledge to be correctly executed
- Operations must be carried out in a certain order
- Visual inspection of fitting and tolerances, i.e. subjective assessment of the quality results
- Accuracy/precision demanding
- Need of adjustment
- Geometric environment has a lot of variation (tolerances), i.e. level of fitting and adjustment vary between the products
- Need of clear work instructions
- Soft and flexible material
- Lack of (immediate) feedback of properly done work, e.g. a click sound and/or compliance with reference points

In order to facilitate comparison with the sensitivity from the stability analysis it needs to be normalized between 0 (low) and 1 (high) according to Table 1.

Color-coding	Number of HC	Complexity level	Normalized
Green	0	Low	0
Green	1	Low	0,0625
Green	2	Low	0,125
Green	3	Low	0,1875
Yellow-Green	4	Rather Low	0,25
Yellow-Green	5	Rather Low	0,3125
Yellow-Green	6	Rather Low	0,375
Yellow-Green	7	Rather Low	0,4375
Yellow	8	Average	0,5
Yellow	9	Average	0,5625
Yellow	10	Average	0,625
Yellow	11	Average	0,6875
Yellow-Red	12	Rather High	0,75
Yellow-Red	13	Rather High	0,8125
Yellow-Red	14	Rather High	0,875
Red	15	High	0,9375
Red	16	High	1

Table 1. Normalization of complexity

3.3. Normalization of Stability Analysis

The Stability Analysis returns an RMS value of the overall sensitivity of a part (the geometrical robustness). In order to normalize this value between 0 (very robust) and 1 (un-robust) it was necessary to determine suitable values corresponding to this.

An analysis was made at an automotive company. 401 geometry system solutions were analyzed with the stability analysis to form an extensive base. The analysis only considered manual assembly parts, from 2 different types of vehicles that were evenly distributed between different exterior and interior areas of the cars.

For each area the best (low RMS value) and the worst (high RMS value) system solution were selected and the median value for the best and worst solution was calculated for all areas. The results:

- Best solutions: 1,43-1,67, median value 1,6
- Worst solutions: 2,58-10,69, median value 6

To set a baseline for what a typical good and bad geometry system solutions are the median value of the best and worst solutions was used. Based on this, 1.6 and lower values are set as 0 (very robust) and 6 and higher values are set as 1 (un-robust). Values in between are calculated as (1):

$$Stab_{norm} = \frac{(RMS_{value} - 1.6)}{6 - 1.6} \qquad (1)$$

4. Results

4.1. Geometrical Robustness analysis considering assembly complexity in software RD&T

A robustness value for a geometry system solution can now be introduced that incorporates both sensitivity to variation and assessment of assembly complexity by applying a RMS operation on the two normalized values. A calculation function for this has been implemented as a demonstrator in the CAT software RD&T, see Figure 3.

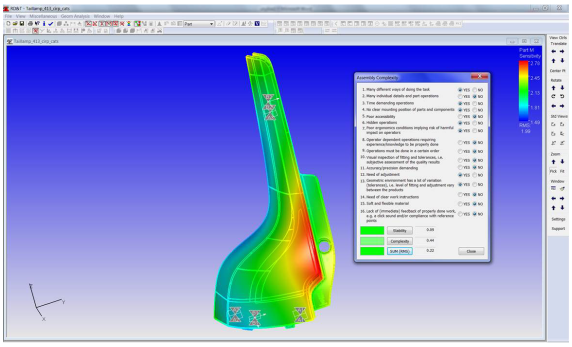

Fig. 3. New robustness value in RD&T

The CAT user judges the 16 HC criteria with yes/no options and the individual normalized values of stability and complexity are calculated and when the SUM button is selected the total RMS value is calculated, see Figure 4.

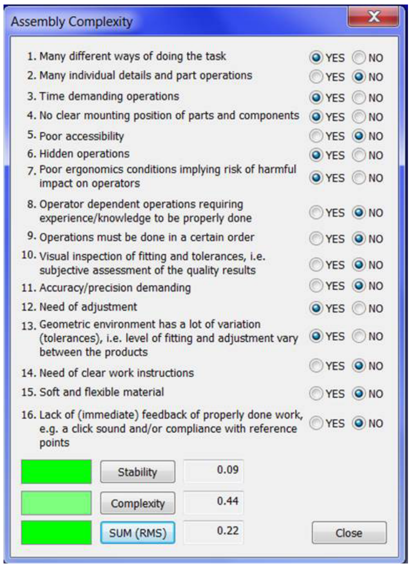

Fig. 4. Calculation window

4.2. Industrial test case

To test the introduced robustness value a simplified industrial case with known assembly problems was selected. The part is a rear lamp for a car. This geometry system solution was initially defined as in Figure 5a with as large as possible A-locating plane giving a RMS sensitivity to variation of 1,99. However, due to the position of the Z2 locator this could not be realized with a screw like Z1 and Z3, instead a clip was used. Unfortunately the assembly of the clip was blind (no visibility), there was no feedback if the clip was in the correct position and the clip had to be fitted before the screws. All of this resulted in an assembly operation that required a lot of skill of the operator, definitely an operator dependent assembly. The geometrical quality of this solution proved to be poor and had problems to fulfill geometrical requirements.

The geometry system was revised according to Figure 5b with the body in white being modified around the Z2 locator to allow the use of a screw instead of a clip. This however decreased the size of the A-plane and increased the sensitivity to variation giving a RMS value of 2,28.

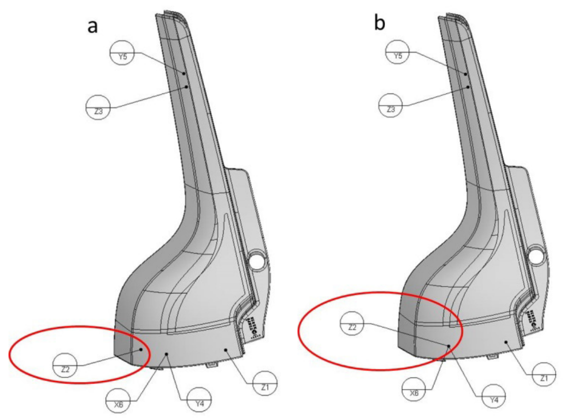

Fig. 5. (a) initial geometry system; (b) revised geometry system

Although this solution was worse according to the used method (Stability analysis) it proved to give better geometrical quality and easier assembly. Clearly, it is not possible to predict the geometrical robustness of a part that is assembled manually only on the propagation of the locators. Calculating this case using the introduced robustness value instead gives the following results:

- Initial solution requires yes on questions 6,8,9, and 16 with a stability RMS of 1.99
- Revised solution requires no on all questions with a stability RMS of 2,28

See Figure 6 and 7 for calculation results.
The calculation shows that the revised solution has a robustness value of 0,08 and the initial solution a value of 0,13. This means that, in this case, the introduced geometrical robustness value shows that a geometry system solution that is easier to assemble gives less sensitivity to variation although the stability analysis result is worse which is consistent with the actual results.

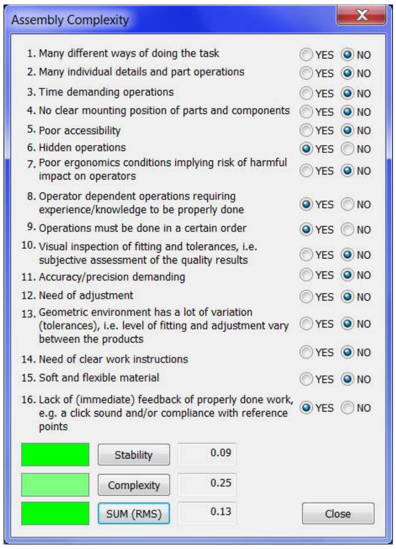

Fig. 6. Initial solution

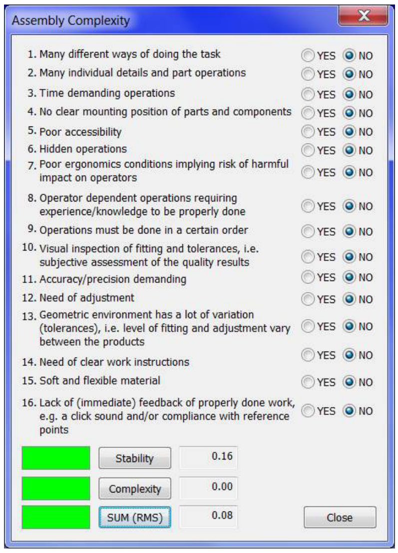

Fig. 7. Revised solution

5. Discussion

Predicting sensitivity to variation, or geometrical robustness, is difficult for parts that are manually assembled. In the virtual world it is usually presumed that all locators are in contact and all degrees of freedom are locked. However an operator does not always manage this, for different reasons, creating a discrepancy between the virtual results and actual results. Unfortunately this discrepancy is propagated and increased in the following geometry assurance work, when tolerances are added to the CAT model and 3D tolerance calculations are performed. Previous research has identified a number of Complexity criteria that should be avoided to keep the discrepancy as small as possible. A new robustness value that combines geometrical stability analysis and complexity criteria has been introduced in this paper to help the geometry engineer to create robust system solutions as early as possible in the development phase. The purpose of this is to catch the worst errors early, it will not be a replacement of different activities that occur later in the development such as ergonomics evaluation, station balancing, work-time studies etc. However, it will create an awareness of the problem in very early product development which will be very useful and will increase quality and simulation accuracy.

Further research needs to be done to establish a proper working procedure using the new robustness value. Also more studies are needed to refine and validate the method.

6. Conclusions

A robustness value for a geometry system solution has been introduced that incorporates both sensitivity to geometrical variation and assessment of assembly complexity. The main purpose of this is to create awareness of potential assembly problems as early as possible in the product development, enabling increased geometrical robustness.

A calculation function for the robustness value has been implemented in a CAT software and tested on an industrial case.

Further research is needed to validate the usage and refine the robustness value.

References

[1] Wickman, C., 2005, "Visualizing the Effect of Geometrical Variation in Assembled Products – Predicting Visual Quality Appearance", PhD Thesis, Chalmers University of Technology, Göteborg, Sweden.

[2] Maxfield, J., Dew, P. M., Zhao, J., Juster, N. P., Taylor, S., Fitchie, M. and Ion, W. J., 2000, "Predicting Product Cosmetic Quality in the Automobile Industry" Proceedings of the 33rd International Symposium on Automotive Technology and Automation (ISATA), Dublin, Ireland.

[3] Wickman, C. and Söderberg, R., 2010, "Retrospective Analysis and Evaluation of Non – Nominal Visualization as Means for Evaluation of Perceived Quality in the Automotive Industry", Proceedings of the 8th International NordDesign Conference 2010, August 25-27, Göteborg, Sweden.

[4] Forslund, K., 2009, "Visual Robustness: Effects of Variation on Product Appearance and Perceived Quality", Licentiate Thesis, Chalmers University of Technology, Göteborg, Sweden.

[5] Cid, G., Thiebaut, F., Bourdet, P. and Falgarone, H., 2007, "Geometrical Study of Assembly Behaviour, Taking into Accounts Rigid Components Deviations, Actual Geometric Variations and Deformations", In Davidson, J.K. Models for Computer Aided Tolerancing in Design and Manufacturing. Springer, Netherlands. pp. 301-310.

[6] Söderberg, R., Lindkvist, L. and Carlson, J. S., 2006, "Virtual Geometry Assurance For Effective Product Realisation", 1st Nordic Conference on Product Lifecycle Management – NordPLM`06, Göteborg, January 25-26, Sweden.

[7] Shah, J. J., Ameta, G., Shen, Z. and Davidson, J., 2007, "Navigating the Tolerance Analysis Maze", Computer-Aided Design & Applications, 4(5), pp. 705-718.

[8] Lööf, J., 2010, "Managing Geometrical Variation through Optimization and Visualization", PhD Thesis, Chalmers University of Technology, Göteborg, Sweden.

[9] Falck, A. and Rosenqvist, M. 2012, "What are the obstacles and needs of proactive ergonomics measures at early product development stages? – An interview study in five Swedish companies", International Journal of Industrial Ergonomics 42(5), pp. 406-415.

[10] Falck, A. Örtengren, R. and Rosenqvist, M., 2012, "Relationship between complexity in manual assembly work, ergonomics and assembly quality", Nordic Ergonomics Conference NES 2012, August 19-22, Stockholm, Sweden.

[11] Rosenqvist, M., Falck, A. and Söderberg, R., 2012, "Robust design and geometry assurance considering assembly ergonomics", Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition IMECE2012, Nov. 9-15, 2012, Houston, Texas, USA.

[12] Rosenqvist, M., Falck, A., Wärmefjord, K. and Söderberg, R., 2013, "Operator related causes for low correlation between cat simulations and physical results", Proceedings of the ASME 2013 International Mechanical Engineering Congress & Exposition IMECE2013, Nov. 13-21, 2013, San Diego, California, USA.

[13] Sivadasan, S., Efstathiou, J., Calinescu, A. and Huatuco, L. H., 2006, "Advances on measuring the operational complexity of supplier-customer systems", European Journal of Operational Research, 171, pp. 208-226.

[14] Frizelle, G. and Suhov, Y. M., 2001, "An Entropic Measurement of Queueing Behaviour in a Class of Manufacturing Operations", In Proceedings of Royal Society London A, 2001 London, England pp. 1579-1601.

[15] Urbanic, R. J. and Elmaraghy, W. H. 2006. "Modeling of Manufacturing Process Complexity" ISBN 978-1-84628-210-2

[16] Zhu, X., Hu, J. S., Koren, Y. and Marin, S. P. 2008, "Modeling of Manufactuing Complexity in Mixed-model Assembly Lines", Journal of Manufacturing Science and Engineering, 2008, 130(5), 10 pages.

[17] Mattsson, S., Gullander, P. and Davidsson, A., 2011, " Method for Measuring Production Complexity", International Manufacturing Conference IMC 28 – Manufacturing Sustainability, 30th August – 1st September, 2011, Dublin City University, Ireland

[18] Falck, A. Örtengren, R. and Högberg, D., 2010, "The Impact of Poor Assembly Ergonomics on Product Quality: A Cost Benefit Analysis in Car Manufacturing", Human Factors and Ergonomics in Manufacturing & Service Industries 20(1), pp. 24-41.

[19] Harrington, H.J., 1987, "Poor Quality Cost", New York: Dekker, ISBN 0-8247-7743-3.

[20] Bank, J., 1992, "The essence of total quality management", Prentice Hall, New York, ISBN: 013284902x.

[21] Booker, J. D., Raines, M. and Swift, K. G., 2001, "Designing Capable and Reliable Products", Butterworth-Heinemann, Oxford, ISBN 0 7506 5076 1.

[22] Taguchi, G., 1986, "Introduction to quality engineering: designing quality into products and processes", Tokyo: Asian Productivity Organisation.

[23] RD&T webpage 2013-10-09 http://www.rdnt.se/

[24] 3DCS webpage 2013-10-09 http://ww.3dcs.com/

[25] VSA webpage 2013-10-09 http://www.plm.automation.siemens.com/en_us/products/tecnomatix/quality_mgmt/variation_analyst/

[26] CETOL webpage 2013-10-09 http://www.sigmetrix.com/tolerance-analysis-software-cetol/

[27] Wärmefjord, K., 2011, "Variation Control in Virtual Product Relization – A Statistical Approach", PhD Thesis, Chalmers University of Technology, Göteborg, Sweden.

[28] Forslund, A., 2012, "Optimization of Geometric Robustness of Aero Structures in Early Design Phases", Lic Thesis, Chalmers University of Technology, Göteborg, Sweden.

[29] Lorin, S., 2012, "Geometrical Variation Simulation for the Development of Products with Plastic Components", Lic Thesis, Chalmers University of Technology, Göteborg, Sweden.

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