Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 43 (2016) 94 – 99

www.elsevier.com/locate/procedia

14th CIRP Conference on Computer Aided Tolerancing (CAT)

# Variation Analysis considering manual assembly complexity in a CAT tool

Rosenqvist, Mikael[a]*, Falck, Ann-Christine[b], Lindkvist, Lars[c], Söderberg, Rikard[d]

[a,b,c,d] *Department of Product and Production Development, Chalmers University of Technology, SE-41296, Göteborg, Sweden*

* Corresponding author. Tel.: +46-733-167925. *E-mail address:* mikros@chalmers.se

## Abstract

Virtual geometry assurance is a key component of today's product development. Much of the virtual geometry assurance is done in Computer Aided Tolerancing (CAT) tools. Earlier research has shown that manual assembly complexity influences the geometrical quality of the product and that assembly tolerances are seldom used in CAT simulations for manual assembly parts. In this study a method for including manual assembly complexity in variation analysis in CAT is introduced and discussed. The method has been tested and implemented in a CAT tool using a real industrial case with promising results.

Peer-review under responsibility of the organizing committee of the 14th CIRP Conference on Computer Aided Tolerancing

*Keywords:* Tolerancing, Complexity, Robust Design

## 1. Introduction

### *1.1. Introduction to the subject*

In the automotive industry geometry assurance is the key component of the quality assurance work. Traditionally there has been much focus on esthetical requirements [1, 2, 3 and 4] but today functional requirements play an equally important role [5].

Virtual verification and quality assurance is necessary today to be competitive in the automotive industry, therefore the geometry assurance work is usually done virtually using CAT tools (Computer Aided Tolerancing) [6, 7, and 8]. The CAT simulations are usually done by specific geometry assurance engineers belonging to a specialist geometry assurance department.

Many contributions have been made to implement Taguchi´s [9] ideas of robust design into geometry assurance [10, 11, 12 and 13]. This means that the CAT tools available have a high maturity and are very comprehensive in their simulation capabilities. One of the challenges today is to create a simulation model that replicates reality in a correct way and has all necessary input parameters correctly defined [14, 15, 16 and 17].

In this paper the aim is to introduce a new method for adding manual assembly process tolerances to a CAT simulation model. This is based on a previously developed assessment model for evaluating manual assembly complexity [18].

### *1.2. Nomenclature*

**Nomenclature**

*Geometry Assurance*: a set of activities with the purpose to ensure that all geometrical requirements on the product are fulfilled.
*CAT*: Computer Aided Tolerancing, 3D tolerance chain stack up analysis
*Variation analysis*: analyses variation in critical dimensions (measures) of the design
*Contribution analysis*: presents a ranked list of points and tolerances, contributing to measurement variation
*Geometry system solution*: Locating scheme, tolerances, fasteners etc. for a part
*Geometry assurance process*: A sub-part of the product development process, a description of how the geometry assurance work is integrated in the product/production development processes
*Manual assembly complexity*: A method that measures how difficult a part will be to assemble

Peer-review under responsibility of the organizing committee of the 14th CIRP Conference on Computer Aided Tolerancing
doi:10.1016/j.procir.2016.02.020

### *1.3. Related work*

Previous research [18,19 and 20] has defined a method on how to assess manual assembly complexity and a new robustness value [21] that incorporates both sensitivity to variation and assembly complexity. Several other approaches to define manual assembly complexity have been made [22, 23, 24 and 25] but none of them focus on early product development. The need for manual assembly complexity to also influence variation analysis has also been established [26] and it has also been identified that process tolerances are seldom used in CAT simulation models for manual assembly parts [16].

However very little research has combined CAT simulations, robust design and manual assembly complexity, this paper aims at expanding this field.

### *1.4. Scope of the paper*

The paper suggests a new method to include manual assembly complexity in variation simulation in a CAT tool and test the method using an industrial test case.

The industrial test case shows promising results, improving accuracy of the simulation results. The need for more research to validate and test the suggested method is proposed.

In section 2 geometry assurance in CAT is described. Next, in section 3 objectives and limitations are presented. In section 4 the suggested method is described and the result from the test case is presented and discussed in section 5 and concluded in section 6.

## 2. Geometry assurance in CAT

### *2.1. CAT tool RD&T*

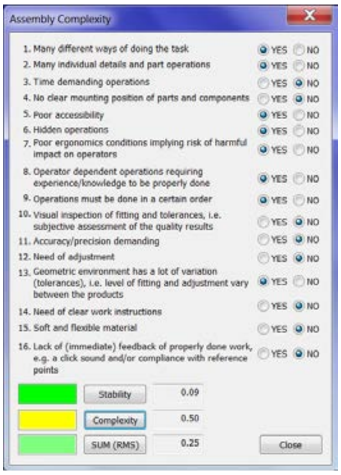
In this study the CAT simulation software RD&T has been used. The software uses a Monte Carlo-based algorithm for generating variation. RD&T has modules for geometry assurance activities in the entire geometry assurance process.

All simulations in this study are done using RD&T, for more information about RD&T see [27]. For more examples of CAT tools see [28 and 29].

The simulations used have been the standard variation and contribution analysis, commonly available in all CAT tools and the new unique manual assembly complexity analysis described in section 2.2.

### *2.2. Manual Assembly complexity in CAT*

Previous research [18] has established a method that assesses manual assembly complexity and shown that this is coupled to quality problems. The 16 high and low complexity criteria were based on interview answers from a large number (n=64) of very experienced design and manufacturing engineers in Swedish manufacturing enterprises. These criteria have been tested and validated in two extensive studies in Swedish Automotive companies. The studies analyzed the quality outcomes of over 100 000 vehicles and about 100 different assembly tasks. The results clearly showed that the higher the complexity level in manual assembly tasks the higher were the reactive costs for correction of assembly related errors and scraps [18 and 20]. There could be other criteria not found in this studies, but as a baseline for the research these will be used. This method has been implemented in the CAT tool RD&T [21]. The method calculates two normalized values between 0 and 1, one for the geometrical robustness (stability or locator sensitivity) and one for manual assembly complexity. A low value indicates a robust geometry system solution and a high value indicates an un-robust geometry system solution. See Figure 1.



Assembly Complexity

1. Many different ways of doing the task ● YES ○ NO
2. Many individual details and part operations ● YES ○ NO
3. Time demanding operations ○ YES ● NO
4. No clear mounting position of parts and components ○ YES ● NO
5. Poor accessibility ● YES ○ NO
6. Hidden operations ● YES ○ NO
7. Poor ergonomics conditions implying risk of harmful impact on operators ● YES ○ NO
8. Operator dependent operations requiring experience/knowledge to be properly done ● YES ○ NO
9. Operations must be done in a certain order ● YES ○ NO
10. Visual inspection of fitting and tolerances, i.e. subjective assessment of the quality results ○ YES ● NO
11. Accuracy/precision demanding ○ YES ● NO
12. Need of adjustment ○ YES ● NO
13. Geometric environment has a lot of variation (tolerances), i.e. level of fitting and adjustment vary between the products ● YES ○ NO
14. Need of clear work instructions ○ YES ● NO
15. Soft and flexible material ○ YES ● NO
16. Lack of (immediate) feedback of properly done work, e.g. a click sound and/or compliance with reference points ○ YES ● NO

| | | |
|---|---|---|
| 🟩 | Stability | 0.09 |
| 🟨 | Complexity | 0.50 |
| 🟩 | SUM (RMS) | 0.25 |

Fig. 1. Assembly complexity analysis in RD&T.

Stability and Complexity, are then summarized with a RMS operation forming a robustness value that not only considers sensitivity to variation but also how complex the product will be to assemble for the operator in the factory.

A complete definition of the analysis can be found in [18, 19 and 20].

### *2.3. Geometry assurance process*

Regardless of which process is used for assembly it is subjected to variation, in this study the focus will be on variation that an operator adds to a manual assembly task. This has previously been proven to be coupled to the complexity of the task [15, 16 and 18].

The addition of variation to the assembly process will affect the characteristics of the final product both in esthetics and function. In this study the focus will be on the esthetics but the same methodology can be applied regardless of characteristics.

In order to secure the desired geometrical quality level of the product a number of geometry assurance activates must be performed during the product development process. Many of these activities are done with the help of virtual tools, like CAT. A geometry assurance process that focuses on virtual verification using CAT tools has recently been defined [26] and this study suggests a method to solve one of the identified needs in the geometry assurance process.

## 3. Methods

### 3.1. Objectives

The objective of this study was to introduce a new method to include manual assembly complexity in variation simulation in a CAT tool and to test the method using an industrial test case.

The study aims at expanding the use of manual assembly complexity in geometry assurance done in a CAT tool.

The purpose is to introduce the expanded method and discuss how it can be used. Further, to identify necessary in-data and how to establish that data.

### 3.2. Limitations

Only manual assembly parts and their process tolerances have been included in this study. Semi-automated or automated assembly processes have been excluded from the research, but the result could be applicable to semi-automated processes if the operator is responsible for the final result. Automated processes do not have operator dependence and are not included. Further only rigid simulations have been performed. Validation of the method to determine baseline manual assembly tolerances is not part of the scope for this paper.

RD&T has been used as CAT tool and the method is only valid in this but the method can be implemented in any CAT tool.

## 4. Results

### 4.1. Proposed new method in CAT tool RD&T

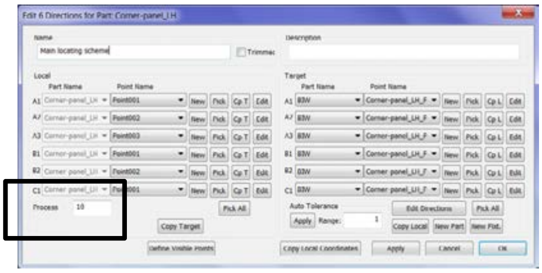
Previous research [21] has already established a method for calculating a normalized value for manual assembly complexity in the CAT tool RD&T that returns a value between 0 (low complexity) and 1 (high complexity). This value will be used in the proposed method to calculate a manual assembly tolerance that will automatically be added to all locators.

In order to use this a new working method is needed that incorporates manual assembly process tolerances in the CAT simulation model in a consistent and repetitive way. The method should calculate process tolerances based on the type of part/assembly and the manual assembly complexity. The proposed method is described below:

1. Perform a manual assembly complexity assessment using the previously established method for a part. The simulation will return a value of 0-1. If the value is 0 then nothing further needs to be done since the assembly operation has so low complexity that the operator will not add any variation.
2. Perform analysis of actual variation in production (see chapter 4.2), $T_{mea}$, either by tests or analyzing existing measurement data
3. Calculate baseline manual assembly tolerance using:

$$T_{man} = \frac{T_{mea}}{Complexity}$$

4. This value, $T_{man}$, in mm will represent the maximum size of manual assembly tolerance that the operator can add to the locators of the part.
5. $T_{man}$ is inputted in RD&T when the locating scheme is defined as process tolerance, see Figure 2.



Edit 6 Directions for Part: Corner-panel_LH

Name: Main locating scheme

☐ Trimmed

Description:

Local

| | Part Name | Point Name |
|---|---|---|
| A1 | Corner-panel_LH | Point001 |
| A2 | Corner-panel_LH | Point002 |
| A3 | Corner-panel_LH | Point003 |
| B1 | Corner-panel_LH | Point001 |
| B2 | Corner-panel_LH | Point002 |
| C1 | Corner-panel_LH | Point001 |

Process: 10

Target

| | Part Name | Point Name |
|---|---|---|
| A1 | BIW | Corner-panel_LH_F |
| A2 | BIW | Corner-panel_LH_F |
| A3 | BIW | Corner-panel_LH_F |
| B1 | BIW | Corner-panel_LH_F |
| B2 | BIW | Corner-panel_LH_F |
| C1 | BIW | Corner-panel_LH_F |

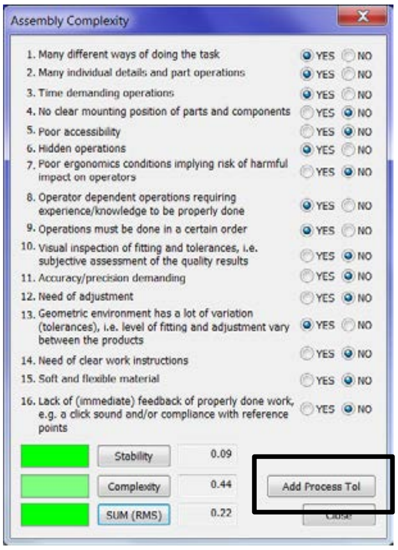
Auto Tolerance Range: 1

Fig. 2. Locating scheme definition with process tolerance.

6. Assembly complexity simulation is performed in RD&T and the robustness value is calculated.
7. Manual assembly process tolerances are added to the parts location scheme using the Add Process Tol, see Figure 3. It will add a tolerance to each locator according to this:

$$T_{loc} = T_{man} \times Complexity \times \langle i|j|k \rangle$$

Where i, j, k is the steering vector of the locator.



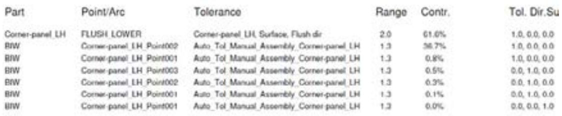
Assembly Complexity

1. Many different ways of doing the task ● YES ○ NO
2. Many individual details and part operations ● YES ○ NO
3. Time demanding operations ● YES ○ NO
4. No clear mounting position of parts and components ○ YES ● NO
5. Poor accessibility ○ YES ● NO
6. Hidden operations ● YES ○ NO
7. Poor ergonomics conditions implying risk of harmful impact on operators ○ YES ● NO
8. Operator dependent operations requiring experience/knowledge to be properly done ● YES ○ NO
9. Operations must be done in a certain order ● YES ○ NO
10. Visual inspection of fitting and tolerances, i.e. subjective assessment of the quality results ○ YES ● NO
11. Accuracy/precision demanding ○ YES ● NO
12. Need of adjustment ○ YES ● NO
13. Geometric environment has a lot of variation (tolerances), i.e. level of fitting and adjustment vary between the products ● YES ○ NO
14. Need of clear work instructions ○ YES ● NO
15. Soft and flexible material ○ YES ● NO
16. Lack of (immediate) feedback of properly done work, e.g. a click sound and/or compliance with reference points ○ YES ● NO

| | | |
|---|---|---|
| 🟩 | Stability | 0.09 |
| 🟩 | Complexity | 0.44 |
| 🟩 | SUM (RMS) | 0.22 |

Fig. 3. Assembly complexity simulation with process tolerance.

8. When performing a variation simulation, the added process tolerances will affect the predicted total variation in the measures and appear in the contribution analysis, see Figure 4.



| Part | Point/Arc | Tolerance | Range | Contr. | Tol. Dir.Su |
|---|---|---|---|---|---|
| Corner-panel_LH | FLUSH_LOWER | Corner-panel_LH, Surface, Flush dir | 2.0 | 61.0% | 1.0, 0.0, 0.0 |
| BIW | Corner-panel_LH_Point002 | Auto_Tol_Manual_Assembly_Corner-panel_LH | 1.3 | 36.7% | 1.0, 0.0, 0.0 |
| BIW | Corner-panel_LH_Point001 | Auto_Tol_Manual_Assembly_Corner-panel_LH | 1.3 | 0.8% | 1.0, 0.0, 0.0 |
| BIW | Corner-panel_LH_Point003 | Auto_Tol_Manual_Assembly_Corner-panel_LH | 1.3 | 0.5% | 0.0, 1.0, 0.0 |
| BIW | Corner-panel_LH_Point002 | Auto_Tol_Manual_Assembly_Corner-panel_LH | 1.3 | 0.3% | 0.0, 1.0, 0.0 |
| BIW | Corner-panel_LH_Point001 | Auto_Tol_Manual_Assembly_Corner-panel_LH | 1.3 | 0.1% | 0.0, 1.0, 0.0 |
| BIW | Corner-panel_LH_Point001 | Auto_Tol_Manual_Assembly_Corner-panel_LH | 1.3 | 0.0% | 0.0, 0.0, 1.0 |

Fig. 4. Contribution Analysis.

If the geometry system solution is changed, a new assessment of the complexity should be done and new manual assembly process tolerances can be added giving new predicted variation.

### 4.2. *Examples of operator induced variation*

Example 1. A plastic trim part is mounted using two pins, one in a round hole and one in a slot and a number of push in clips. The operator locates the part with the two pins and then pushes the part in the mounting direction to engage the clips. This assembly operation can induce variation in several ways, for example:

- The clips do not have a clear sound or visual feedback when fully engaged, making it difficult for the operator to know if the part is correctly assembled. The incorrectly fitted clip(s) will give the part a new, unintentional, position and add variation to the position. This example would result in yes on criteria 16.
- It is not possible for the operator to see if all the clips match their mounting holes because the part obstructs the view during the assembly and some clips might not be inserted at all. This example would result in yes on criteria 6.

Example 2. A headlamp is mounted with 3 screws. One screw in a full-steering hole, one screw in a slot and one screw in an oversized hole.

- Depending on which screw the operator decides to tighten first the position will be different. If for example the screw in the oversized hole is tightened first the position will be different than the intendent position adding variation. This example would result in yes on criteria 1, 4, 8 and 14.

### 4.3. *Establishing baseline manual assembly tolerance*

For each type of part and type of assembly process a baseline manual assembly tolerance needs to be established. In the automotive industry regular inspection measurements, both of parts, subsystems and the assembled products, are part of the normal quality assurance procedures. The measurement data is usually stored in some sort of statistical system where the data can be viewed and analyzed [30].

Unfortunately, the error in the positioning of the locators is not measured and actually impossible to measure due to the fact that the part is positioned using the locators. What is measured is the position of the part in areas that are possible to reach.

For this method it is needed to determine the variation between the part and locators. Therefore, it is needed to translate the variation measured in the reachable inspection points to variation in the locators. Preferably using existing measurement data that is measured as a part of the normal quality assurance.

Using Root cause analysis, it is possible to analyze if variation in an assembled product is caused by the assembly process. Several studies have been done previously on this [31, 32]. A method for using inspection data from repeatability studies and transforming it into locator variation has been established previously [33]. This method makes it possible to separate the variation caused by the locators from other sources of variation.

Prerequisites for using the method are:

- Inspection points measured in all directions (x, y, z)
- More inspection points than locators
- Inspection points located in areas where the lever effects from the movements in the locators are high
- At least 50 and preferably 100 observations made

All of these criteria are usually met in a normal measurement plan in the automotive industry.

It is presumed that this method can be adopted to establish the baseline manual assembly tolerance, in order to do this several industrial validation cases need to be carried out to provide verification. If this works it will be possible to use existing measurement data to establish a database of baseline manual assembly tolerances that can be used in the product development work.

### 4.4. *Industrial test case*

In this section, the suggested method is applied to an industrial test case. This serves as a first validation of the method and is used to exemplify the need for manual assembly process tolerances in CAT simulations.

The case is the manual assembly of a plastic side bumper of a European heavy truck. The part is located and fastened with both clips and screws. For this purpose, a gap relation between the middle and side part of the bumper is evaluated. See Figure 5.

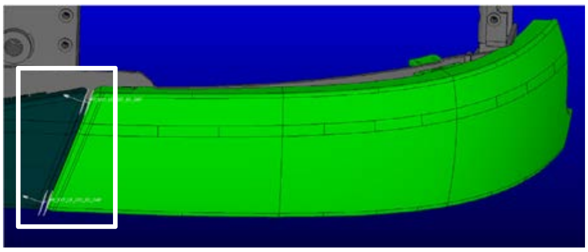


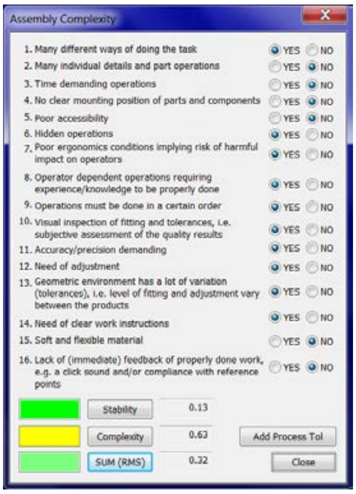
Fig. 5. Plastic side bumper gap relation

As a start point the CAT simulations made by the geometry assurance engineers in the truck company were analyzed. The geometrical requirement for the gap relation was set to 6mm±2mm by the design department. The CAT simulations showed a predicted variation of 6mm±2.6mm where only 0.26% of the simulation was outside of ±2mm. A result showing that this geometry system would work in 99.74% of all produced trucks. The simulation is very comprehensive with tolerances on all ingoing parts and features but has no process tolerances for the manual assembly.

At the time of this study the measurement of gap relation in production was not running at full pace and therefore only 12 trucks have been officially measured, of which 4 trucks were outside of specification. Another 20 trucks were inspected in production by the authors and 5 of these were outside of specification. An interview of the quality assurance production personnel confirmed that 25-30% of the trucks usually are out of specification in this gap relation and are corrected by manual adjustment.

These results in production show a big discrepancy from the CAT simulations. The single parts are also measured and they are all within specification or close to, so the additional variation is mainly coming from another source.

The assembly operation is then assessed using the manual assembly complexity method in RD&T, see figure 6.



1. Many different ways of doing the task ● YES ○ NO
2. Many individual details and part operations ○ YES ● NO
3. Time demanding operations ○ YES ● NO
4. No clear mounting position of parts and components ○ YES ● NO
5. Poor accessibility ○ YES ● NO
6. Hidden operations ● YES ○ NO
7. Poor ergonomics conditions implying risk of harmful impact on operators ● YES ○ NO
8. Operator dependent operations requiring experience/knowledge to be properly done ● YES ○ NO
9. Operations must be done in a certain order ● YES ○ NO
10. Visual inspection of fitting and tolerances, i.e. subjective assessment of the quality results ● YES ○ NO
11. Accuracy/precision demanding ● YES ○ NO
12. Need of adjustment ● YES ○ NO
13. Geometric environment has a lot of variation (tolerances), i.e. level of fitting and adjustment vary between the products ● YES ○ NO
14. Need of clear work instructions ● YES ○ NO
15. Soft and flexible material ○ YES ● NO
16. Lack of (immediate) feedback of properly done work, e.g. a click sound and/or compliance with reference points ○ YES ● NO

🟩 Stability 0.13
🟨 Complexity 0.63
🟩 SUM (RMS) 0.32

Fig. 6. Assembly complexity analysis

The analysis shows a good geometrical robustness, 0.13 but a somewhat poor Complexity, 0.63. This implies that the operator will add process tolerances to the assembly.

Unfortunately, since a very limited amount of measuring data is available the method in chapter 4.2 could not be used. Instead a simple physical test was performed to determine the baseline manual assembly tolerance (see 4.1 and 4.2) and this was approximated to ±5mm.

10mm Process tolerance was inputted in RD&T according to section 4.1 and automatic process tolerances were added to the locators using the suggested method and hereby the CAT variation simulation was redone with the new input data.

The new variation simulation results predict that around 15% of the trucks will be out of specification and the assembly tolerances are the top contributors to variation. This conforms well with the observations of the quality assurance personnel in production who state that the assembly is the main contributor to errors for this part.

This clearly shows the need for manual assembly complexity analysis in early product development phases and the need for manual assembly tolerances in the CAT simulation model to be able to predict variation accurately.

## 5. Discussion

To create CAT simulation models that include every source of variation is a very complex and time consuming task. The manual assembly operation of parts is often considered as a nominal process, i.e., not adding any variation to the variation simulation. However, in reality, all assembly operations add variation to some extent.

The proposed method in CAT is simple to use and helps the simulation engineer to add process variation to the simulation model in a structured way using a validated assessment method for manual assembly complexity. However, the establishment of the baseline process tolerance for each type of component and/or assembly type is not so straightforward and requires measurement data from production. A suggestion on how this can be done has been presented but more research is required to define and validate this. A research project around this is currently in its startup phase.

The industrial test case shows promising results, that decrease the gap between simulations results and actual measured results in production. More tests should be performed and a generic method of how to use the method needs to be established before it can be applied in the industry.

## 6. Conclusions

The proposed method in the CAT tool RD&T enables the addition of manual assembly process tolerances to be added in a convenient and structured way to the simulation model using a verified assessment model. This facilitates improved accuracy in the simulation results and highlights the need for consideration of manual assembly complexity proactively, in early product development phases.

The industrial test case shows promising results, improving accuracy of the simulation results.

More test cases need to be done to validate the method and more research is needed to investigate the establishment of baseline assembly tolerances.

## Acknowledgements

This work was carried out at the Wingquist Laboratory VINN Excellence Centre within the Area of Advance - Production at Chalmers University of Technology in Göteborg, Sweden, supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA). The support is gratefully acknowledged. Furthermore, the authors acknowledge the financial support provided by 'Fordonsstrategisk Forskning och Innovation' (FFI).

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

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

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

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

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

[14] Lindau, B., Rosenqvist, M., Lindkvist, L. and Söderberg, R., 2015, "Challenges moving from physical into virtual verification of sheet metal assemblies", Proceedings of the ASME 2015 International Mechanical Engineering Congress & Exposition IMECE2015, Nov. 13-19, 2015, Houston, Texas, USA.

[15] 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.

[16] 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.

[17] Lindau, B., Andersson, A., Lindkvist, L. and Söderberg, R., 2012, "Using Forming Simulation Results In Virtual Assembly Analysis", Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition IMECE2012, Nov. 9-15, 2012, Houston, Texas, USA.

[18] Falck, A. Örtengren, R. 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" Int. J. of Industrial Ergonomics 42 (2012) pp. 406 – 415.

[19] Falck, A. och Rosenqvist, M. 2014 "A model for calculation of the costs of poor assembly ergonomics" (part 1) International Journal of Industrial Ergonomics: volume 44 (2014) pp. 140-147.

[20] Falck, A., Örtengren, R. och Rosenqvist, M. (2014) Assembly failures and action cost in relation to complexity level and assembly ergonomics in manual assembly (part 2) International Journal of Industrial Ergonomics: volume 44 (2014) pp. 455-459.

[21] Rosenqvist, M., Falck, A., Lindkvist, L. and Söderberg, R., 2014, "Geometrical robustness analysis considering manual assembly complexity", Proceedings of the 5th CATS 2014 - CIRP Conference on Assembly Systems and Technologies CATS2014, Nov. 13-14, 2014, Dresden, Germany.

[22] 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.

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

[24] 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.

[25] 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.

[26] Rosenqvist, M., Falck, A. and Söderberg, R., 2015, "Working procedure for early proactive geometry assurance considering manual assembly complexity", Proceedings of the ASME 2015 International Mechanical Engineering Congress & Exposition IMECE2015, Nov. 13-19, 2015, Houston, Texas, USA.

[27] RD&T webpage 2015-11-14 http://www.rdnt.se/

[28] 3DCS webpage 2015-11-14 http://ww.3dcs.com/

[29] VSA webpage 2015-11-14 http://www.plm.automation.siemens.com/en_us/products/tecnomatix/quality_mgmt/variation_analyst/

[30] CM4D webpage 2015-11-18 http://ats-cm4d.com/

[31] Carlson, J. S., 1999, "Root Cause Analysis for Fixtures and Locating Schemes Using Variation Data", Proceedings of the 6th CIRP International Seminar on Computer-Aided Tolerancing, pp. 111–120.

[32] Ceglarek, D., and Shi, J., 1999, "Fixture Failure Diagnosis for Sheet Metal Assembly With Consideration of Measurement Noise", Journal of Manufacturing Science and Engineering , 121 (4), pp. 771-777.

[33] Wärmefjord, K., Söderberg, R. and Carlson, J. S., 2010, " Including assembly fixture repeatability in rigid and non-rigid variation simulation" Proceedings of the ASME 2010 International Mechanical Engineering Congress & Exposition IMECE2010, Nov. 12-18, 2010, Vancouver, Canada.