Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 27 (2015) 71 – 76

www.elsevier.com/locate/procedia

13th CIRP conference on Computer Aided Tolerancing

Adaptive modeling of non-rigid assembly orientation processes in a statistical CAT simulation

J. F. Klinger[a,]*, M. Bohn[a] and F. Litwa[a]

[a]*Daimler AG, Benzstrasse, 71063 Sindelfingen, Germany*

* Corresponding author. Tel.: +49-7031-90-78044; fax: +49-711-3052127834. *E-mail address:* julius_friedrich.klinger@daimler.com

Abstract

One of the most common uses for Computer Aided Tolerancing (CAT) in the passenger car industry is body design, which universalized, consists of non-rigid assembly processes. There are a number of theoretical approaches to model the joining behavior of assemblies with elastic FEM approaches combined with statistical computation. On the other hand the rising complexity of today's body-in-white production chain makes simplifications inevitable when fast results for tolerance optimization are required.

Multiple use-cases representing different scenarios are analyzed. The scenarios vary in the stiffness of the involved components, the joining environment and the general geometrical set-up. Comparing mass production measurement data with simulation output reveals the limits of CAT simulations in certain cases. One of those cases is where so-called geo-stations improve the dimensional output quality of assemblies compared to the single parts. To account for this phenomenon an adaptive approach to model geo-stations in different ways is presented, i.e. as an entity either provoking an additional influence of deviation or supplying geometrical correction. A matrix is used to suggest the appropriate kind of modeling depending on the deduced parameters.

Peer-review under responsibility of the organizing committee of 13th CIRP conference on Computer Aided Tolerancing

Keywords: computer aided tolerancing; dimensional management; body-in-white; assembly process; jigs and fixtures

1. Dimensional management in the automotive industry

Modern mass production in the automotive industry is very sensitive towards fabrication tolerances. To ensure the complete functionality of the assembly two main aspects have to be considered. First of all a large amount of single components need to be adapted to each other regarding their geometrical specifications, i.e. permitted tolerances and the occurring distributions, cp. [1]. Secondly effects resulting from the assembling processes need to be taken into account [2]. The permitted deviations for the single components as well as the processes need to be defined according to the special environment of mass production and the proposition to avoid any kind of refinishing operations.

1.1. Tolerance compatible body-in-white design

One prerequisite to obtain a robust body-in-white assembly is a tolerance compatible design thereof. For example sliding flanges and sufficient hole clearances enable an adjustable body-in-white production which is able to react to single part and subassembly deviations. This especially holds for stiff structural parts which can hardly be deformed by the clamping during the joining operation.

1.2. Application of tolerance simulation

To be able to define the permitted deviation in the development phase the application of computation tools is required. Computer Aided Tolerancing (CAT) is a valuable tool to analyze the effect of single component deviations on the precision of functional dimensions of the final assembly if hardware is not yet available. Regularly utilized CAD-based tools are the CATIA V5-integrated 3DCS or VisVSA [3] for instance. The investigated fields run from subassemblies of the body-in-white, which universalized, consists of non-rigid assembly processes, to the installation of mounting parts made

Peer-review under responsibility of the organizing committee of 13th CIRP conference on Computer Aided Tolerancing
doi:10.1016/j.procir.2015.04.046

from plastic (cp. [4]), as the simulation tools allow a comparatively plain evaluation of concepts.

In body-in-white development CAT is used in close interaction with CAD models to take geometrical effects into account. To ensure the accuracy of certain functional dimensions, single component variations as well as process characteristics are considered. A general difficulty with simulations is the strong dependency of the results' accuracy on the modeling approaches and quality of the input data, demanding a representation as close to reality as possible. On the other hand the rising complexity of today's body-in-white production chain makes simplifications inevitable when fast results for tolerance optimization are required. This conflict of objectives points out the need for an easy to handle tolerance simulation which still delivers results of sufficient accuracy.

2. Deviation impact of body-in-white positioning processes

2.1. Connection between single part and assembly quality

Most computer aided tolerancing methods are based on some kind of statistical summation of impact factors such as single part and certain process deviations. But reality shows that the influence of process steps is not always a share adding deviation in the body-in-white manufacturing process. Certain processes actually improve the dimensional quality of the product. There are highly accurate welding stations, so-called geo-stations, which deliver output assemblies that are closer to the nominal sizes than the input subassemblies or individual components were, as is shown in detail in chapter 3. Chase et al. introduce three sources of variation [5]; dimensional and kinematic variation resulting from assembly inaccuracies and deformation and geometric variation as a result of form errors. Referring to this modeling approach, the dimensional and kinematic adjustments overcome geometric inaccuracies.

2.2. Impact factors on assembly quality

To obtain a body-in-white assembly of high accuracy there are of course a number of prerequisites to be fulfilled. If there are single parts of poor quality, they need to be flexible so that a geo-station can bend them into position before any joining operation takes place. At least where this requirement cannot be fulfilled a tolerance compatible design as mentioned in chapter 1.1 is needed. Self-evidently a persistent tolerance compatible design is in general one of the key impact factors to maintain the required level of dimensional quality.

More over the geo-station itself has to feature precision of a high level when it comes to its locating pins and clamping fixtures. If jigs are installed, the dimensional quality is closely reviewed. But also during their use the precision needs to be monitored frequently to prevent deviations caused by wear phenomena.

3. Analysis of representative use cases

To back the hypothesis devised in chapter 2.1 an analysis of measurement data was carried out. The quality of single parts and the resulting assemblies was assessed and compared. Assembly processes of different passenger cars and different set-ups concerning the single parts' stiffness, the geometrical configuration etc. were researched. The measurement data was evaluated in greater detail in [6].

3.1. Use-case 1 representing form closure

The first use case analyzed is creating a form closure between the two joined parts. The tail lamp housing is welded into the outer side panel. The dimensions in X-direction of the two single parts are interpreted and compared to the values of the assembly at the same measurement points. The X-dimension is referring to the global coordinate axis having its origin in the middle of a vehicle's front axis and facing towards the rear axis.

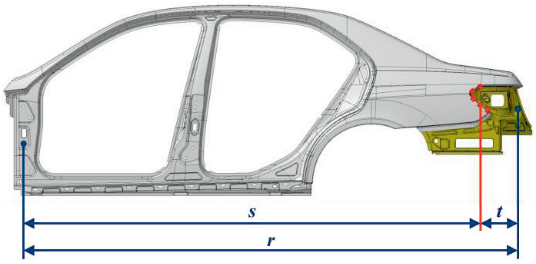

Fig. 1. Measurements carried out at the side wall rear end

As illustrated in Fig. 1 for the side panel the relative dimensions between the X-/Z-reference at the A-pillar to several points on the connecting flange to the lamp housing were evaluated. Those measurements are referred to as "s" in Fig. 1. The blue dot in the A-pillar area highlights the reference hole of the side wall, to which the measurement points on the flange, highlighted by the red dotted line, were evaluated. Similar points at the lamp housing flange were verified with the X-reference at that part, indicated by the blue dot on the parts colored yellow and the respective measurement "t". In the geo-station, where both parts are joined to form the assembly, the mentioned X-references are the main locators for the parts in X-direction. As a result the two X-references of the single parts in the assembly were matched as specified by "r".

The lamp housing and the side wall measurements were obtained by a CMM measurement machine, while the assembly was audited by an inline measurement system. This is why there is a much larger sample size available for the assembly measurements. The values displayed a very poor dimensional quality of the single components. Nevertheless the resulting assembly astonishes with very accurate dimensions. Measurement results from the vehicle's left hand side parts are exemplified in Table 1.

The values declared as mean difference describe the difference between the mean value of the measurements and the midpoint of the tolerance zone assigned at the measurement spot. As shown the single part deep drawing as well as the assembly welding processes show a very small statistical spread which is hardly beyond the range of the measurement accuracy. Moreover the small sample sizes for the single parts do not allow a detailed assessment of the standard deviation.

Table 1. Characteristic measurement values of single parts and resulting assembly of use-case 1

Dimension	Side wall "*s*"	Lamp housing "*t*"	Assembly "*r*"
Mean difference	-0.27	0.57	-0.01
Standard deviation	0.16	0.12	0.06
Sample size	57	26	500

On the other hand there is a large discrepancy concerning the mean difference, as the single parts display much larger values here. The negative value of the side wall indicates a too short distance between its reference point and the analyzed measurement point at the joining flange front tip. The values of other measurements at the flanges, which are not presented here in detail, confirm that the two diagonal flange sections are located too far to the vehicle's front end and are positioned too close together. The dimensional quality of the lamp housing is by far worse. As the reference point is located behind the researched area in the longitudinal direction, the large positive mean difference suggests the same behavior of the joining flange as for the side wall, just in the opposite direction. Again, both flange sections are located too close together and also too close to the reference point, which is one of the main positioning elements in the geo-station to create the assembly. If the form closure at the flanges would be the decisive impact factor for the dimensional quality of the assembly, the dimension "r", which refers to the resulting distance between the reference points of the two single parts in the assembly, would be way to short. But as the measurements of the assembly shows, this gauge is perfectly in specification. The same behavior can be found with the single parts and assembly of the right hand side, which was also analyzed. This leads to the conclusion that not the positive locking, but the positioning in the geo-station is the main impact on the dimensional quality of the assembly.

3.2. Use-case 2 representing no form closure

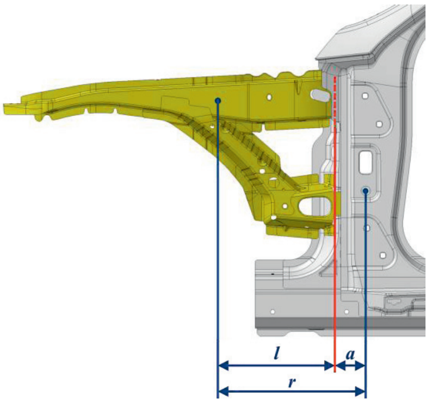

Fig. 2. Measurements carried out at the side wall front end

The second researched use case is representing an established connection by means of a block situation, i.e. there is no influence of any further geometrical interlocking. The upper level longitudinal beam front subassembly is joined with the sidewall subassembly. The two subassemblies are positioned by the geo-station and are then spot welded at the interfacing X-plane, represented by the dotted red line in Fig. 2.

Also here the X-dimensions were analyzed. As above, the connecting surfaces, which are the flanges of the longitudinal beam and front surface of the sidewall, were related each to the subassemblies X-Reference. This gives the dimensions "l" and "a" in Fig. 2. For the complete assembly, the X-references were set in proportion to each other, see measure "r". Though there are two subassemblies which form an assembly, the outset dimensions are actually determined by single part quality. The whole front upper level longitudinal beam is actually plugged in the investigated geo-station, as can be seen from Fig. 2. But the analyzed dimensions, the distances between the two flanges and the reference hole (blue dot), originate only from the upper shell part of the longitudinal beam. The same holds for the side wall assembly. The reference hole (blue dot) and the contact surface at the dotted line are features of the same piece part of the A-pillar.

The analyzed measurement data base for this use-case is not as comprehensive as the one of the first use case. Still conclusions can be drawn regarding the subassemblies and assembly quality. The high sample size of the subassembly longitudinal beam allows the conclusion that position relevant flanges is out of specification. Again, the statistical spread is fairly low as extracted from Table 2. But the upper and especially the lower flange show a significant mean difference. This could not only lead to a misplacement in X-direction, but also to a tipping of the longitudinal beam. For the A-pillar there is a certain lack of data. However, some measurements were carried out and also here a considerable mean difference is identifiable. The resulting assembly on the other hand shows only minor mean differences. To be able to evaluate the potential tipping, Table 2 does not only contain the accuracy characteristics in X-, but also in Z-direction.

Table 2. Characteristic measurement values of single parts and resulting assembly of use-case 2

Dimension	Longitudinal beam "*l*" (upper/lower flange)	A-pillar "*a*"	Assembly "*r*" (X/Z)
Mean difference	0.26/-1.93	-0.51…0.2	0.03/0.23
Standard deviation	0.27/0.26	-	0.07/0.11
Sample size	196/185	ca. 6	500

Hence the data in the table shows that there neither is a misalignment of the longitudinal beam nor a tipping of the same. The tipping might have been prevented by the general geometric set-up. As can be seen in Fig. 2 there is a support structure below the main longitudinal beam. But to overcome misalignment due to the malposition of the lower flange, its deformation is required. If this deformation was elastic, the parts would experience a certain spring back when being released by the geo-station, as there is no complete form closure of the parts themselves holding them in position. Since the measured dimensions disprove this, plastic deformation must have been taking place, at least as a part of the total deformation happening during the geo-welding.

3.3. Use-case 3 representing the potential of geo-stations to adjust dimensions

The last use-case represents a set-up, where the pure geometric potential of a geo-station can be analyzed, since there are no form closures or block situations which if applicable need to be overcome. Dimensional quality in the main body-in-white assembly line is assessed. The accuracy of measurement points (red dots) at the rear floor of a passenger car is compared to the position of the same points after the whole vehicle's floor was assembled, compare dimensions "f" and "r" in Fig. 3. Between the front and the rear floor no geometrical interlocking exists. To ensure a flexible body-in-white assembly, which allows adjustability of geometry, the two large assemblies are solely linked by sliding flanges. As the subassemblies are very rigid at that stage of assembly process, they cannot be bent anymore making sliding flanges inevitable.

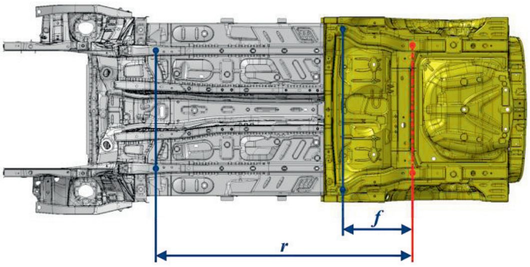

Fig. 3. Measurements carried out at the body-in-white floor

As both components analyzed in this use-case study are large subassemblies, both are frequently measured by inline measurement technology. This gives a large sample size, as depicted in Table 3. The evaluated data shows that the mean differences and standard deviations are consistently low, for the rear floor subassembly and the complete floor assembly. Of course there is a difference in the values, but this is to be neglected in consideration of the limited measurement accuracy.

Table 3. Characteristic measurement values of single parts and resulting assembly of use-case 3

Dimension	Rear floor (left/right)	Completed floor (left/right)
Mean difference	0.23/0.40	0.25/0.62
Standard deviation	0.09/0.14	0.12/0.15
Sample size	1000/450	300/300

Thus this use-case displays the potential of body-in-white positioning processes to not only improve, but also simply to maintain a high level of dimensional quality.

4. CAT Modeling of Geo-Stations

As substantiated in chapter 3 geo-stations play a decisive role for the dimensional quality of an assembly. Thus a detailed modeling of their impact is required to establish an accurate prediction of manufacturing tolerances by CAT.

4.1. In use approaches of representation

Currently there are two main approaches to represent the accuracy impact of the positioning processes in a geo-station. The first is based on pure statistical summation of tolerances of single process steps and on the assumption of totally rigid piece parts. With this method the error distributions of two single parts, which are to be joined, and the joining process are added up by statistical convolution. One of the commonly used algorithms is the Monte Carlo method. For that a few thousand runs are carried out with picking random values according to the distribution pattern of each contributor. The large number of resulting measures then supplies the statistical background to evaluate the expected output quality. This method is based solely on statistical computations, taking individual distribution patterns and geometrical conditions into account. As topological and material properties are disregarded, the user can only influence those physical boundary conditions by selecting the appropriate joining locations and fitment set-up.

The other common approach is elastic tolerance simulation, which has become a focus of research in the past years, see for example [7]. To link statistical simulations with FEA methods necessitates extra-ordinary computational capacities, which still is a challenge for the elastic simulation. Liu et al. introduced an approach to obtain the computation efficiency which is required for practical applications [8]. Ungemach developed a method to integrate this approach to commercial tools [9]. Still, elastic tolerance simulation has not completely arrived in the industry applications yet. However, the main advantage of elastic tolerance simulation is the observance of spring back phenomena. The forces acting on the deviation afflicted piece parts caused by the jigs and fixtures of the geo-station are creating a warped assembly. The omission of those forces caused by the opening clamps will then result in a backward deformation which is simulated by elastic CAT.

4.2. Shortfalls of current approaches

As mentioned the exclusively statistic simulation does not take physical properties of the parts set-up into account. The use-cases one and two presented in chapter 3 though prove that some kind of deformation is taking place. This lowers the eligibility of this approach for configurations like the mentioned use-cases.

In addition to the described computational efforts elastic CAT does not take plastic deformation behavior into account, as the term already indicates. Except contact conditions most approaches actually do not regard non-linear behavior at all. The presented use-case two most certainly suggests the occurrence of plastic deformation. If the flanges of the longitudinal beam in that example would not be plastically dragged into position, the assembly would not be dimensionally stable. Elastic deformation would cause a spring back behavior, which results in a sustainable misplacement if no rate-action is installed. Hence for this example it can be concluded that elastic CAT is not able to model the occurring phenomena correctly.

4.3. Improved representation of geo-stations

The approach presented in this paper aims to better reflect practical phenomena, but also to establish a method which can be applied in the industry with manageable effort. It is based on the statistical evaluation by application of the Monte Carlo method. Non-linear behavior is not modelled itself, but represented by an adaptive modelling of the clamping conditions, fitment set-up and deposited tolerance information.

Besides these modifications, a single procedure for all occurring joining configurations is not sufficient. Depending on the geometrical and other physical boundary conditions, the dimensional impact of the geo-station may differ. Hence the joining instance to be modelled is classified according to these aspects, which are displayed in Fig. 4.

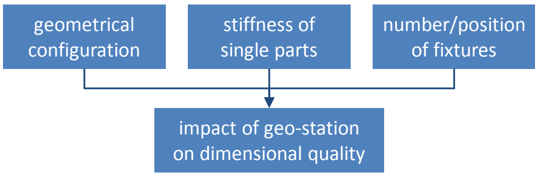

Fig. 4. Main aspects of impact of geo-stations on accuracy

In the first place, for each geo-station the geometrical set-up has to be analyzed. For example in use-case one, there is a positive locking between the joining partners, which necessitates a deformation, if another dimension than the one arising from the parts' geometries is desired. Use-case three does not imply a deformation to achieve a flexible resulting dimension, since the sliding flanges ensure adjustability in X-direction.

The deformation discussed in connection with use-cases one and two is only achievable, if the stiffness of one or both joining partners is sufficiently low. In use-case two for example the connection surface of the A-pillar is a very rigid surface being a part of an important structural part. So here all the necessary deformation needs to be mustered by the longitudinal beam, which is feasible in this case, since the flanges are comparatively flexible.

Another important aspect is the quantity and position of fixtures. Right at the spot where a fixture or a pin positions a part correctly, there will be only the deviation caused by the accuracy of the clamping element. For areas of a part with a considerable distance to a fixture, additionally the shape tolerance of the part has to be taken into account. Features for which the dimensional quality is crucial need to have some kind of fixture close by.

Ranking the observed configuration for each general aspect it has to be graded according to the three levels established. Depending on the evaluation the configuration can be classified according to Fig. 5. This gives 27 different categories as can be derived from the figure. Of course to establish this number of simulation approaches does not yield the results contemplated. The aim of this classification rather is to determine, whether the tolerances of the single components or the tolerances of the joining process have a larger impact on the deviation of the resulting assembly. The classification should be applied on each two interacting components in a geo-station for each orientation which is in the focus of research.

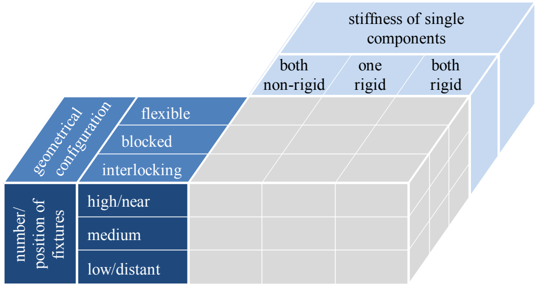

Fig. 5. Classification pattern of joining configuration

4.4. Application of improved representation on use-case

The presented approach is applied on use-case one. Surveying the X-direction again, especially for the lamp housing there is a high number of fixtures. As the geometrical configuration is interlocking, the tolerances of the single parts should have an impact. But as both parts can be considered as non-rigid, the impact of the process, i.e. the geo-station's jigs and fixtures, play the decisive role. So in this case it is important to map all the essential fixtures in the simulation and to mount both parts digitally in the rig. The contact conditions of the two parts are insignificant in this case.

This modified way of modelling is compared to the conventional way of carrying out a Monte Carlo simulation. Usually, for a rigid modelling one would stick to the isostatic holding fixture representation. The new approach #1 does maintain the same fixture representation, only the tolerances of the fixtures are set to real life data. With the new approach #2 more fixtures than the isostatic number are taken into account which is realized by mediating selected fixtures. Depending on its dimensional importance the fixtures which are mediated are rated by a weighting factor.

The modified approach also is tested for use-case two. As explained for this set-up a blocked geometrical configuration is on hand. While the A-pillar is a rather rigid sector, the longitudinal beam is quite non-rigid. So especially for this component the representation of the geo-station positioning shall be dominating for the simulation. As for use-case one the new method #1 implies improved fixture tolerances, but also the negligence of the block situation, i.e. positioning only by the jigs and fixtures. The conventional approach on the other hand does take the block as a simulation premise. New method #2 includes compared to #1 additionally the mediation between fixtures. The results of both comparisons are displayed in Table 4.

Table 4. Comparison of computed standard deviation and measurement data on the basis of use-case one and two, dimension "*r*" in X-direction

Sixfold standard deviation [mm]	Conventional modelling	New approach #1	New approach #2	Measurement
Use-case one	0.73	0.62	0.53	0.36
Use-case two	0.87	0.68	0.68	0.42

The table shows that the measured standard deviation is way lower than the values the simulations suggest. Nevertheless the modified approaches get much closer to the real value than the conventional modelling does. For use-case two there is no difference between the simulation results of both new approaches, as mediation has no impact for the X-direction. The X-fixation is ensured by one hole-pin-combination, so no mediation can be performed.

The general divergence between measurement data and simulation output might be caused by imprecise input data. The modified approach focusses on the way of modelling. The quality of the input data remains the same compared to the conventional approach. To further close the gap between simulation and reality the refinement of the input parameters need to be improved. Here this implies a more exact representation of the jigs' and fixtures' inaccuracies.

5. Evaluation of findings

Starting with the evaluation of measurement data, this paper points out the impact of geo-stations on dimensional quality of assemblies. It is verified that processes like geo-welding do not compulsory have a negative influence on accuracy, but also can improve the same. This hypothesis is proven in detail with the help of three use cases.

Moreover the studied behavior in geo-stations necessitates diverse modelling of the joining process in CAT applications. Depending on the geometrical set-up and other boundary conditions, there are different impact factors which dominantly influence the assembly's accuracy. An approach to evaluate the configuration which is currently the subject of research, to classify it and to model it accordingly is presented. This can be achieved without computation intensive FEA simulation, but only by purposeful representation and selection of the modelling key aspects. Thereby a closer to reality representation of the positioning and joining processes is permitted.

6. Conclusion and perspective

The introduced approach is easily implementable on industrial applications. To be able to fully take advantage of the presented ideas, there are still some refinements required. The developed classification scheme needs to be applied on further use cases to conduct a fine tuning of this method.

Besides the modelling also the input data which represents the geo-stations needs to be modified. The stored tolerance values of the jigs and fixtures may no longer be based on the general specifications of geo-stations, but on continuous process control measurement. This way the real position of pins and clamps as wells as the pin's diameter could be taken into account. Though those tolerance values already are modified for the simulation of the use-cases, more exact representation is required. A further development could also spend efforts on improving the representation wear phenomena of the positioning elements.

References

[1] Stockinger A. Computer Aided Robust Design. Verknüpfung rechner–unterstützter Entwicklung und virtueller Fertigung als Baustein des Toleranzmanagements. PhD-Thesis, University of Erlangen-Nürnberg, Erlangen; 2010. pp. 20ff.

[2] Klein B. Prozessorientierte Statistische Tolerierung im Maschinen- und Fahrzeugbau. Renningen: Expert; 2011.

[3] Lustig R. Integration und Verarbeitung von Verformungsinformationen im Umfeld rechnerunterstützter Toleranzanalysen. PhD-Thesis, University of Erlangen-Nürnberg, VDI, Düsseldorf; 2008. pp. 1 ff.

[4] Hetsch K, Bohn M. Toleranzmanagement im Automobilbau. München: Hanser; 2013

[5] Chase KW, Magleby SP, Glancy CG. A Comprehensive System for Computer-Aided Tolerance Analysis of 2-D and 3-D Mechanical Assemblies. In: Geometric Design Tolerancing: Theories, Standards and Applications; 1998. pp. 294-307

[6] Wissing C. Analyse der Produktionsabläufe zur Prozessstreuungsquantifizierung. Master of Science-Thesis, Supervisor: Julius F. Klinger, Karlsruher Institut für Technologie, Karlsruhe; 2013.

[7] Voß R. Bewertung des Einflusses von Randbedingungen für eine Toleranzsimulation nachgiebiger Baugruppen im Karosserierohbau. 19. Symposium „Design for X", Neukirchen; 2008.

[8] Liu S, Lee H-W, Hu SJ. Variation simulation for deformable sheet metal assemblies using mechanistic models. Transactions of NAMRI/SME; 05/1995. pp. 235 - 241

[9] Ungemach G. Simulation toleranzbehafteter Karosseriestrukturen und deren virtuelle Qualitätsbeurteilung. PhD-Thesis, Helmut-Schmidt-Universität, Hamburg; 2009.