

Sensitivity analysis of several Body-in-White single part and assembly parameters using tolerance analysis

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Abstract:

In this contribution a method is shown which describes how to interlink product-/ and process-development information with an optimization tool. For the permitted range of the design parameters (input variables), a Design of Experiments is performed inside the optimization tool. To solve the calculated designs (calculating the deviations of the assembly – specific quality feature) a method for connecting tolerance analysis (solver) is regarded. The results are then displayed in the optimization environment and an optimization of the input parameters can be performed to reach certain quality requirements. For a better understanding of the described approach an application example for the automotive Body-in-White (BiW) sector is furthermore given.

The paper concludes with an outlook on future research topics e.g. how optimization results (changes in specific product-/ and process-development information) are infecting the design process during the product development.

Keywords: automotive product development, tolerance analysis, optimization, method development.

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1 Introduction

Nowadays, there is a strict competition between producing companies within the automotive industry. To satisfy the customers' needs it is important to offer a diversified product range. Thus, the number of derivatives of each car increases [1]. Competitive advantages can be reached by reducing the time to market of a new product, which means in the automotive industries a cut down in the products development time. One of the main contributors in realizing this cut down is a more intense IT-usage during the product development [2]. Thus, time consuming and expensive hardware prototype phases can be reduced despite the technical feasibility of the data.

Today's mass production environment requires assemblies to be built up with a specific dimensional accuracy, ensuring that the assembly is able to fulfill its functional requirements or that it can be assembled to higher-level assemblies. The manufacturing process of single parts always results in deviations of these parts and also the assembling process itself causes deviations, due to inaccuracies in the positioning of the parts (in the manufacturing plant), the joining process and elastic deformation, etc. [3].

In general, tolerance analysis is used to provide a restriction, in which tolerance range single parts are allowed to deviate, so that the functionality of the assembly is guaranteed. Certain information is needed to build up such a tolerance analysis model. This data can be divided into product data, such as part geometry and tolerance information, and process data, such as the assembly graph, jig and fixture concept, joining locations and measurement points. This information is necessary to define contact conditions, tolerances and measurements in tolerance simulation software as shown in figure 1. The build-up process of these tolerance simulation models in the automotive industry is time consuming and, due to human interaction, fault-prone.

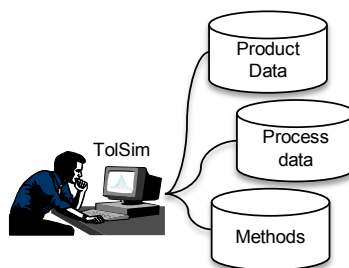


Figure 1 Current process to build-up tolerance simulation models

At present times, there are more than one hundred assemblies attached to a modern Body-in-White (BiW) structure which itself consists of several hundred parts. In order to ensure a manufacturability of the assemblies to the BiW structure in series production process an experienced tolerance planning engineer is required to develop adequate tolerance concepts. Regarding the multidimensional orientation of the tolerance chains in a BiW structure, it is not easy to find an optimal concept for attaching certain parts. Therefore, long-term experience is required. The usage of IT-tools is indispensable for helping the engineer in finding the right decision. To find the optimal solution, optimization tools can be used. The content of this paper is an approach showing how to interlink an optimization software to product-/ and production development data and to a CAT-simulation tool to perform sensitivity analysis on the simulations input parameters. Therefore, in the second chapter a

brief overview on the state of the art is given. The basic concept for an interlinkage is given in chapter three. Furthermore, a process integration of the approach in the automotive BiW sector is shown. Thereby, the concept was implemented for the first time using optiSLang (for the sensitivity analysis) and 3DCS (for the tolerance analysis). The paper closes with a conclusion and outlook on future research topics.

2 State of the art

Nowadays, in order to build up a tolerance simulation model in the automotive BiW industry certain information is required, as indicated earlier. Figure 2 shows how the different kinds of information are used to build up a tolerance analysis model.

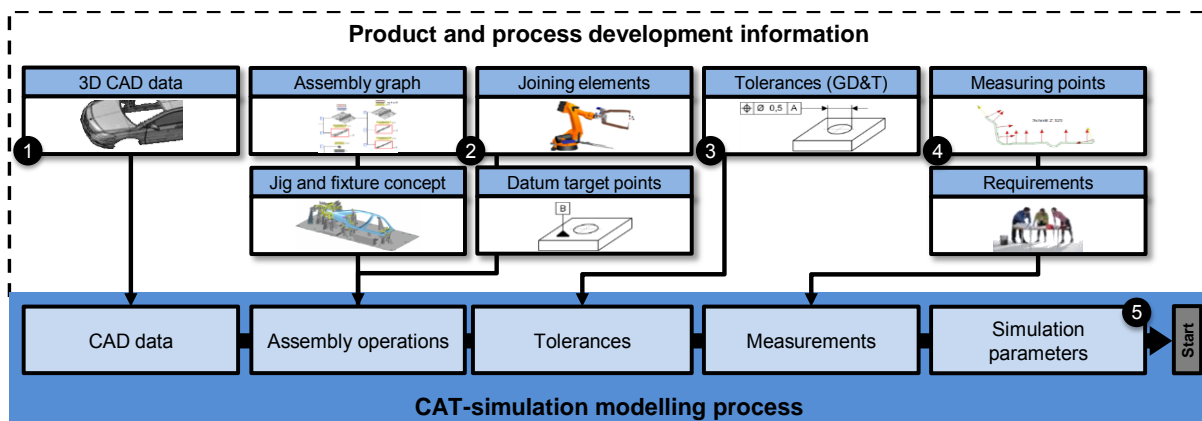


Figure 2 Dependencies of Product and Process information with regards to the CAT simulation model

CAD-geometry is first needed to display the deviations of and between parts (❶ in figure 2). Furthermore, to map the manufacturing process in the simulation model different kinds of information is used (see ❷ in figure 2). The assembly graph sets up the model tree in the simulation environment. Additionally, the assembly graph provides the logical order of assembling the parts. Thereof, the number of assembly operations is derived. Joining elements, jig and fixture layout and datum target points can be used to assign points to the assembly operations. The tolerance information of the single parts, which is created during the product development process, is directly transferred to the simulation model (❸ in figure 2). Also, additional tolerances caused by the manufacturing process (inaccuracies in the positioning process of the parts) are to be created in the simulation model. Measurement points are furthermore used to define the quality feature(s) in the tolerance simulation environment (closing dimension of the tolerance chain) (❹ in figure 2). The last step is to define several simulation parameters (❺ in figure 2). Afterwards, the simulation model can be executed.

Several quality features have to be fulfilled in the BiW automobile body manufacturing process to ensure a robust manufacturing process of the assembly. The different kinds of features can be divided into dimensional technical specifications and quality features at the outer skin of a vehicle. Example of the first kind of quality feature are all the technical connections to the BiW (e.g. the whole pattern for connecting the chassis). If these specifications are within the required tolerance range, a correct assembling process of the additional mounted parts to the BiW is guaranteed. The number of such measurements for

BiW is round about several hundred measurements. On the other hand, examples for the second type of quality feature are the gap and flushness measurements. Fulfilling these requirements ensures an aesthetical high quality product as well as a faultless function of the external parts (e.g. recesses for a correct door opening). The amount of these measurements is also round about several hundred features. Figure 3 shows the different types of quality features. [4]

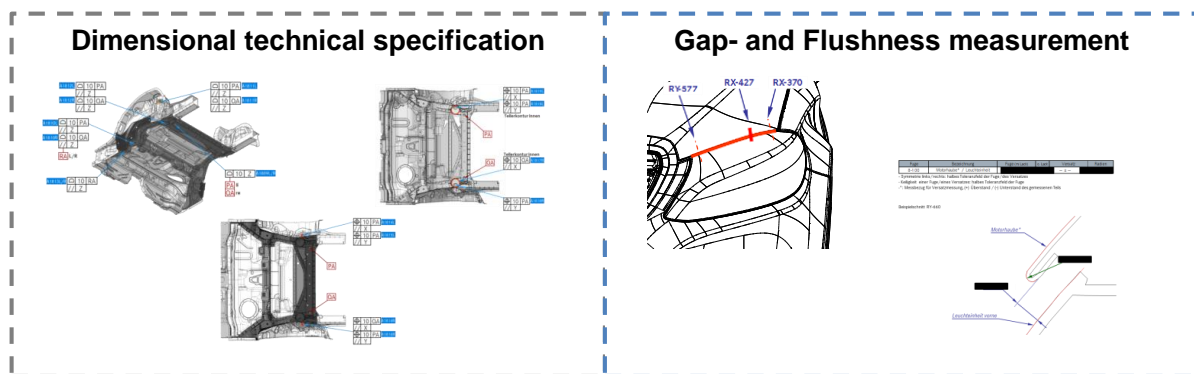


Figure 3 Different kinds of quality features in the automotive industry

As described in figure 1, all the different kinds of input parameters have to be brought to the tolerance simulation environment. Therefore, the software offers different kinds of interfaces which shall be described hereinafter.

As for importing the CAD geometry to the CAT environment, the existing tolerance simulation tools offer interfaces for the common data formats (e.g. *.step, *.iges, *.jt ...). Regarding the import of information for the build-up process of the simulation model (assembly operation information), the interfaces of the different software are not highly standardized. In this regard, each software manufacturer is developing its own solution. For example, the 3DCS Variation Analysis software offers the possibility to import and export moves, tolerances and measurements in a simple text file (MTM import function). Also, there is an interface to store the whole simulation model (containing CAD file path, assembly operation information, tolerances, measurements and simulation parameters) in an XML related format, whereas the software Variation Analysis offers the possibility to store the whole simulation model in a text based way (*.csv). These differences determine the extent at which an automated procedure can be achieved [5, 6]. In order to reach the automation of the tolerance simulation build-up process Ref. [7] mentions the need for a neutral exchange format like XML. This is why the focus of attention in this work regarding the tolerance simulation tasks is on the usage of the 3DCS software.

The development of adequate tolerance concepts for BiW can be supported by the usage of optimization tools as mentioned before. Therefore, in addition to the description of the interfaces of the tolerance simulation software it is also necessary to summarize the interfaces of the frequently used optimization tools with regards to a customized integration of and towards other tools. In Ref. [8] the three optimization tools LS-OPT, optiSLang and AutoForm-Sigma are compared with regards to the implementation of an optimization task. Thereby the openness of the program code is considered. Regarding the import of several input parameters the software LS-OPT offers an easy implementation of LS-DYNA projects and also extends to the inclusion of other simple ASCII files. Whereas the software solutions

ModeFrontier and optiSLang offer some script nodes which enable a customized integration of the optimization tool towards other disciplines based on their specific API [9, 10]. The required openness of the program code to realize the approach leads to a usage of one of these two software solutions. What also has to be mentioned is that the software 3DCS itself provides the possibility for a simple optimization. Thereby, two optimization possibilities are available. On the one hand a tolerance cost optimization is possible “[...] ... to achieve best quality at a minimum of costs.” Therefore the user can “[...] ... allocate the largest possible tolerance while still meeting dimensional objectives”. On the other hand, it is possible to perform a tolerance quality optimization where the quality will be optimized “[...] ... for a given fixed budget” [5].

For the interlinkage of the product and process development information (input data) and tolerance simulation model to the optimization tool a standardized exchange format is required. In Ref. [11] the authors presented the basic approach to interlink these three fields of engineering. In their approach the main exchange format between the fields of product data management and tolerance simulation is based on a XML database. An XML readability of the optimization tool is required to have a consistent exchange format between all the three disciplines. Thus, handing over the input parameters of the sensitivity analysis and the target features of the optimization task makes it necessary to create an input deck in the used software: optiSLang. Being a part of a more complex script, this deck is able to read the provided tolerance simulation XML, build an optiSLang project for the execution of a Sensitivity Analysis and finally perform an optimization using the results obtained from the Sensitivity Analysis. As part of this contribution this script is described in more detail.

Current tolerance optimization tasks mainly focus on the optimization of one of the input parameters of the tolerance simulation model shown in figure 2. For example the nominal dimension of a tolerated feature and its applied tolerance range. The basic method of simultaneous optimization of this parameter is given in Ref. [12]. Whilst Ref. [13, 14] extends this approach by considering manufacturing cost functions of the tolerated features. Ref. [15, 16] takes time-variant deviations of the system into account. There are also approaches existing which consider the optimization of the parts alignment concept. In Ref. [17] a general methodology is shown to evaluate assemblies in context of a robust and geometrical stability. Furthermore, Ref. [18] uses this approach to search for the optimal alignment concept with respect to the applied geometric tolerances. Basic engineering guidelines of robust design of fixture configurations are provided. Ref. [19] extends this approach by taking manual assembly complexity into account.

All the approaches have in common that they focus on a single input parameter shown in figure 2 used for the tolerance simulation model creation. As stated in Ref. [11], a main research question should be if there is a possibility for optimization several of the input parameters. Also, the author claims for a basic database carrying all these input parameters. As a logical continuation of the research the main focus of this contribution is a principal concept of linking the database towards an optimization tool. Moreover, an application example should be given to clarify the functionalities.

3 Proposed Approach

3.1 General Approach

Figure 4 shows the general approach of linking product and process data with the optimization software, therefore representing the methodology considered in Ref. [11]. A basic distinction can be done between the parameters of an optimization problem: whether they are continuous or discrete. Continuous design parameters can take nominal values in a certain range ($\mathbf{p}_{inf}, \mathbf{p}_{sup}$) and may carry deviations from this nominal value ($\mathbf{p} - \Delta\mathbf{p}_{lower}; \mathbf{p} + \Delta\mathbf{p}_{upper}$). Discrete design parameters, on the other hand, can only adopt specific values taken from a closed, finite set. The multiobjective optimization problem can be mathematically formulated as follows Ref. [20, 21]:

$$\min_{\mathbf{p} \in P} f(\mathbf{p}) \quad (1.a)$$

$$\text{over:} \quad \mathbf{P} = \{\mathbf{p}_{st}, \mathbf{p}_{dev}\} \quad (1b)$$

$$\text{subjected to:} \quad g_i(\mathbf{p}) \leq 0, \quad i = 1, 2, \dots, n$$

The definition of continuous design variables can be found in formula 1.c:

$$\mathbf{P}_{st} = \{\mathbf{p}_{st} \in \mathbb{R}^m | \mathbf{p}_{inf} \leq \mathbf{p} \leq \mathbf{p}_{sup}\} \quad (1.c)$$

Parameters carrying certain deviations are defined as follows:

$$\mathbf{P}_{dev} = \{\mathbf{p}_{dev} \in \mathbb{R}^m | \mathbf{p} - \Delta\mathbf{p}_{lower} \leq \mathbf{p} \leq \mathbf{p} + \Delta\mathbf{p}_{upper}\} \quad (1d)$$

where \mathbf{p} are the design parameters carrying upper and lower bounds ($\mathbf{p}_{inf}, \mathbf{p}_{sup}$) and m characterizes the dimension of the design space. g_i represents the i^{th} inequality constrain function. To find the Pareto optimal solutions of the equation means searching for a feasible point $\mathbf{p}^* \in \mathbb{R}^m$ ensuring there is no other feasible point $\mathbf{p} \in \mathbb{R}^m$ so that $\forall i, j; f_i(\mathbf{p}) \leq f_i(\mathbf{p}^*)$ with strict inequality in at least one condition, $f_j(\mathbf{p}) < f_j(\mathbf{p}^*)$. Single objective optimization problems ($m = 1$) have to satisfy the Karush-Kuhn-Tucker condition for the solution \mathbf{p}^* of the Pareto optimum as required in Ref. [21].

When considering a Robust Design Optimization (RDO), the goal is to obtain a solution which is robust against uncertainties on the design variables. The multiobjective optimization extends to stochastic variables (X) and is formulated as follows:

$$\min_{\mathbf{p} \in P} f(\mathbf{p}; X) \quad (1.e)$$

$$\min_{\mathbf{p} \in P} \Delta f(\mathbf{p}; X) \quad (1.f)$$

$$\Delta f = \max f(\mathbf{p}; X) - \min f(\mathbf{p}; X) \quad (1g)$$

$$\mathbf{p}_k \in \mathbf{S}, \quad \mathbf{S}^k = \{\mathbf{p}_k, j = 1 \dots J^{(k)}\}; \quad X_l \in \mathbf{S}, \quad \mathbf{S}^l = \{X_l, j = 1 \dots J^{(l)}\} \quad (1.h)$$

$$\text{subjected to:} \quad g_a(\mathbf{p}; X) + \Delta g_a(\mathbf{p}; X) \leq 0, \quad a = 1, 2, \dots, m \quad (1i)$$

where X is the stochastic variable, \mathbf{S} represents the Set of sampling points \mathbf{p}_k . g_a represents the a^{th} inequality constrain function. The stochastic variables can be expressed with

$$X \sim N(\boldsymbol{\mu}_X, \mathbf{Cov}_X) \quad (1.j)$$

where $\boldsymbol{\mu}_X$ characterizes the mean value and \mathbf{Cov}_X the covariance matrix of normal distributed uncertainties (N).

In the particular case of the BiW in an automobile body manufacturing process, the input parameters for a tolerance simulation and further optimization can be classified as shown in figure 4. The variation of the CAD-geometry (e.g. flange angle and dimension, ① in figure 4) is represented by a continuous design variable without deviation equal to formula 1c (e.g. $p_{CAD_{flange\ angle}}, p_{CAD_{flange\ size}}$). The assembly graph (② in figure 4) represents a discrete design variable having a finite number of characteristics

$p_{ASM} = [p_{ASM_1}, p_{ASM_2}, \dots, p_{ASM_l}]$, $l \in \mathbb{N}^+$. Additionally the design variables (③, ④, ⑤ in figure 4) jig and fixture concept, joining elements and datum target points are continuous and in this case without uncertain deviation ($p_{Jig}, p_{Join}, p_{Datum}$). For the Tolerances (⑥ in figure 4) on the other hand a deviation has to be considered (p_{Tol}) equal to formula 1d.

If additional uncertainties such as inaccuracies in the manufacturing process were to be considered, then stochastic variables (X) can be included in the system. Stochastic deviations in the jig and fixture (e.g. positioning inaccuracies of the parts) are represented by X_{JigPos} , deviations of the joining process (e.g. deviations of the weld gun accuracy due to clearance in the welding robots guidance) are characterized by $X_{JoinPos}$ and uncertainties of the alignment (e.g. wear of the manufacturing station) are represented by $X_{DatumPos}$. Different distribution types have to be considered regarding each specific stochastic variable (e.g. the influence of wear follows a trapezoidal distribution).

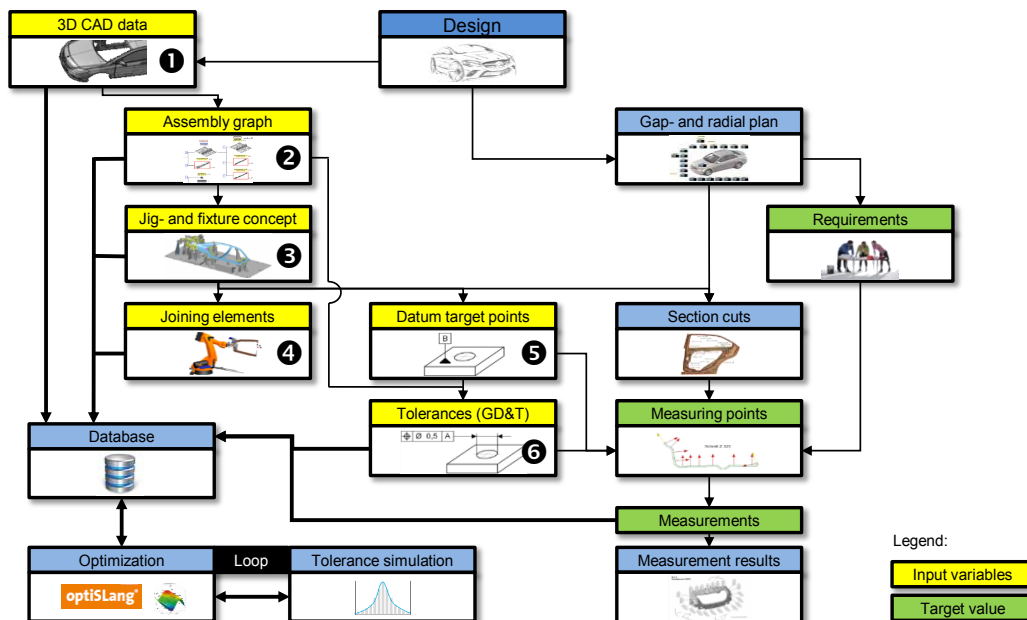


Figure 4 General Approach for sensitivity analysis of product and process information using tolerance simulations

Nowadays, solving an optimization task entails performing an initial sampling on the design variables in their set range. The first step is the creation of a predefined number of sample designs (r_k). The sampling method can be basically divided in two different approaches: deterministic Design of Experiments (deterministic DoE) and Stochastic Sampling. Ref [23] provides a brief overview of the different methods and explains their intended application. Advanced Latin Hypercube Sampling (ALHS) is to be employed in those cases with a high number of input variables but where the calculation of many samples is not possible because of high processing times. Moreover, a single-switch-method is available to reduce correlation errors. After the calculation of the selected samples, these are used as nodes to calculate a response surface covering the entire design space. Currently, the program optiSLang offers a response surface approach called Metamodel of Optimal Prognosis (MOP), which automatically searches for the best response surface technique according to the selected validation method. For the time being, the available techniques are Polynomial Least Squares

Regression (PLSR), Moving Least Squares (MLS) and ordinary Kriging. The resulting response surface is then used in the optimization problem.

The variation of the values of some design variables may have an effect on other design variables of the tolerance simulation model. In this case, variables such as CAD data, the assembly graph or the jig and fixture concept (❶, ❷ and ❸ in figure 4) have a significant influence in the values that other variables will take. For example, a change in the assembling order of different parts would lead to different layout concept as well as the redesign of joining elements, datum target points and tolerances. The repercussions of an assembly graph change would also extend to crash and welding gun simulations, among others. On the other hand, other design variables do not have such great consequences on other variables (❹, ❺ and ❻ in figure 4). For example, modifying datum target points or tolerances would have an effect only on the upper and lower measuring point specification limits (USL and LSL). In order to maintain a calculation effort at a manageable state, first, these design variables with a low impact on other variables are selected as modifiable.

In order to hand over the information to the optimization tool and to the tolerance simulation tool Ref [11] proposes the usage of a common database. The implementation of this general approach is regarded in more detail in the following chapter.

3.2 Process integration

First of all, the product and process information to build up a tolerance simulation model is exported from the PDM/CAD system to an external tool (❶ in figure 5) which represents the database and ensures further processing of the data.

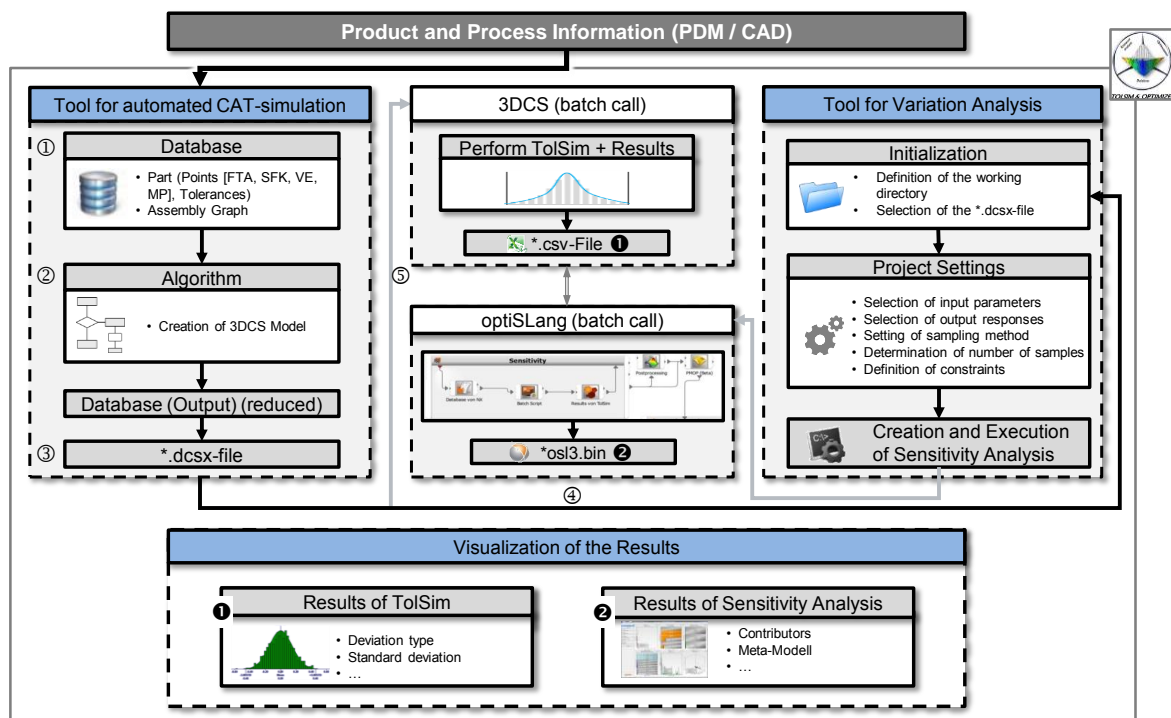


Figure 5 Implementation of the general approach in the automotive Body-in-White environment

enables the selection of the response parameters (e.g. standard deviation) for the sensitivity analysis by the user. Additionally, the tool offers the possibility to edit several parameters of the sensitivity analysis project (e.g. sampling method, number of samples, etc.).

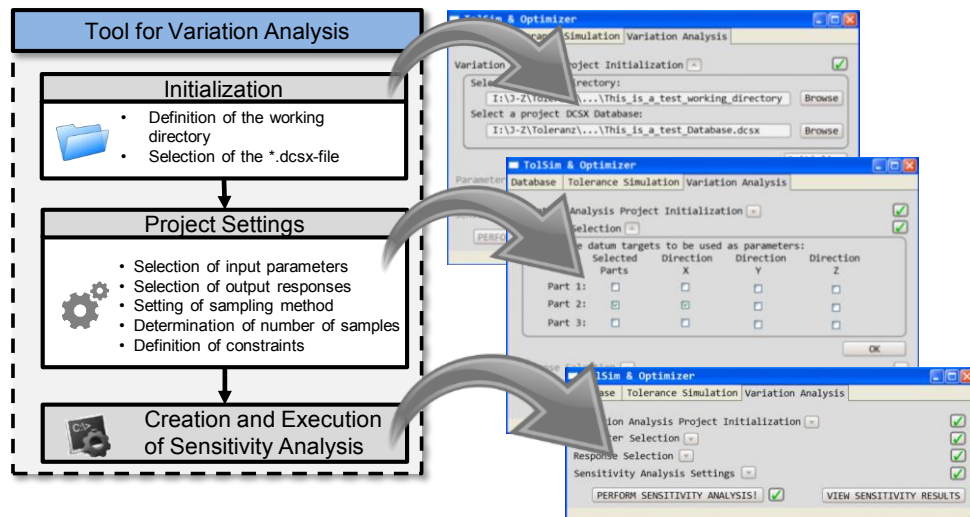


Figure 7 Required user settings to perform a sensitivity analysis

Once the settings for the sensitivity analysis have been input by the user through the GUI, the problem is ready to be run. By starting the analysis, the user calls for the execution of a *.cmd batch-script which is responsible for the control and coordination of all other sub-scripts and routines (see ① in figure 8).

Therein, first of all the several folders are created in the selected working directory. To enable a smooth interlinkage of the predefined user-input parameters towards the optimization tool, the specific information (datum target point coordinates, direction) is stored in a text file. With the help of a simple macro, a text file containing the simulation results is also created. The last step of the *.cmd is an optiSLang batch-call which then reads a python script which is responsible for the creation of the sensitivity analysis project (see ② in figure 8).

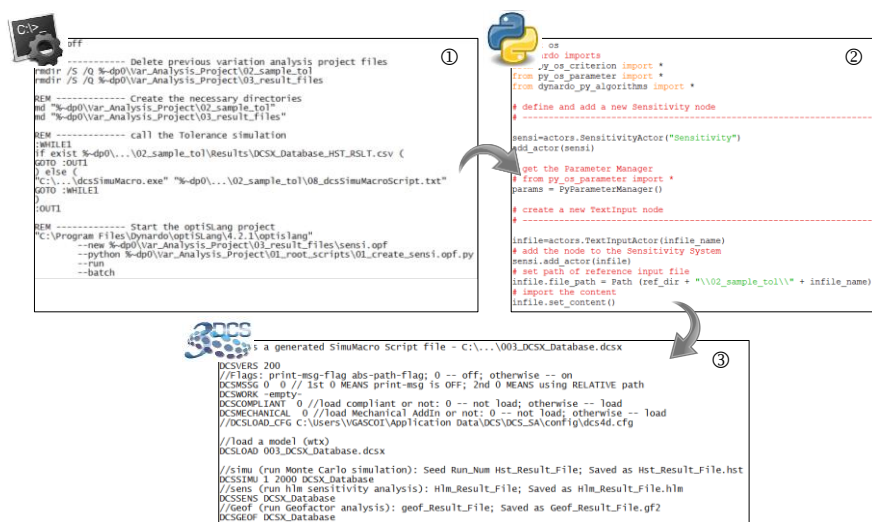


Figure 8 *.cmd call, Python script (creates optiSLang project), tolerance simulation batch call

Summarizing the tasks performed by the Python script, first, the parameters for the DoE are selected (sampling method, samples, range for the upper and lower bounds for the allowed deviation of the selected datum target points etc.). Then, the parametric system is created, which includes the input node (input.txt), the solver node (solver.bat) and the output node (output.txt). Afterwards, these nodes are completed: the input node is filled up with the information of the input text file created in the first step (①), the output node is handed the information of an example result text file and the solver node is assigned the commands in an external prepared batch file. Finally, the Post-Processor and MOP nodes are created and all the necessary connections are done.

The first step in the solver script (see ③ in figure 8) enables the usage of the input.txt file in the tolerance simulation environment. This file will later carry the modified coordinates for the datum target points for the DoE. Therefore, the information is included in the *.dcsx file. Thus, it is possible to perform a tolerance analysis with a slightly modified datum target system. For this matter, the tolerance analysis is batch-called. The resulting file of the specific design is stored afterwards in the specific design folder and subsequently translated to a text file to ensure usability in the output node of the optimization tool. Solving all the required designs makes it possible to create a MOP and study the sensitivity results.

4 Conclusion and Outlook

The considered approach to perform sensitivity analyses in several BiW single parts and assembly parameters with the help of tolerance analysis presents several possibilities. It is for example possible to perform HLM-analysis to find out the main contributors in a tolerance chain. Therefore, the tolerance range has to be set as an input parameter. The existing tools on the market already offer this calculation. The essential part and the unique feature of this approach in comparison to the state of the art is the easy way of considering more than one input variables (tolerances, joining information, jig and fixture concept, etc.) in a “tolerance sensitivity analysis”. Therefore, a common database which carries the required information in a system independent format (XML) is used. To avoid multidisciplinary system knowledge of a tolerance planning engineer a customized tool has been developed which enables tolerance analysis and optimization on a selected system (database) without deeper knowledge on the software involved. Once the user has defined the relevant input parameters for their sensitivity analysis and their maximum allowed deviation, the simulation model is handed over to the optimization software (XML related format). Therein, the set-up of the required sensitivity analysis is performed in batch mode using specifically developed scripts. The results of the sensitivity analysis are then transferred back into the customized tool.

It is therefore possible to perform a study of options in a very short amount of time. Different alignment concepts of parts can be considered to find the most robust solution regarding the quality features on a given set of parameters. Thus, a minimum in the deviation of the quality features in BiW (gap and flushness measurements, dimensional technical specifications) can be achieved. Future research might prove the feasibility of the methodical approach using a demonstrator which carries different kinds of input data.

5 Referenzen/Literaturangaben

- [1] Imhof T.: „Warum immer mehr Automodelle erfunden werden“
<http://www.welt.de/motor/article127300636/Warum-immer-mehr-Automodelle-erfunden-werden.html> [published 2015-04-07; last accessed 2015-12-17]
- [2] Backhaus R.: „Porsche Panamera: 16% weniger Entwicklungszeit dank Simulation.“
<http://www.atzonline.de/Aktuell/Nachrichten/1/8819/Porsche-Panamera-16-Prozent-weniger-Entwicklungszeit-dankSimulation.html>
[published: 2008-11-28; last accessed 2015-12-17]
- [3] Klein B.: Prozessorientierte Statistische Tolerierung im Maschinen- und Fahrzeugbau, Expert-Verlag, Renningen, 2011
- [4] Litwa F.: „Daimler AG – Virtuelle Produktenwicklung im Automobilbau: Fokus Toleranzmanagement, Digitale Fabrik.“, Vorlesung Universität des Saarlandes, Saarbrücken: Februar 2015
- [5] Dimensional Control Systems, Inc: Software Help Manual.3DCS Version 6.19.0.0.0; 1994-2010
- [6] Variation Analysis Systems: Software Help Manual. Visualization Mockup Version Teamcenter 11; 2015
- [7] Litwa F. et al: "Automated point-based tolerance analysis model creation for sheet metal parts", 13th CIRP Conference on Computer Aided Tolerancing 2014 b, Hangzhou, China
- [8] Gascó Claramut V. J.: "Robustheitsanalyse der relevanten Einflussfaktoren auf die Maßhaltigkeit gefertigter Pressteile", RWTH Aachen, Masterarbeit 2015
- [9] N. N.: " CAE-Prozessanbindung, CAE-Softwareintegration "
<http://www.dynardo.de/software/optislang/prozessintegration.html> [last accessed 2015-12-17]
- [10] N. N.: " Modelfrontier Integration Nodes "
<http://www.esteco.com/modelfrontier/modelfrontier-integration-nodes> [last accessed 2015-12-17]
- [11] Litwa F et al: Integrated Approach For Efficient Tolerance Optimization On Sheet Metal Parts. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. 20, Milan, Italy, 27.-30.07.2015
- [12] William Li, Wu C.F.J.: “An integrated method of parameter design and tolerance design”; Quality Engineering 1999, 11:3, 417-425
- [13] Jeang A., Chang C.-L.: “Concurrent Optimization of Parameter and Tolerance Design via Computer Simulation and Statistical Method” Springer-Verlag London; Journal of advanced manufacturing technology 2002. 19:442-447
- [14] Jeang A., Chang C.-L.: Combined Robust Parameter and Tolerance Design Using Orthogonal Arrays” Springer-Verlag London; Journal of advanced manufacturing technology 2002. 19:432-441
- [15] Walter M. et al: “Toleranz-Kosten-Optimierung bewegter Systeme mittels Partikelschwarm-Optimierung“, DfX Symposium 2014
- [16] Walter M. et al: “Least Cost Tolerance Allocation for Systems with time-variant Deviations”, 13th CIPR conference on Computer Aided Tolerancing
- [17] Soderberg R., Lindkvist L.: “Computer aided assembly robustness Evaluation”, Journal of Engineering Design, 10:2, 165-181, DOI: 10.1080/095448299261371
- [18] Moroni G. et al: “Robust design of fixture configurations”, 24th CIRP Design Conference, Procedia CIRP 21 (2014) 189-194

- [19] Rosenqvist M. et al: "Geometrical robustness analysis considering manual assembly complexity", 5th CIRP Conference on Assembly Technologies and Systems, Procedia Cirp 23 (2014) 98-103
- [20] Ubben P. T. et al: Robust Automotive Suspension Design Using Adaptive Response Surface Based Multi-Objective Optimization, 11th Weimarer Optimierungs- und Stochastiktag
- [21] Augusto O. B. et al: Multiobjective engineering design optimization problems a sensitivity analysis approach, Pesquisa Operacional, Vol 32(3): S. 575-596, Brazilian Operation Research Society 2012
- [22] Miettinen K.: Nonlinear Multiobjective Optimization, New York: Springer-Verlag 1998; ISBN 978-1-4615-5563-6
- [23] Will J., Most T.: Metamodell of Optimal Prognosis (MOP) – an Automatrix Approach for User Friendly Parameter Optimization," 6th Weimar Optimization and Stochastic Days, Weimar