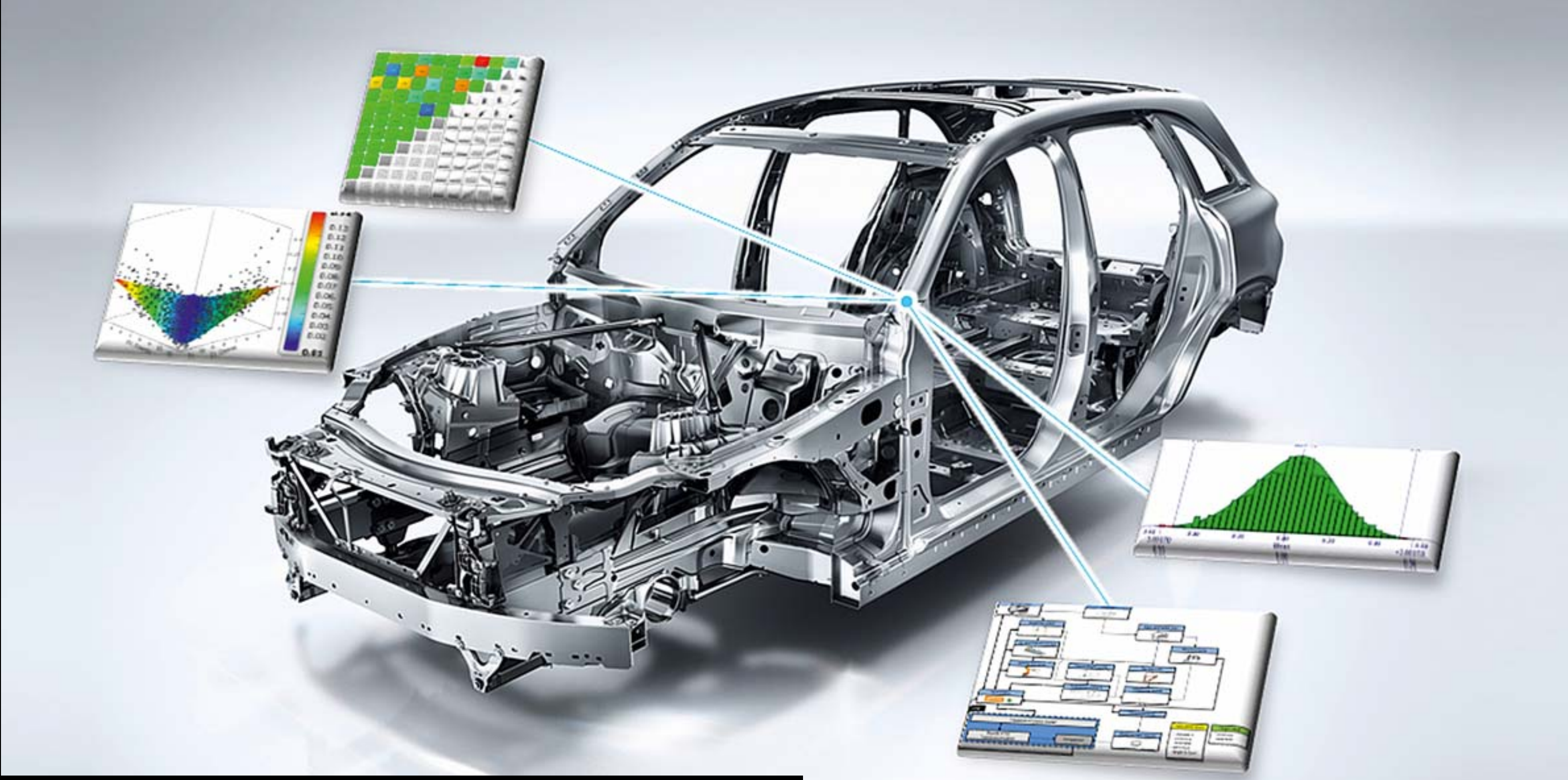

CUSTOMER STORY // AUTOMOTIVE INDUSTRY

SENSITIVITY ANALYSIS OF SEVERAL BODY-IN-WHITE PARAMETERS USING TOLERANCE ANALYSIS

In order to ensure the manufacturability of assemblies to the Body-in-White structure in car series production, optiSLang supports engineers at Daimler AG in the planning and developing of adequate tolerance concepts.

Introduction

Today's mass production environment requires assemblies to be built up with a specific dimensional accuracy, ensuring the fulfillment of functional requirements and their processability to a higher-level of assembly. The manufacturing of single parts always produces some deviations. The assembling process itself also causes inconsistency, for example, due to inaccuracies in the positioning of the parts at the manufacturing plant or in the joining process as well as due to elastic deformation.

Tolerance analysis generally provides ranges, in which single parts are allowed to deviate, thus, the functionality of the assembly is still guaranteed. It needs certain information to build up such a tolerance analysis model properly. A distinction can be drawn here between product data, such as part geometry and tolerance information, as well as process data, for instance the assembly graph, jig and fixture concept, joining locations or measurement points. This information is necessary to define contact conditions, ranges and measurements with the help of tolerance simulation software. In the automotive industry, the build-up process of these tolerance simulation models is time consuming and, due to human interaction, fault-prone.
Today, more than one hundred assemblies are attached to a sophisticated Body-in-White (BiW) structure, which itself already consists of several hundred parts. In order to ensure a manufacturability of the assemblies to the BiW structure in series production, experienced engineers are required for planning and developing adequate tolerance concepts. Regarding the multidimensional orientation of the tolerance chains in a BiW structure, it is a challenge to find an optimal concept for attaching certain parts. Beside long-term experience, the usage of IT-tools is indispensable for helping the engineer in making the right decision. This article will explain an approach how to interlink optimization software, product and production development data as well as CAT-simulation tools in order to conduct a sensitivity analysis on simulation input parameters. Furthermore, it will be shown how this approach can be integrated in the process of the automotive BiW sector. The concept was firstly implemented by using the software optiSLang for the sensitivity analysis and 3DCS for the tolerance analysis.

State of the art

Fig. 1 shows how the different kinds of information are used to build up a tolerance analysis model. First of all, a CAD-ge-

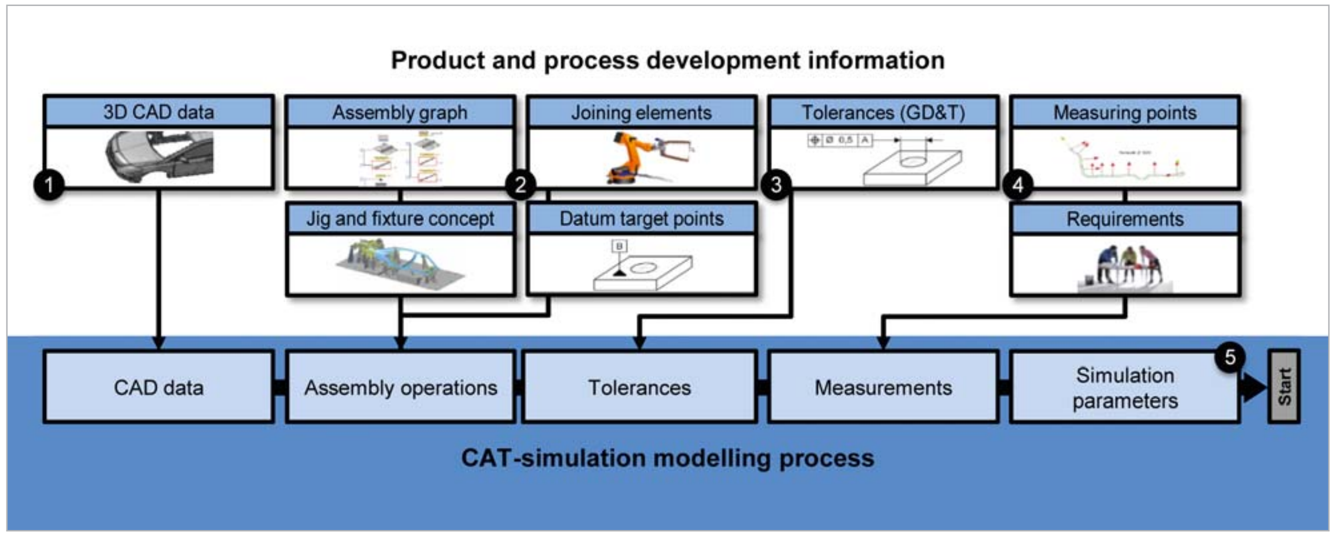

Fig. 1: Dependencies of product and process information with regard to the CAT simulation model

ometry is needed to display the deviations of and between the parts (refer to 1 in Fig. 1). Furthermore, different kinds of information are used to map the manufacturing process in the simulation model (refer to 2 in Fig.1). The assembly graph sets up the model tree in the simulation environment. It additionally provides the logical order of part assembling and, thereof, the engineer can derive the number of assembly operations. In order to assign points to the assembly operations, joining elements, jig layouts, fixture layout and datum target points are used. The tolerance information of the single parts, which is created during the product development process, is directly transferred to the simulation model (refer to 3 in Fig.1). Also, additional tolerances caused by the manufacturing process, such as inaccuracies in the positioning process of the parts, will be considered in the simulation model. Measurement points are furthermore used to define the quality features in the tolerance simulation environment as a closing dimension of the tolerance chain (refer to 4 in Fig.1). The last step is to define several simulation parameters (refer to 5 in Fig.1). Afterwards, the simulation model is ready for application.

Several quality features have to be fulfilled in the BiW manufacturing process to ensure a robust manufacturing of the assembly. They can be divided into dimensional technical specifications and quality features at the outer skin of a vehicle. Examples of the first type are all technical connections to the BiW, for example the whole pattern for connecting the chassis. If these specifications do not violate the required tolerance ranges, a correct assembling process of the additional mounted parts to the BiW will be guaranteed. Examples for the second type of quality features 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 number of both types of quality features sum up to several hundred measurements. Fig.2 shows sample drawings of the two different categories.

In order to reach a high level of automation during the build-up process of tolerance simulation and the import of the required information to the CAT environment, a neutral exchange format like XML is needed. In this project, 3DCS

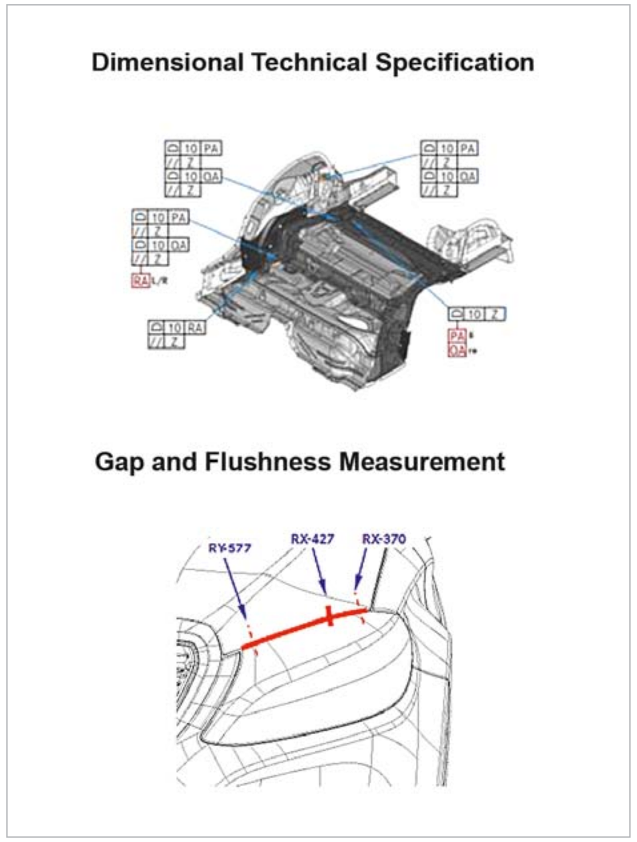

Fig. 2: Different kinds of quality features in the automotive industry

software was chosen to fulfill this precondition. The tool also provides basic functionality for an optimization. There are two optimization possibilities available for the procedure. On the one hand, a tolerance cost optimization is possible

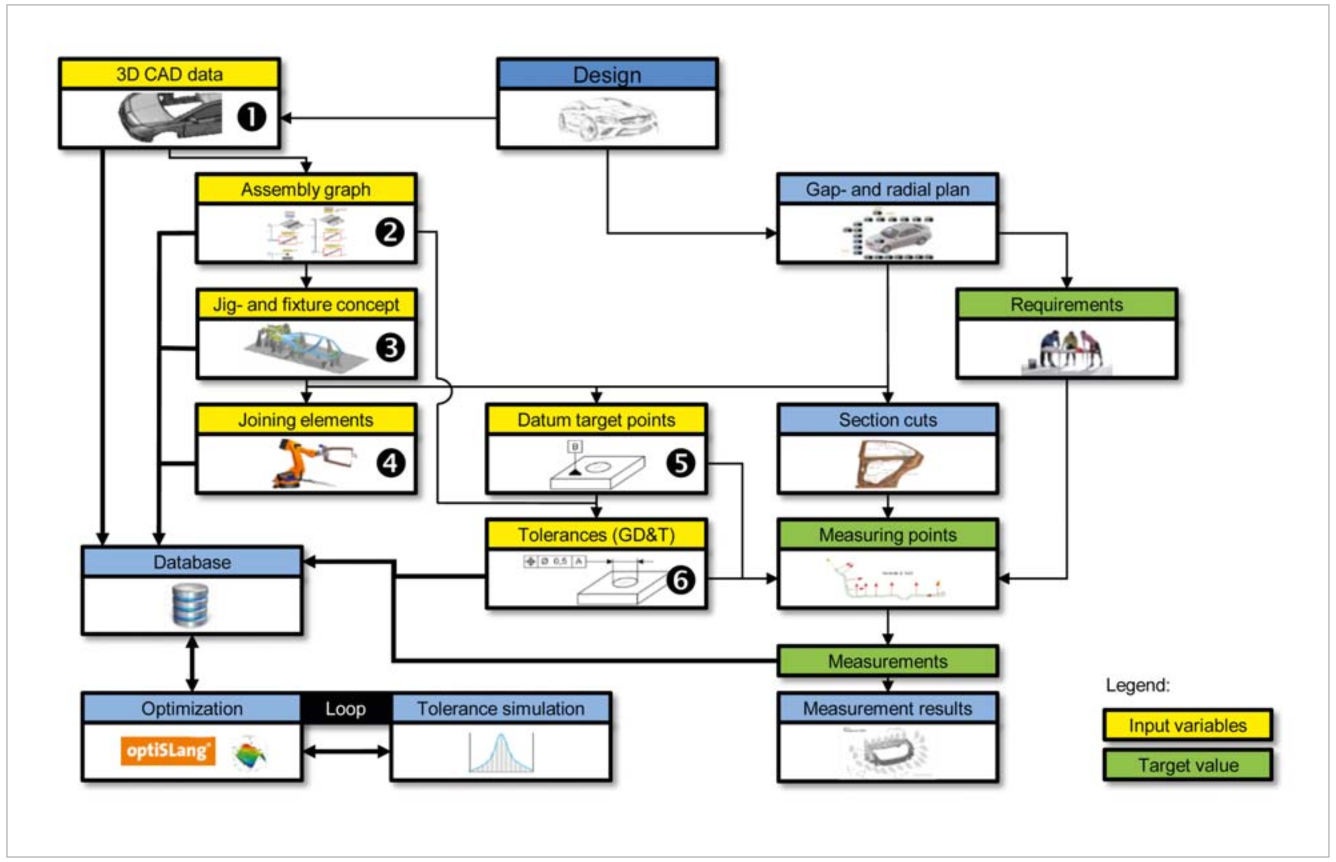

Fig. 3: General approach for a sensitivity analysis of product and process information using tolerance simulations

to achieve best quality at a minimum of costs. The user can allocate the largest possible tolerance while still meeting dimensional objectives. On the other hand, a tolerance quality optimization could be performed where the quality would be optimized for a given fixed budget.

Hence the development of adequate tolerance concepts for BiW can furthermore be supported by the usage of optimization tools. The software platforms LS-OPT, optiSLang and AutoForm-Sigma were compared with regard to the optimization task. Thereby, the degree of openness of the program code was a major focus. Regarding the import of several input parameters, the software LS-OPT offers an easy implementation of LS-DYNA projects and can also be extended to the inclusion of other simple ASCII files. The software solutions ModeFrontier and optiSLang, on the contrary, offer some script nodes which enable a customized integration of the optimization tool towards other disciplines based on their specific Application-Programming-Interface (API). Here, the software optiSLang was chosen for application.

For the interlinkage of the product and process development information (input data), as well as the tolerance simulation model to the optimization tool, a standardized exchange format is required. Since the main exchange format is based on an XML database, the optimization tool has to provide absolute readability of this format to secure a consistent exchange between all the 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. This script will be described in detail later in this article.

What the approaches in literature have in common are to focus only on a single input parameter used for optimization .Consequently, a main research question is to find a possibility for the optimization of several input parameters. There is also a need for a basic database capable of processing all these input parameters. Thus, the main focus of this project is a principal concept of linking the database towards an optimization tool. An application example will be given here to clarify these functionalities.

Proposed Approach

General Approach

Fig. 3 shows the general approach of linking product and process data with the optimization software. A basic distinction between the parameters of an optimization problem is whether they are continuous or discrete. Continuous design parameters can take nominal values in a certain range ($\boldsymbol{p}_{inf}, \boldsymbol{p}_{sup}$) and may carry deviations from this nominal value ($\boldsymbol{p} - \Delta\boldsymbol{p}_{lower}; \boldsymbol{p} - \Delta\boldsymbol{p}_{upper}$). Discrete design parameters, on the other hand, can only adopt specific values taken from a closed, finite set. The multi-objective optimization problem can be mathematically formulated as follows:

$$\min_{\boldsymbol{p} \in P} f(\boldsymbol{p}) \tag{1a}$$

over: $$\boldsymbol{P} = \{\boldsymbol{p}_{st}, \boldsymbol{p}_{dev}\} \tag{1b}$$

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

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

$$\boldsymbol{P}_{st} = \{\boldsymbol{p}_{st} \in \mathbb{R}^m | \boldsymbol{p}_{inf} \leq \boldsymbol{p} \leq \boldsymbol{p}_{sup}\} \tag{1c}$$

Parameters carrying certain deviations are defined as follows:

$$\boldsymbol{P}_{dev} = \{\boldsymbol{p}_{dev} \in \mathbb{R}^m | \boldsymbol{p} - \Delta\boldsymbol{p}_{lower} \leq \boldsymbol{p} \leq \boldsymbol{p} + \Delta\boldsymbol{p}_{upper}\} \tag{1d}$$

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

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

$$\min_{\boldsymbol{p} \in P} f(\boldsymbol{p}; \boldsymbol{X}) \tag{1e}$$

$$\min_{\boldsymbol{p} \in P} \Delta f(\boldsymbol{p}; \boldsymbol{X}) \tag{1f}$$

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

$$p_k \in \boldsymbol{S}, \quad \boldsymbol{S}^k = \{\boldsymbol{p}_k, j = 1 \dots J^{(k)}\}; \quad X_l \in \boldsymbol{S}, \quad \boldsymbol{S}^l = \{\boldsymbol{X}_l, j = 1 \dots J^{(l)}\} \tag{1h}$$

subjected to:

$$g_a(\boldsymbol{p}; \boldsymbol{X}) + \Delta g_a(\boldsymbol{p}; \boldsymbol{X}) \leq 0, \ a = 1, 2, \dots, m \tag{1i}$$

where X is the stochastic variable, $\boldsymbol{S}$ represents the Set of sampling points $\boldsymbol{p}_k$. g_a represents the ath inequality constrain function.

The stochastic variables can be expressed with

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

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 during an automobile body manufacturing process, the input parameters for a tolerance simulation and further optimization can be classified as shown in Fig. 3. The variation of the CAD-geometry, e.g. flange angle and dimension (see 1 in Fig.3), 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 (see 2 in Fig.3) 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 (see 3,4,5 in Fig. 3) jig and fixture concept, joining elements as well as datum target points are continuous and, in this case, without uncertain deviation ($p_{Jig}, p_{Join}, p_{Datum}$). For the tolerances (see 6 in Fig. 3), on the other hand, a deviation has to be considered (p_{Tol}) equal to formula 1d.

Additional uncertainties, such as inaccuracies in the manufacturing process, can be considered by including stochastic variables ($\boldsymbol{X}$) in the system. Stochastic deviations in the jig and fixture, e.g. positioning inaccuracies of the parts, are represented by $\boldsymbol{X}_{Jig_{Pos}}$. Deviations of the joining process, for instance deviations of the weld gun accuracy due to the clearance in the welding robot guidance, are characterized by $\boldsymbol{X}_{Join_{Pos}}$. Uncertainties of the alignment, e.g. wear of the manufacturing station, are represented by $\boldsymbol{X}_{Datum_{Pos}}$. Different distribution types have to be considered regarding each specific stochastic variable, for example, the influence of wear follows a trapezoidal distribution.

Nowadays, solving an optimization task entails the performance of an initial sampling on the design variables in their set range. The first step is the creation of a predefined number of sample designs ($\boldsymbol{r}_k$). The sampling method can basically be divided in two different approaches: deterministic Design of Experiments (DoE) and stochastic sampling. In cases where a high number of input variables are involved causing an unjustifiable amount of processing times, an Advanced Latin Hypercube Sampling (ALHS) should be employed. Moreover, there is also a single-switch-method available to reduce correlation errors. After the calculation of the selected samples, the results are used as nodes to calculate a response surface covering the entire design space. The program optiSLang offers a response surface approach named Metamodel of Optimal Prognosis (MOP), which automatically searches for the best response surface technique according to the selected validation method. Other 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.

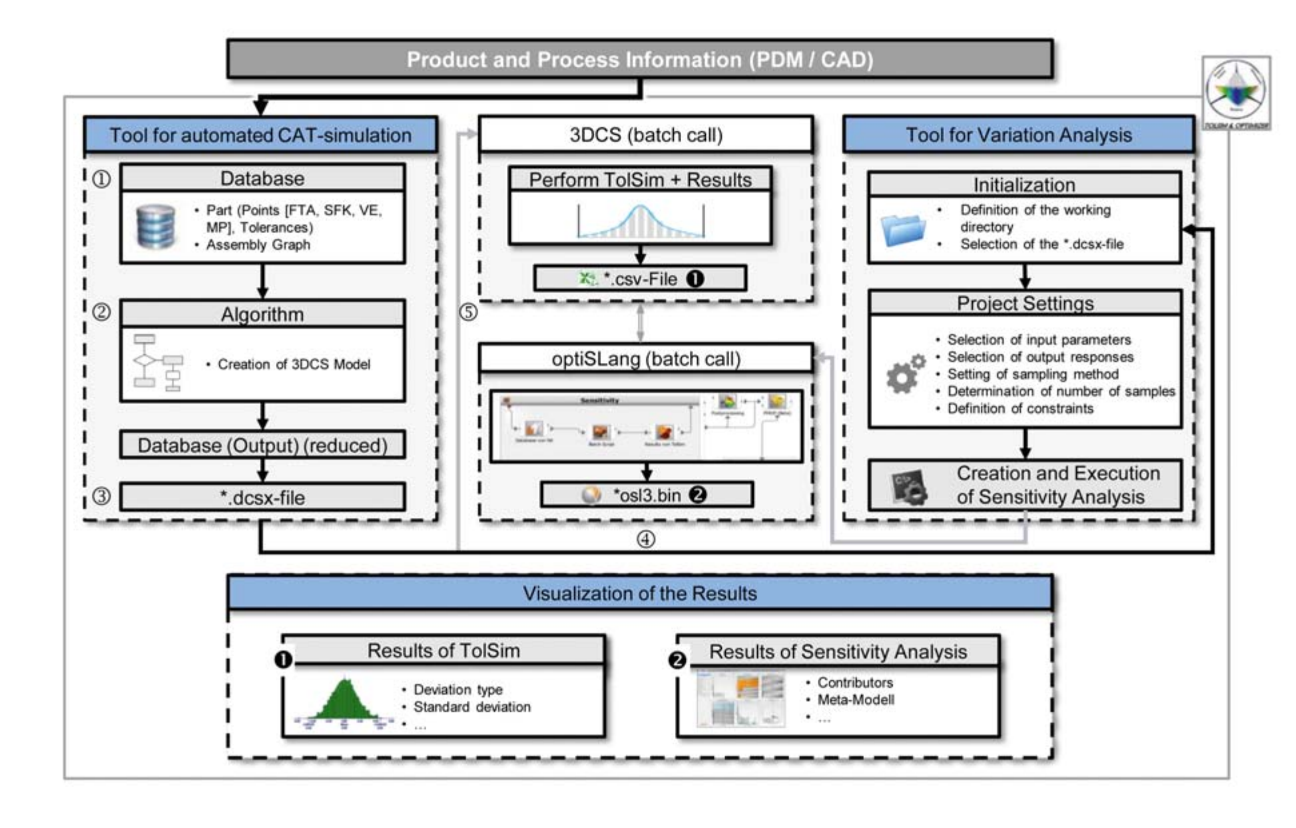

Fig.4: Implementation of the general approach in the automotive Body-in-White environment

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 (see 1,2,3 in Fig. 3), have a significant influence on the values of other variables. For example, a change in the assembling order of different parts or the redesign of joining elements, datum target points and tolerances would lead to different layout concepts. The repercussions of a changed assembly graph would also influence, among others, the crash and welding gun simulations. On the other hand, other design variables do not have such great consequences on other variables (see 4,5,6 in Fig.3). For instance, modifying datum target points or tolerances would only have an effect on the upper and lower measuring point specification limits (USL and LSL). In order to maintain the calculation effort at a manageable state, these design variables having a low impact on other variables were firstly classified as modifiable. The usage of a common database was proposed in order to hand over the information to the optimization tool and to the tolerance simulation tool. The implementation of this general approach will be clarified in more detailed in the following chapter.

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 (see 1 in Fig.4), which represents the database and ensures further processing of the data.

The regarded CAD system, Siemens NX, provides an API called NX Open. Using this API enables an access to specific information stored in the CAD model. Thereby, the API provides a standardized communication code where the user can select the preferred programming language. Fig. 5 shows an example of the data access using NX Open and the GUI for a derived database.

In the next step, the information of the database is used to create a tolerance simulation model. For this reason, the data is reduced and appropriately structured with the help of a specially developed algorithm (see 2 in Fig.4). As a result, the restructured information can be exported to the tolerance simulation model. In this application, an XML based DCSX format was used for export (see 3 in Fig.4). This format can be imported directly in the tolerance simulation environment to run a tolerance analysis.

In this project, the reduced XML format is used for a sensitivity analysis being performed based on the input parameters of the tolerance simulation. The external tool shown in Fig.6 hands over the XML information to the variation analysis section (see 4 in Fig.4). In this example, a variation of the datum target system of the parts is conducted. Thereby, the objective is to Figure out which is the alignment concept leading to a minimum deviation in a gap and flushness measurement. To register the datum target points as an input parameter, the reduced XML is parsed. The different datum target points of the parts are listed and the user is then able to select the parameters which are allowed to be modified in the sensitivity analysis (see Fig.6). Furthermore, the reduced XML format is used to perform a first tolerance analysis on the "start design" of the variation analysis project. The tolerance analysis software 3DCS is therefore batch called (see 5 in Fig.4). Afterwards, the resulting file of this analysis, carrying the required gap and flushness measurements, is imported by the external tool. This enables the user to select the response parameters, e.g. standard deviation, for the sensitivity analysis. Additionally, the tool offers the possibility to edit several parameters of the sensitivity analysis project, e.g. sampling method, number of samples, etc..

Once the user has defined the settings for the sensitivity analysis through the GUI, the script can be run to solve the optimization task. 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 Fig.7).

Taking that into consideration, several folders are firstly created in the selected working directory. To enable a smooth interlinkage of the predefined user-input parameters towards the optimization tool, the specific information, for example, datum target point coordinates and 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 for the creation of the sensitivity analysis project (see 2 in Fig.7 on previous page).

Summarizing the tasks performed by the Python script, the parameters for the DoE are selected first, like 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 with the information of the input text file created in the first step (see 1 in Fig.7 on previous page), 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 completed. The first step in the solver script (see 3 in Fig.7 on previous page) 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 an MOP and study the sensitivity results.

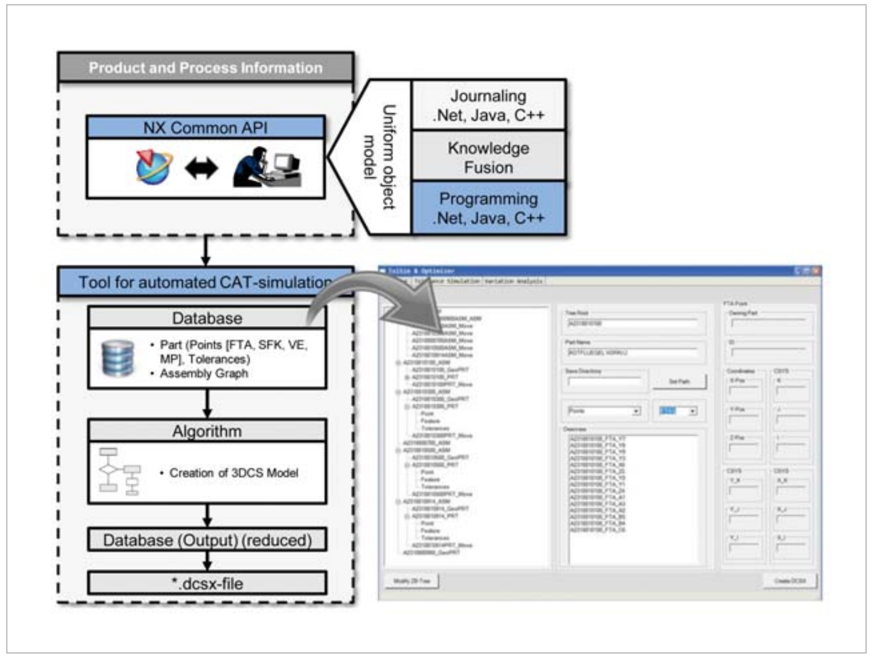

Fig. 5: Product and production data access using NX-Open and storage of the data using an external tool

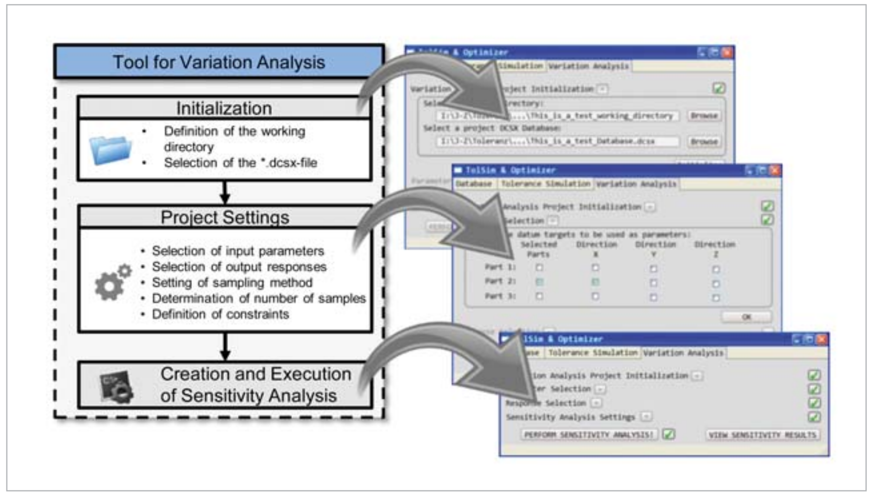

Fig.6: Required user settings to perform a sensitivity analysis

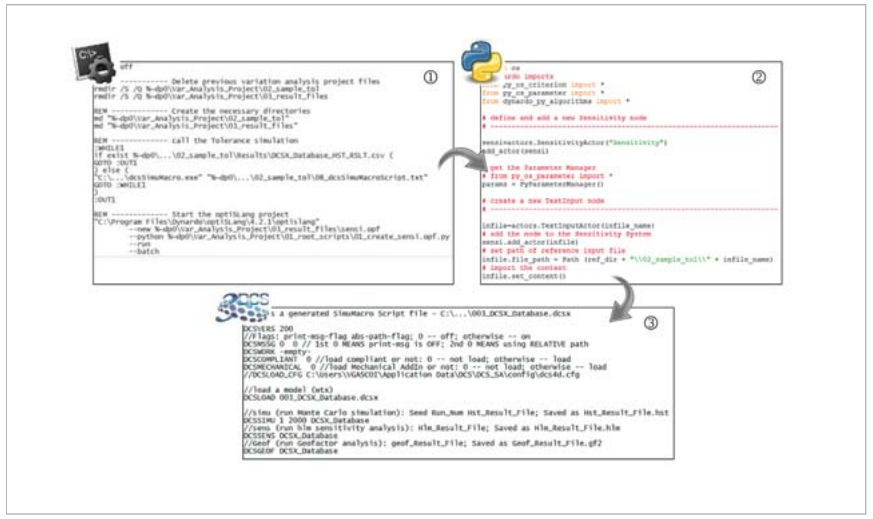

Fig.7 *.cmd call, the Python script creates optiSLang project, the tolerance simulation in batch call

Conclusion and Outlook

The considered approach to perform sensitivity analyses in several BiW single parts and assembly parameters with the help of tolerance analysis opens several opportunities. It is, for example, possible to perform an HLM-analysis to Figure out the main affecting 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 functionality. The essential part and the unique feature of this approach is an easy way of considering more than one input variable in a tolerance sensitivity analysis, for example, tolerances, joining information, jig and fixture concept, etc.. A common database achieves this by processing the required information in a system independent format (XML). With this customized tool, engineers can run tolerance analysis and optimization on a selected system (database) without deeper knowledge of the multidisciplinary system or the involved software. Once the user has defined the relevant input parameters for a sensitivity analysis and its maximum allowed deviation, the simulation model is simply handed over to the optimization software using the XML related format. In that respect, 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. Thus, a study of options can be conducted in a very short amount of time. Different alignment concepts of parts are considered to find the most robust solution regarding the quality features on a given set of parameters. The deviation of the quality features will be minimized in BiW (gap and flushness measurements, dimensional technical specifications). Future research might prove the feasibility of the methodical approach using a demonstrator which carries different kinds of input data.

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