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Title Story // optiSLang® for ANSYS®

Understanding the Acoustic Behavior of Electrical Drives

Optimization of Crash Relevant Vehicle Structures

Evaluation of Scattering Parameters in Joining Technologies

Optimization and Robustness Analysis in Ship Design

RDO-JOURNAL

optiSLang

multiPlas

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OPTISLANG® VERSION 4 – EASY AND FLEXIBLE TO USE

The development of optiSLang v4 was strongly influenced by the question: How can efficient CAE-based Robust Design Optimization (RDO) be easily implemented into daily procedures of virtual product development?

The new version optiSLang 4 enables every engineer and designer dealing with CAD/CAE models to perform drag and drop RDO workflows. The automated generation of an interactive process chain using the optiSLang modules of sensitivity analysis, optimization and robustness evaluation is now possible with an absolute minimum amount of user input, such as parameter limits, objective functions or constraints. The software automatically filters the most important parameters and evaluates the prognosis quality of the response variation with the help of meta models. A best practice management chooses, accordingly to the specific RDO task, an optimization strategy with the most effective algorithms. The new graphical user interface is designed to back up this workflow approach. In addition, the software supports direct access to parametric modeling CAE environments like ANSYS or SimulationX as well as to programming environments like EXCEL, MATLAB or Phyton.

From ANSYS Workbench version 14.0, optiSLang inside ANSYS Workbench provides the full integration of functionality inside the parametric modeling environment of ANSYS. Complex parametric studies can be easily conducted with drag and drop functionality without leaving ANSYS Workbench. Thus, an integrated modular RDO workflow can be implemented to shorten product development phases, secure optimal product properties and, at the same time, ensure the reliability and robustness requirements.

This software project would not have been possible without users who have continually driven forward the development with their practical applications as well as without partners like CADFEM or the support program of ANSYS Inc.. I would like to say thank you to them.

The second issue of our RDO-Journal will inform you again about interesting case studies from various economic fields promoting state-of-the-art methodology in CAE-based Robust Design Optimization. I hope you will enjoy reading our magazine.

Yours sincerely

Johannes Will, Managing Director Dynardo GmbH

Weimar, June 2013

CONTENT

INSIDE

OPTISLANG® FOR ANSYS®

A standard introduction of CAE-based Robust Design Optimization (RDO) in virtual product development places high demands on process automation, parametric models and algorithmic efficiency as well as operating reliability. Algorithm wizards and user guidance by best practice modular workflows make optiSLang version 4 an easy and flexible to use software tool for RDO projects.

State-of-the-art algorithms

For the last 10 year, optiSLang has been established as a multi-purpose toolbox for CAE-based RDO. During the initial development phase of the software, the focus was concentrated on improving the functionality and efficiency of the underlying algorithms necessary to conduct a sensitivity analysis, optimization or robustness evaluation. The goal was to make the user capable of dealing with large numbers of variables using any nonlinear CAE-solver. With the innovative technology of the Metamodel of Optimal Prognosis (MoP) and improved algorithms, challenging RDO tasks can now be efficiently solved.

Parametric modeling

However, it also became obvious that for a standard introduction of RDO, some more barriers have to be overcome. First of all, the availability and generation of suitable CAE parametric model is a key requirement. Here, the ANSYS Workbench has been established as one of the most powerful parametric modeling environments including bidirectional interfaces to major CAD programs and being capable of collecting all available CAE and CAD data in a central parameter manager.

Process integration and automation

Consequently, the system integration, process automation and job control, which represented further barriers, were also integrated into ANSYS Workbench to update one or multiple designs from the parameter manager. At the same time, users asked us to improve our optiSLang functionality of process integration and process automation. In this context, we decided to develop a direct integration of optiSLang into parametric modeling environments with the same priority as the integration of external CAE-codes into optiSLang's process automation functionality. To reach this goal, optiSLang was recoded from scratch and all optiSLang functionality was designed using C++ code with related interfaces which can be used by optiSLang`s GUI the same way as inside third party modeling environments. The first result of this concept was the release of the new optiSLang version 4 inside ANSYS Workbench in 2011. In 2012, we released the stand-alone optiSLang GUI version 4 providing enhanced functionalities in process integration and automation. The new graphical user interface supports the file based process integration, the direct access to parametric modeling CAE environments like ANSYS or SimulationX as well as to programming environments like EXCEL, MATLAB or Phyton.

For ANSYS Workbench users, the decision to use the integrated optiSLang version or to integrate ANSYS workbench into optiSLang is driven by the availability of all necessary input and output parameters in the ANSYS Workbench parameter manager. If all parameters are available, optiSLang inside ANSYS Workbench is the best solution. If input or output parameters have to be added, the integration of ANSYS Workbench projects into optiSLang and the extension of parameter and process workflows using optiSLang process integration functionality is the solution to solve an RDO problem. For integration of ANSYS Workbench projects, the Integration node as well as the file base communication via optiPlug functionality is available. Thus, optiSLang's functionality of signal processing is included and the CAE workflow can be expanded by additional solvers or pre and post processing tools .

Best practice modules

However, parametric modeling, process automation and integration are just prerequisites before we can start solving an RDO task. To achieve a regular, daily use of tools like optiSLang, we cannot expect every user to be a specialist in defining algorithmic settings and workflows. Therefore, a state-of-the-art optimization software has to provide best practice algorithms with best available defaults and wizard guidance. Furthermore, a modular usage of a sensitivity analysis, optimization or robustness evaluation has to be possible. We think that multi-purpose optimization toolboxes like optiSLang have to be capable of facing this type of paradigm shift just in the same way general purpose FEM systems did 20 years ago. In that time, experts carefully designed their meshes and programmed the FEM solution procedure as well as the post processing. The broad use of FEM in today's virtual prototyping was only possible after modules like "mesh" and "solve" became available where algorithmic innovations are applied and best practice solution are conducted. The necessary input has to be minimized and users are safely guided to perform their engineering task. In accordance to these requests, optiSLang provides three modules for best practice RDO algorithms and workflows:

1. **sensitivity analysis** to understand the design, to reduce parameter to the most important ones, to check forecast quality of response variation and to automatically generate the best possible meta model
2. **optimization** to improve design performance
3. **robustness evaluation** to check design robustness exposed to scattering material parameter, production tolerances or scattering environmental conditions

As a consequence, in optiSLang inside ANSYS, the 3 modules can be applied with drag and drop onto the scenery of the project page (see figure 1). With these modules, the user input is reduced to an absolute minimum amount, which is the setting of parameter ranges, scatter, constraints and objectives (see figure 2,3). All algorithm settings are generated with best practice defaults and a wizard guided modular workflow. Within the optimization modules, algorithms are available choosing the most efficient and fitting optimization strategy on the basis of the sensitivity analysis and user input (see figure 4).

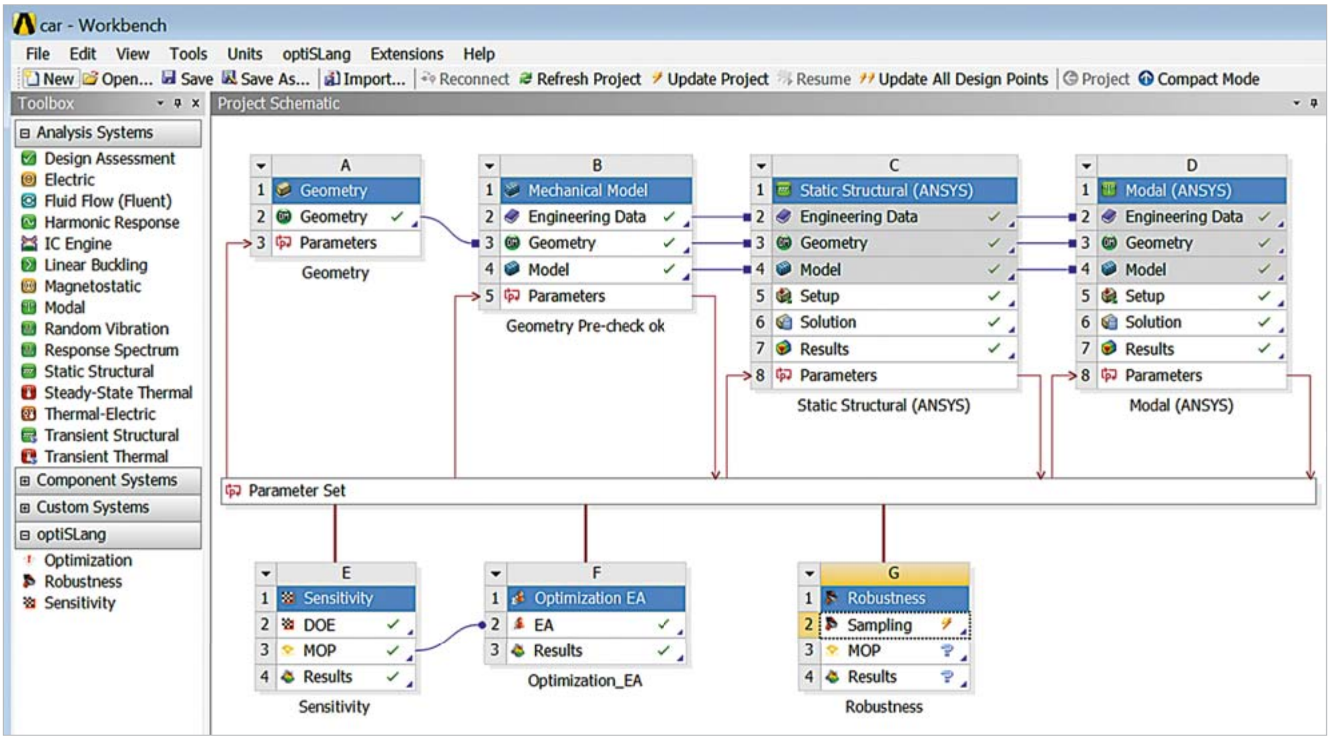


Fig. 1: screen shot of an ANSYS Workbench project page showing the three optiSLang drag and drop modules used to define and RDO application using sensitivity analysis, followed by optimization and robustness evaluation

Coefficient of Prognosis (CoP) and Meta model of Optimal Prognosis (MOP)

Running a sensitivity analysis, optiSLang identifies automatically the most important parameters. To make this procedure as efficient as possible, Dynardo developed the CoP for quantifying the forecast quality of the response variation and as a criteria to find the best possible MOP in the best possible subspace of important parameters. It is also used to quantify the numerical noise at the response values. Finally, the MOP represents the best possible meta model in the best possible subspace of important parameters to maximize the forecast quality of response variations (see figure 5). This methodology is one key for efficiency. Thus, a “no run too much” philosophy can be implemented for sensitivity analysis and optimization to minimize external CAE solver calls.

Secure workflows

Robust Design Optimization will result in the creation and calculation of a significant number of designs. In real world projects, we have to face design failure because modified geometry cannot be regenerated, mesh algorithms fail or the calculation process shows inaccuracy. As a consequence, developing secure saving and storage procedures have first

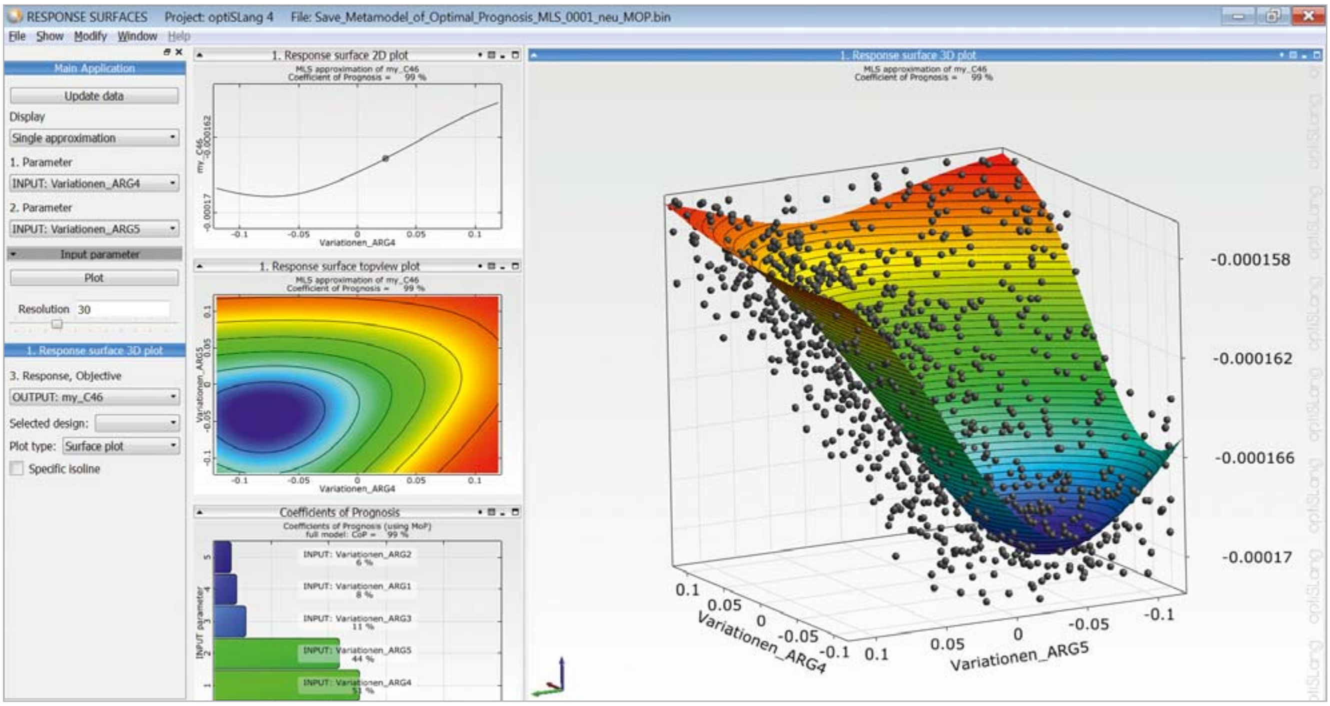


Fig. 2: Post Processing: multiple window GUI for post Processing of meta model og optimal Prognisis

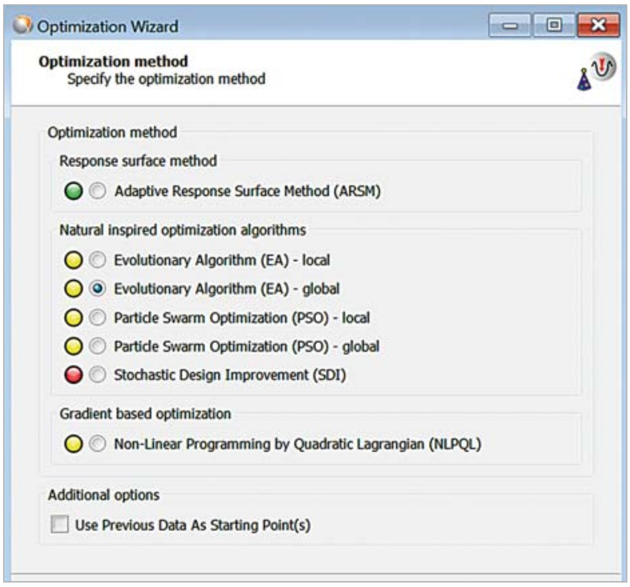


Fig. 3: wizzard indicates the most effective optimizer. green traffic light: recommended optimizer, yellow traffic light: possible alternatives, red traffic light: not recommended

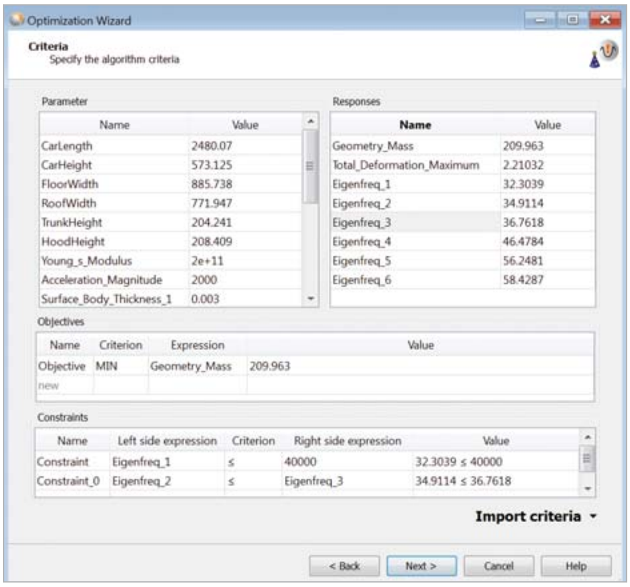
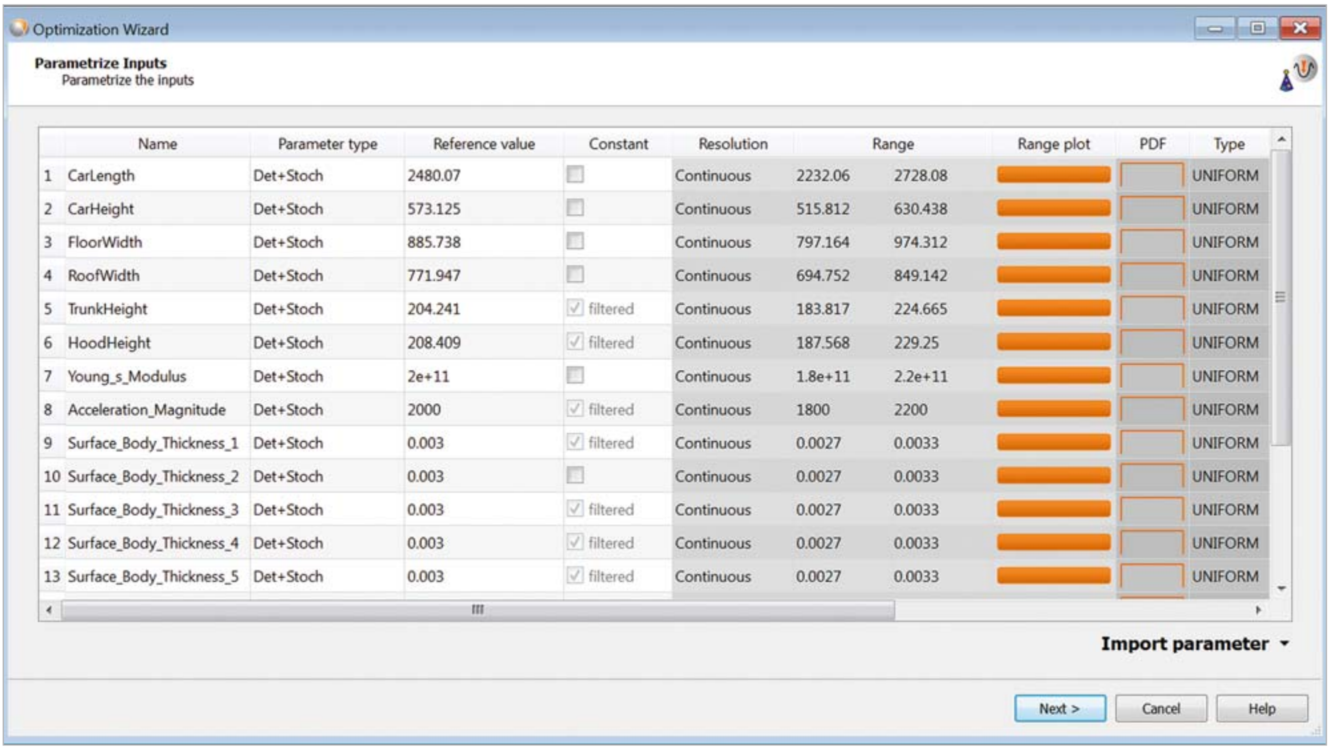


Fig. 4: wizzard for defining constraints and objectives



	Name	Parameter type	Reference value	Constant	Resolution	Range		Range plot	PDF	Type
1	CarLength	Det+Stoch	2480.07		Continuous	2232.06	2728.08			UNIFORM
2	CarHeight	Det+Stoch	573.125		Continuous	515.812	630.438			UNIFORM
3	FloorWidth	Det+Stoch	885.738		Continuous	797.164	974.312			UNIFORM
4	RoofWidth	Det+Stoch	771.947		Continuous	694.752	849.142			UNIFORM
5	TrunkHeight	Det+Stoch	204.241	filtered	Continuous	183.817	224.665			UNIFORM
6	HoodHeight	Det+Stoch	208.409	filtered	Continuous	187.568	229.25			UNIFORM
7	Young_s_Modulus	Det+Stoch	2e+11		Continuous	1.8e+11	2.2e+11			UNIFORM
8	Acceleration_Magnitude	Det+Stoch	2000	filtered	Continuous	1800	2200			UNIFORM
9	Surface_Body_Thickness_1	Det+Stoch	0.003	filtered	Continuous	0.0027	0.0033			UNIFORM
10	Surface_Body_Thickness_2	Det+Stoch	0.003		Continuous	0.0027	0.0033			UNIFORM
11	Surface_Body_Thickness_3	Det+Stoch	0.003	filtered	Continuous	0.0027	0.0033			UNIFORM
12	Surface_Body_Thickness_4	Det+Stoch	0.003	filtered	Continuous	0.0027	0.0033			UNIFORM
13	Surface_Body_Thickness_5	Det+Stoch	0.003	filtered	Continuous	0.0027	0.0033			UNIFORM

Fig. 5: wizzard to define the variation of optimization as well as the scatter of variables

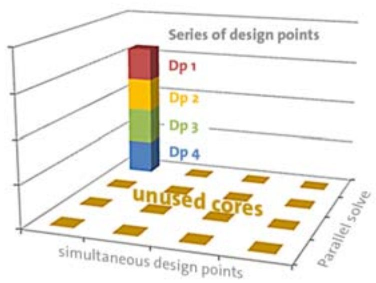
priority. In the optiSLang 4 stand-alone version as well as in optiSLang inside ANSYS Workbench, we integrated a continue crashed session mode preventing any loss of data as well as a design backup to make them available for restart and reevaluation at any time of the workflow.

More efficiency by ANSYS HPC support

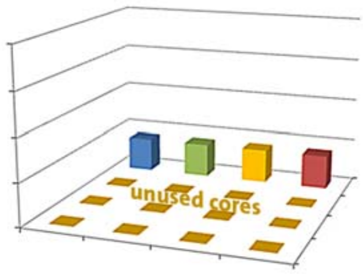
If one design evaluation needs a significant amount of time to be solved, two ways of speeding up the process are available. First, with ANSYS HPC functionality where every design update can be executed by using multiple cores. Second, for simultaneous execution of multiple designs, parametric pack licenses (from v14.5) are available. Here, necessary licenses for updating a design point are multiplied. Thus, user can appropriately distribute jobs across the available compute resources. For example: 4 HPC Parametric Pack Licenses allow for 32 design points to run simultaneously and one additional HPC Parametric Pack License for 64 design points. These techniques enable different systematic approaches using remote compute resources. It is not only possible to run the solution process (the solver) remote, but also other parts of the process chain, like result extraction, can be run on the remote server, which is especially useful for large data sets.

Product bundle "optiSLang for ANSYS"

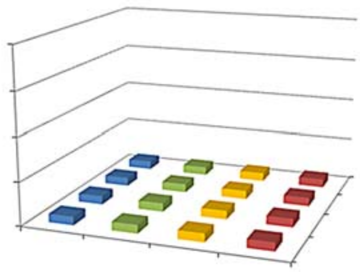
To provide our users access to all that functionality which can be connected to ANSYS Workbench within one license, since April 2013, we have been offering the product bundle "optiSLang for ANSYS" containing optiSLang inside ANSYS Workbench, optiPlug and optiSLang stand-alone including ANSYS Workbench integration node. For distribution, support and improvement, we are glad to work together with the CADFEM GmbH as our long term ANSYS partner.



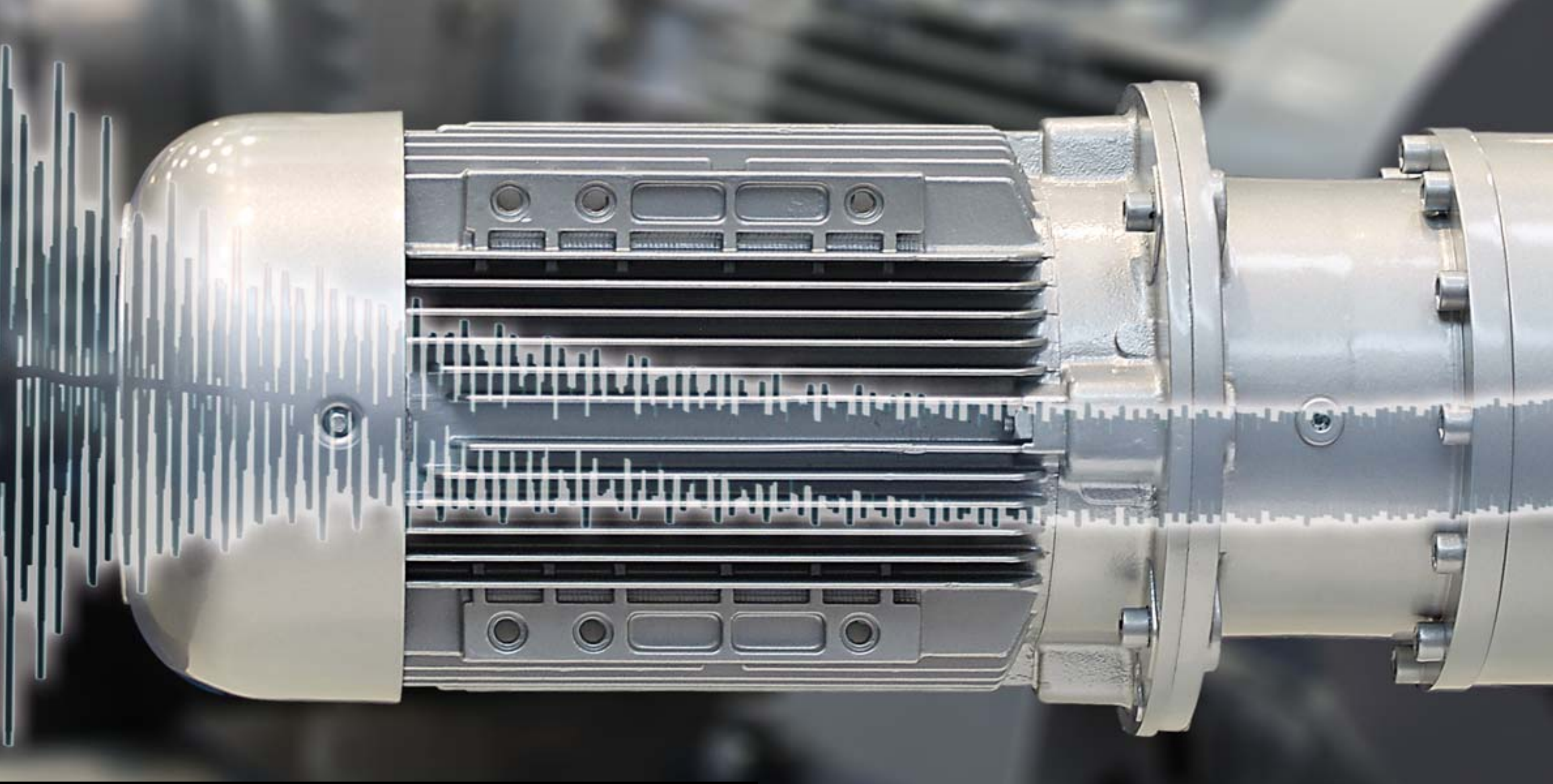
update of 4 design points using one ANSYS License and a Hardware containing 16 cores



update of 4 design points using one ANSYS License + 1 HPC Pack using multiple cores to solve the design



update of 4 design points using one ANSYS License + 1 HPC Pack + 1 HPC Parametric pack to solve 4 design points using 4 cores each at the same time. Theoretically update can be executed 64 times faster



CASE STUDY // ELECTRICAL ENGINEERING

UNDERSTANDING THE ACOUSTIC BEHAVIOR OF ELECTRICAL DRIVES

Operating noise is an important parameter of technical devices operating near humans. Thus, reducing noise emission is often a key goal in order to achieve higher quality standards and new markets.

Engineering the Sound

Operating noise is an important parameter of technical devices operating near humans. Many regulations define maximum values for operating devices. This is especially true for permanent working systems. Furthermore, reducing noise emission is often a key goal in order to achieve higher quality standards and, thus,new markets.

The Sound Propagation Path

Here, the noise sources are categorized into two distinct groups:

1. The first type of noise excitation originates from time varying forces acting on solids. These forces provoke mechanic vibrations (structure bound sound) within the solid parts which propagate up to the outer surface of the bodies. At this outer boundary, the vibrations are partly transferred to the adjacent fluid as a result of a fluid-structure-interaction (FSI).
2. The second type of noise excitation provokes fluid bound vibrations directly. This can be observed in fans, exhaust ventilation and fast moving parts. Here, the vibrations are generated due to the turbulent flow of the fluid.

The process of noise formation and transfer can be described in the frequency domain very conveniently. A particular excitation spectrum $F(j\omega)$ is multiplied with a frequency dependent transfer function $T(j\omega)$ which represents the propagation of noise. For the second type of noise $T(j\omega)$represents solely the propagation through the fluid, while for the first type, the transfer function represents solid-state-wave-propagation, FSI and finally the fluid bound propagation.

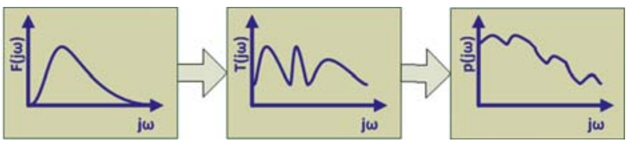


Fig. 1: Block diagram of noise propagation

Electrical Drives as Noise Source

In general, the following sources of noise can be identified in an operating electric motor:

1. Cooling fan (if applicable)
2. Bearings and mechanical connections
3. Vibration of the actuator and housing

From this list, numbers 2 and 3 start as a structure bound sound while 1 generates fluid vibrations directly. 1 and 2 are results of the movement of parts mechanically coupled to the motor while 3 has its origin in the motor's principle of operation itself. Considering this, the Maxwell forces on ferromagnetic parts of the drive are of major interest. These forces are typically maximized to provide the operational torque. The acoustic design for stator's vibration, caused by Maxwell forces, cannot be separated from the design process of the motor itself (which is possible when designing quieter fans and bearings). This article will focus on the third source of operating noise. Furthermore, only structural vibration will be simulated because they correlate with the operating noise in amplitude and frequencies.

Modal Extraction

To predict how the structure will react to the periodic forces, a structural mode superposition analysis can be done. This linear approach is valid because the deformations, caused by the structure bound noise, are small. A mode superposition analysis is much more resource effective than a fully coupled magnetic-structural analysis. By performing a modal analysis, the normal modes and resonant frequencies of the structure can be determined. The results of the modal analysis should be used to determine which normal modes are of interest. The operating noise of an electric drive is mainly determined by the modes which lead to a vibration of the outer housing as a whole. Internal oscillations, for example the stator's teeth, have little contribution to the operating noise.

In Fig. 2 two exemplary normal modes of the outer parts of an electric drive (stator and housing) are shown. The left mode leads to significant deformations at the outer boundary of the motor. The right one depicts mainly a bending of

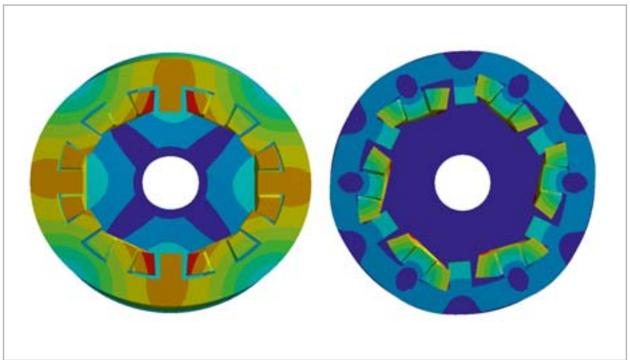


Fig. 2: Normal modes of outer parts of a motor

the stator's teeth. This evaluation of the normal modes and their corresponding frequencies should be used to define the simulation time step in the upcoming analysis to determine the force loads.

Electromagnetic Excitation

When applying a current excitation to the stator's windings, the produced magnetic field interacts with the permanent magnets leading to a tangential force on the rotor and thus a rotational movement. This interaction results in an equal reaction force on the stator. Furthermore, there are also radial forces and torques acting on the stator's teeth. The first step in order to calculate the time dependent forces on the stator's teeth is to simulate the transient magnetic field in the motor. The force is computed by evaluating the Maxwell's stress tensor and integrating it along a path. The stress tensor can be written as:

$$T_M = \begin{pmatrix} B_xH_x - \frac{1}{2}|B||H| & B_xH_y & B_xH_z \\ B_yH_x & B_yH_y - \frac{1}{2}|B||H| & B_yH_z \\ B_zH_x & B_zH_y & B_zH_z - \frac{1}{2}|B||H| \end{pmatrix}$$

The precise mathematical formulation allows its usage only to obtain forces integrating it along closed loops/surfaces. However, in most of the motors, the magnetic co-energy (and, therefore, the terms inside the tensor) is much larger inside the air gap than in the other areas. Fig. 3 shows a contour plot of the magnetic co-energy at the air gap, sta-

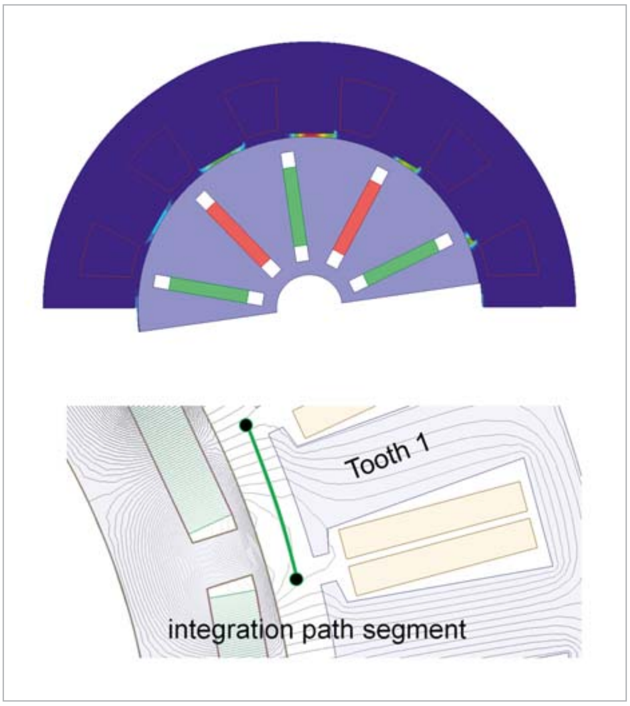


Fig. 3: Co-energy distribution inside the air gap and stator of a synchronous machine with permanent magnets and reduced force integration pathor

tor and windings. The integrated force evaluated along the arc in the air gap is used as a force load on the corresponding tooth. This engineering approach neglects the particular distribution of the force density along the inner side of

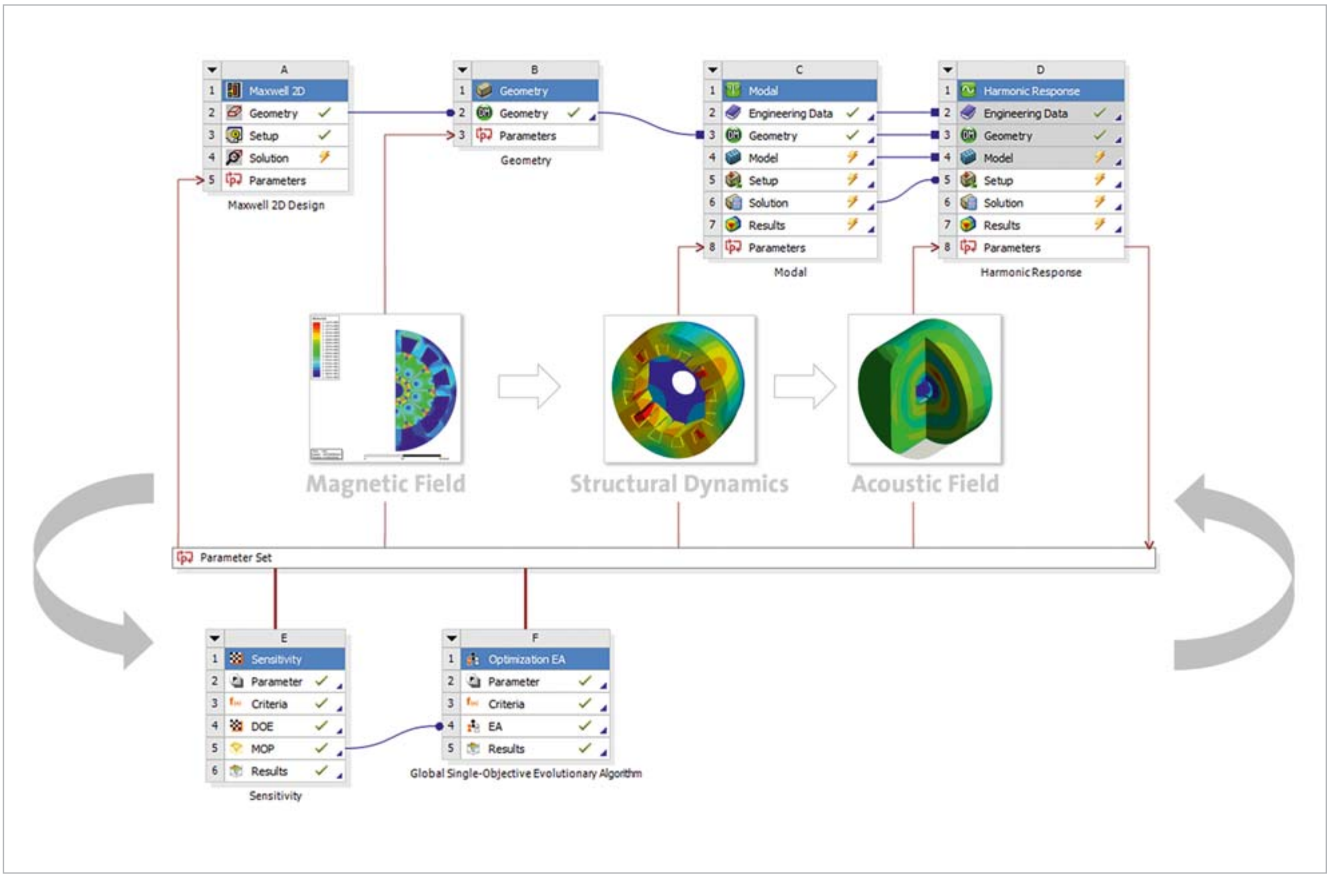


Fig. 4: Full parameterized optimization environment with optiSLang inside ANSYS Workbench

the tooth. The distribution is, however, of minor interest while evaluating the vibrations which will be transmitted to the air at the outer side of the machine.

Harmonic Response Analysis

After determining time dependent forces for each tooth, these quantities are Fourier transformed and used as complex loads in a harmonic response analysis with modal superposition. With this approach, it is possible to determine how the normal modes of the structure will react to the determined magnetic forces.

Sensitivity Analysis and Optimization

Having parameterized the whole workflow, the next step is to couple it to optiSLang inside Workbench for doing a sensitivity study with a subsequent optimization. Several parameters are set in the geometry and also the rotations per second could be varied. The output parameter is the amplitude for the frequency of 600Hz. The sensitivity analysis shows CoPs from 96% – 98% and clearly filters out the important input parameters. This allows doing a quick optimization using the Metamodel of Optimal Prognosis (MOP). As a result, this procedure creates a modified model that vibrates with 30% less amplitude than the original one.

Conclusion

By performing a simulation of the magnetic fields inside a motor, a calculation of the magnetic forces was conducted for evaluating the operating noise according to Maxwell's stress tensor. These forces can be Fourier transformed and applied as excitations to structural mode superposition analysis. This workflow leads to a time and computational resource effective simulation of the vibrations of the motor caused by periodic magnetic forces. This effective workflow can be used as part of the standard motor design process to optimize drives on their operating noise. A seamless workflow can be achieved using ANSYS tools Maxwell and Mechanical combined in the Workbench environment. With optiSLang inside Workbench, a sensitivity study and an optimization can be done in an easy-to-use environment. Thus, an assessment of sound sources and location was performed. For example, magnetic forces that excite stator structure to radiate or distribute sound as well as time varying eddy currents that cause acoustic relevant radial forces were detected.

The workflow also enables the user to develop new designs based on an interdisciplinary optimization workflow in order to meet acoustic regulation and customer comfort criteria.

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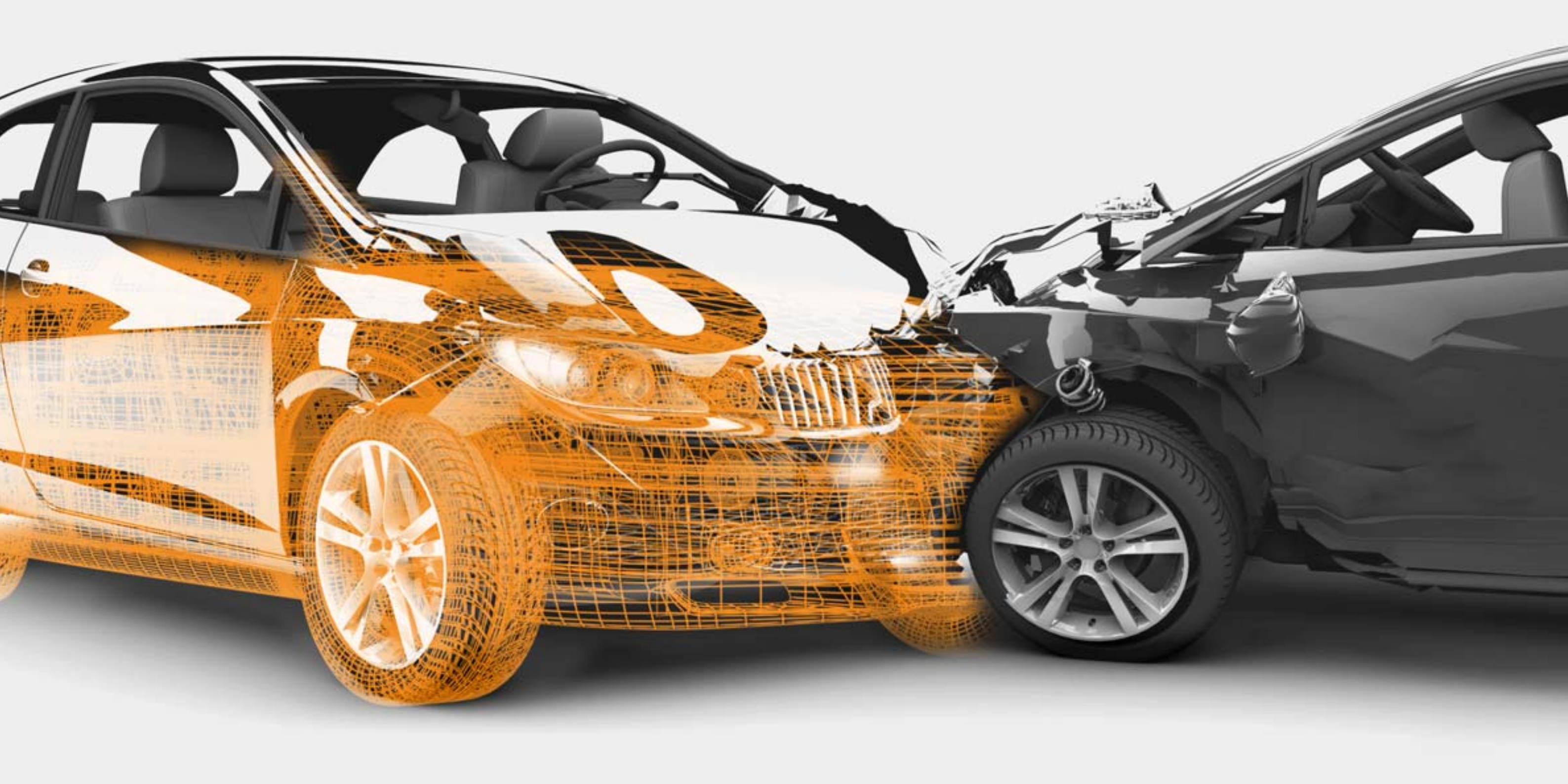

CASE STUDY // AUTOMOTIVE INDUSTRY

OPTIMIZATION OF CRASH RELEVANT VEHICLE STRUCTURES DURING THE CONCEPT PHASE

A reduction in time spent for early phase product development can cut costs significantly. Using RDO methodology, safety related simulations can be carried out a lot earlier than in conventional processes.

In optimization applications used for novel product development methodology, crash behavior evaluations are involved during the early stage of the product development process to save time in later phases. In conventional processes, vehicle safety related simulations like crashworthiness tests, insurance tests and pedestrian safety related tests are carried out separately at a later stage. Furthermore, FEM models used for engineering analyses do not permit easy changes in terms of geometry and topology of the vehicle structures. Therefore, to answer basic questions about the crash behavior of different concepts, a simplified model at concept stage is needed. The method involves usage of implicit parametric CAD models, providing necessary flexibility to the FE mesh. By using a powerful implicit parametric CAD Model, manifold concept studies can be carried out and evaluated based on objective criteria, such as crash behavior, weight or classification tests. Furthermore, selected designs can be optimized to achieve specific goals.

Objectives

The main objective is to develop a methodology which can be used to predict crash behaviour of vehicle structures. The generated knowledge is to be used for ratings of the various concept studies. Furthermore, this methodology should offer potential for optimizations during the early stage of the product development process using simplified structures.

Methodology

General approach

The shown product development process (PDP) on the left hand side of Figure 1 is based on the planning and design process by Pahl/Beitz. The typical PDP begins with an idea followed by the product planning, conceptual design, embodiment design and the detailed design phase. The difference between the Pahl/Beitz and the proposed methodology is the usage of design phase elements, such as FE calculations and optimizations that are usually carried out in the embodiment and detailed design phase of the conceptual planning. The new methodology proposes the use of implicit parametric CAD to illustrate design concepts and support initial FE calculations.

Independent of the product development time schedule, a simplification process (Figure 1) has been carried out to generate three different highly parametric models which can be used for initial crash calculations to demonstrate the capabilities of the presented methodology. By simplifying (abstraction and idealization) detailed vehicle models (FORD Taurus and TOYOTA Yaris), crash relevant structures can be extracted. Within the verification process, the limitations of the models are defined and finally validated with typical crash configurations to ensure the correct response of the simplified models. Due to the parametric setting, these simplified models can be adopted and used for further development processes. At best, the simplification process does not have to be repeated.

Batch process

Figure 2 shows the general batch process of the optimization loop used for the studies. At the first stage, an implicitly parametric CAD model was created using SFE CONCEPT. The mentioned CAD package has powerful auto-mesh functionality with welding and multi-flange definitions to handle relatively complex actual vehicle FE models. A FE mesh of the geometry was exported from SFE CONCEPT in the format to suit LS-Dyna input deck. The boundary conditions, material properties and other inputs were assembled in SFE CONCEPT. Calculations were performed using LS-Dyna solver, MADYMO solver or a combination of both. The critical output parameters of the calculations were identified and processed using MATLAB or combination of LS-Prepost with MATLAB. The whole process was controlled using optiSlang. The software is capable of performing the design of experiments, sensitivity analysis, robustness evaluation and single and multi-parameter optimizations.

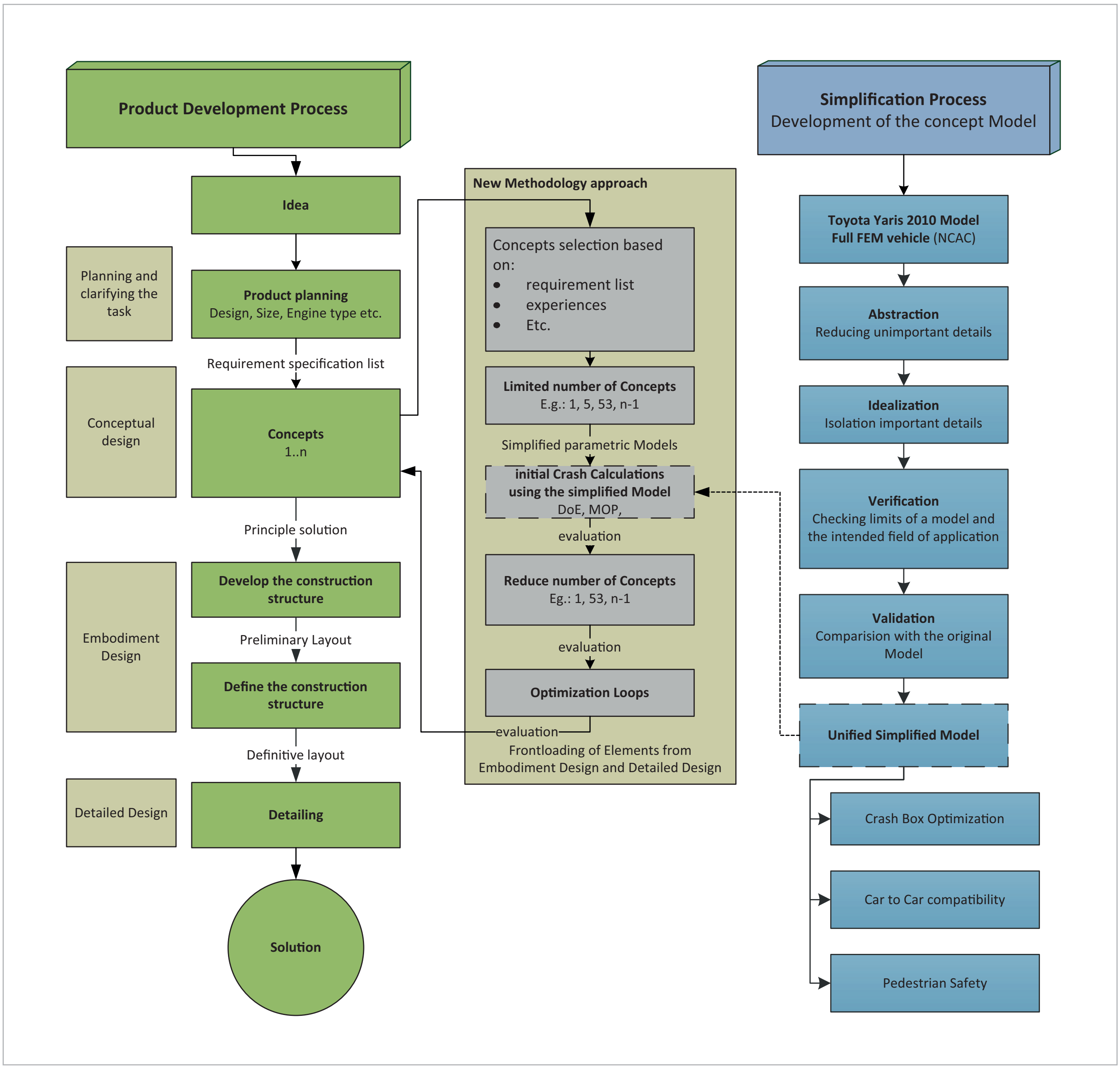

Fig. 1: Methodology for the front end Optimization during the early stage of the product development process

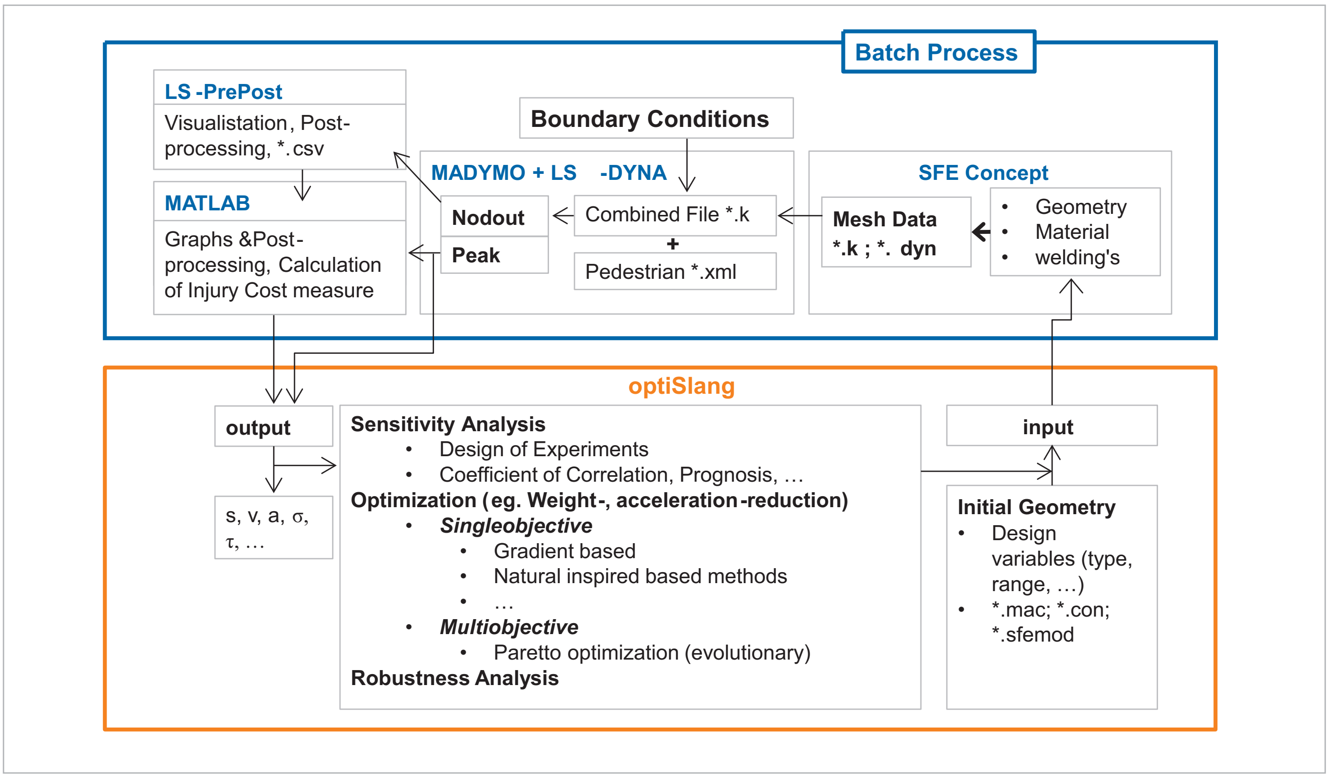

Fig. 2: possible batch process

Example 1 – Crash-box

Low energy vehicle car crashes

The aim is optimizing the front end structures, in particular the crash-box, to absorb the energy of low speed crashes with a velocity of 15 km/h. Here, the crash-box shall absorb major parts of the excess energy, thereby other parts will be exposed to forces within their elastic limits. The deformation and energy absorption of the crash-box is essential especially concerning repair cost reduction and, thus, minimizing insurance contribution. Therefore, reduced models, which replicate the critical output parameters effectively, are crucial to establish a development process within a desired time range.

Simplified Model and Validation

A TOYOTA Yaris has been used as a reference car. The model was validated by NCAC for US regulatory frontal impact load conditions. The internal energy over time distribution of the bumper and the crash-box (inner and outer) was used as the reference value (see Figure 3). The structure test barrier, according to the Research Council for Automobile Repairs (RCAR), was used as an obstacle and the vehicle speed was set to 15 km/h. The number of parts in the Yaris model has been reduced step by step and the crash-box performance of the original Yaris crash-box has been checked regarding to its crash performance in terms of absorbed energy. Figure 4 shows the different simplified models with the calculation time on one workstation. With decreasing number of nodes and parts, the calculation time was reduced significantly. For comparison of the results, the internal energy of the inner crash-box has been plotted. The plot shows the internal energy results of the part concerning the full vehicle calculation and, for comparison, also the reduced version. Furthermore, the absolute difference of the internal energy between the original vehicle and the reduced vehicle was plotted, as well as the absolute difference on the

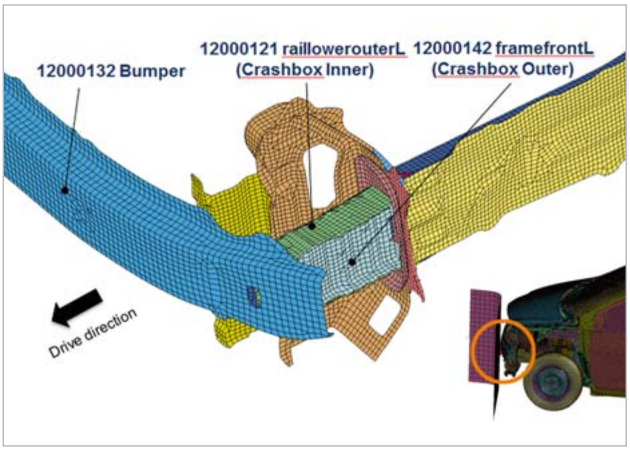

Fig. 3: Relevant TOYOTA Yaris front end parts

second ordinate. Additionally, every plot shows a box with the mean difference of the original Yaris model and the reduced model in terms of the percentile deviation and mean energy deviation. The simplified model had an overall calculation time of 1.5 h and was used for an initial optimization. The deviations from the original model indicated the need for optimization processes for fine tuning parameters of the simplified model and to achieve similar prediction capability as the original model. Therefore, an optimization was started to modify the three different weights and the appending inertias, which were 27 variables in total.

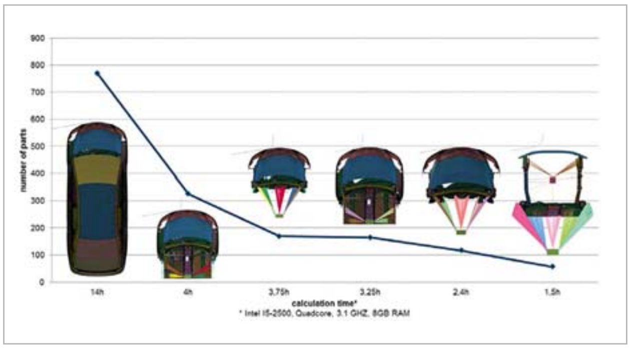

Fig. 4: Simplified model simulation time

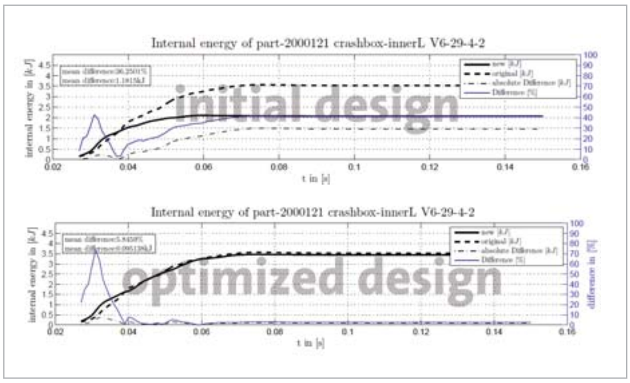

Fig. 5: Comparison of Initial and optimized design of the simplified model (extract)

After 183 calculations, a significant improvement was achieved. The average deviation of the internal energy of the three parts decreased from 17% to 6% (see Figure 5). This result was within desired limits of accuracy to permit the simplified model to run further simulations with highly parametric crash-boxes.

Example 2 – Pedestrian Safety Model

Introduction to pedestrian safety and vehicle front-end design

Pedestrians are the most vulnerable road users. Therefore, their safety needs to be in the focus. Most crash database analysis show that the most frequent pedestrian-to-vehicle crash scenario is a vehicle-front one striking the pedestrian laterally. For a typical sedan shape, the adult pedestrian crash kinematics were observed as leg to bumper, pelvis to bonnet leading edge, torso to bonnet or head to windshield types. For children, leg to bumper, torso or head to bonnet leading edge types were observed. In case of flat front vehicles, the secondary crash injuries were found to be more severe than the primary injuries. The variation of pedestrians from a 6 years old child to 95th percentile male is almost two times in weight and more than twice in height and anthropometric features. With such a manifold requirement for safety, a pedestrian friendly design at concept stage is necessary.

Objective of this Study

A pedestrian crash scenario was shortlisted from crash data base studies, indicating that lateral collisions are recorded statistically more often. The objective was to discover the position with the highest risk to pedestrians. A DoE was planned to study the worst position for lateral pedestrian impact. The possible variations shortlisted for study were the angle of pedestrian to car and the gait positions as shown in figure 6 (A) and (B).

Input Set up (MADYMO) for study

Four pedestrian models having the size of 95th %le male, 50th %le male, 5th %le female and 6 year old child models from TNO are considered as representative for the pedestrian population. The inputs to this study are three joints namely "Human_jt" (referred as angle_6c for child model in statistical figures) in MADYMO, representing the angle of the human being with respect to the car. The rotation of the human is limited to 45° on the left and right, as indicated in figure 6 using notation. A 50th percentile male human model is shown representing a similar position and being used for all other models.

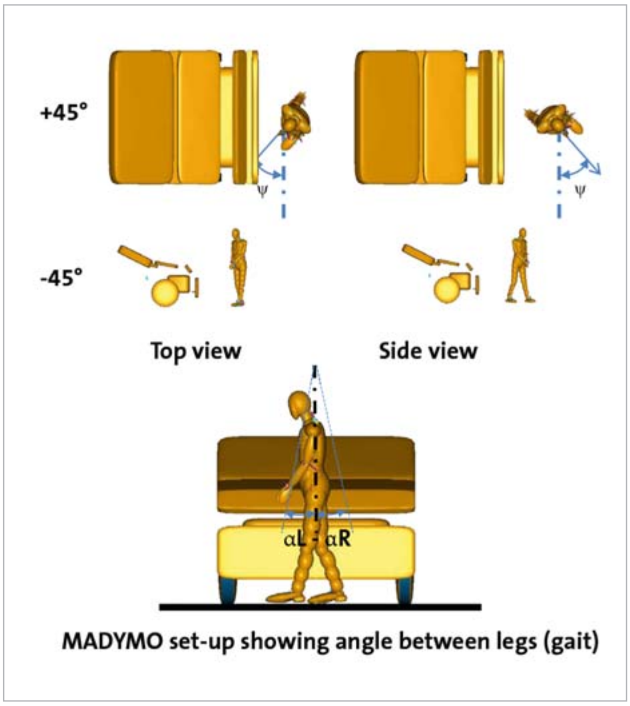

Fig. 6: Pedestrian simulation input set up (Angle with car -ψ)

"HipR_jt" for right leg and "HipL_jt" for left leg (referred to as HipR_6c and HipL_6c for child model in statistical figures) were the two joints in TNO pedestrian model for modifying the gait. The leg angles (gait) are limited to 14.32°

positive and negative for adults and 11.46° on either side for child models, as shown in Figure 6 using notation ‘αL’ and ‘αR’. The total number of variables is 12 (3 per pedestrian model, 4 models).

Pedestrian to vehicle interaction characteristics were modelled based on force deflection characteristics obtained from crash reconstruction studies. Also, body form characteristics concerning vehicle test data were used. An optimization loop with optiSLang, MADYMO and MATLAB was set up similarly to the one explained in Figure 2. To understand the injury risk to a pedestrian by a vehicle profile, the injury to the whole body was considered. Rating and regulatory tests use linear acceleration based criteria for the head, acceleration and displacement based criteria for the chest and penetration based criteria (peak force) for the abdomen. Peak force is also used for pelvis. A combination of bending and compression force factors is applied to long bones of the lower extremity and displacement based criteria is used for knees.

Studies related to the optimization of safety for pedestrians showed a single objective function as more effective to address the correlation of the different injuries. An injury cost based measure represents the hospitalization and medical expense with provision of high penalty for potential impairment or death. The injury cost calculation is shown in Figure 8. The threat to pedestrian was calculated based on Injury Cost (IC) measure using MATLAB based on output from MADYMO simulations.

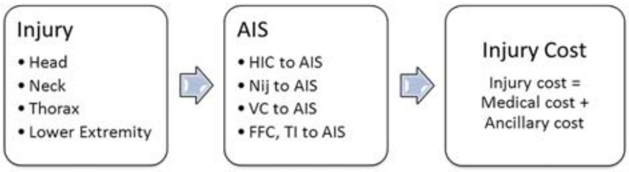

Fig. 8: Calculation of injury cost (abbreviations at end of paper)

DoE results analysis

The preliminary DoE was run with a total of 1000 loops consisting of 4000 simulations (4 pedestrian models x 1000 simulations). The measure computed for output was IC for 4 separate scenarios simulated in series one after another. The total IC represents the sum of all scenarios. Henceforth, 5 outputs and 12 inputs form the tables of statistics explaining them effectively. Figure 9 shows the ranking of the three variables relating to the IC of the child model. The same trend was also found on the other pedestrian models for the respective IC measure. The figure shows an angle of the child model inclination having the highest influence on the outputs, followed by the angle of struck leg and the non-struck leg.

Figure 10 shows the variation of linear and quadratic correlation coefficients for the child scenario. Both the correlation value matrices show a weak relationship between any of the inputs with the output. The same trend was observed in other scenarios with varying levels of correlation but not strong enough (>0.9) to establish some correlation.

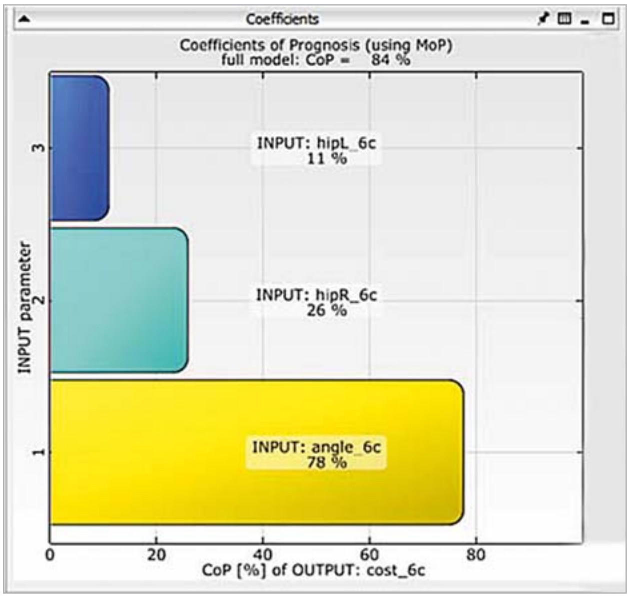

Fig. 9: Coefficient of Prognosis child model

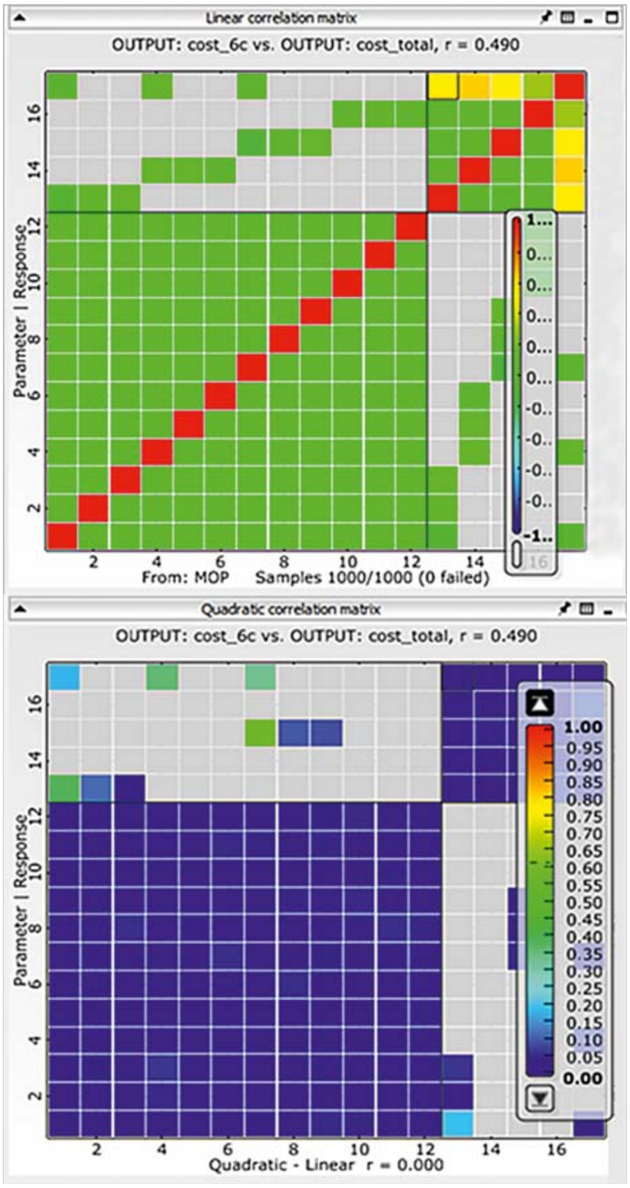

Fig. 10: Linear and quadratic correlation matrix

Figure 11 shows the variation of meta-models based on the simulation of 1000 samples and 4536 samples run. The Coefficient of Prognosis increased from 84% to 93%. The approximated model was generated for three variables with 3% variation allowed. The identical three variables and their order of influence were involved in the generated models.

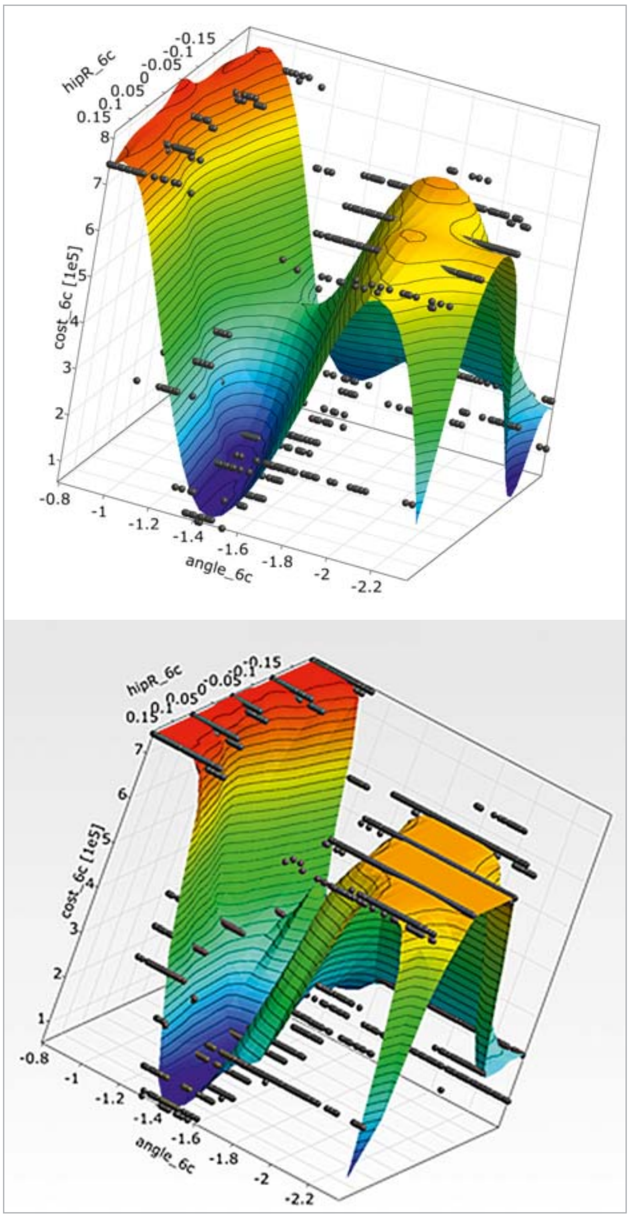

Fig. 11: Meta model with 1000 Samples (top) and 4536 samples – 6yr child (bottom)

Summary and Conclusions

The methodology using multiparameter optimization during the early stage of the product development was shown and two applications have been described. It was shown that the methodology is suitable for the early stage of the PDP in combination with high parametric simulation models, either to simplify FE Models or to identify crucial parameter sets using DoE and MoP.

The simplified crash-box model was found suitable to be used for optimizations. The calculation time reduced significantly with a deviation of 5% compared to the original Model. Further investigations with respect to other important parameters such as accelerations and others have to be carried out. The found optimum has to be reviewed regarding its robustness. The model itself is verified for this specific load case, other load cases have to be verified.

The pedestrian safety results from DoE and the approximated meta-model show that the angle of impact remains an important factor to the injuries sustained especially for children. The perpendicular hit had higher IC indicating it to be a worst case scenario. The variation in leg angles show struck leg backward to be having higher threat to the pedestrian than the struck leg forward. With the input on pedestrian gait and angle, pedestrian simulations for the simplified vehicle front model can be built up to optimize for pedestrian safety.

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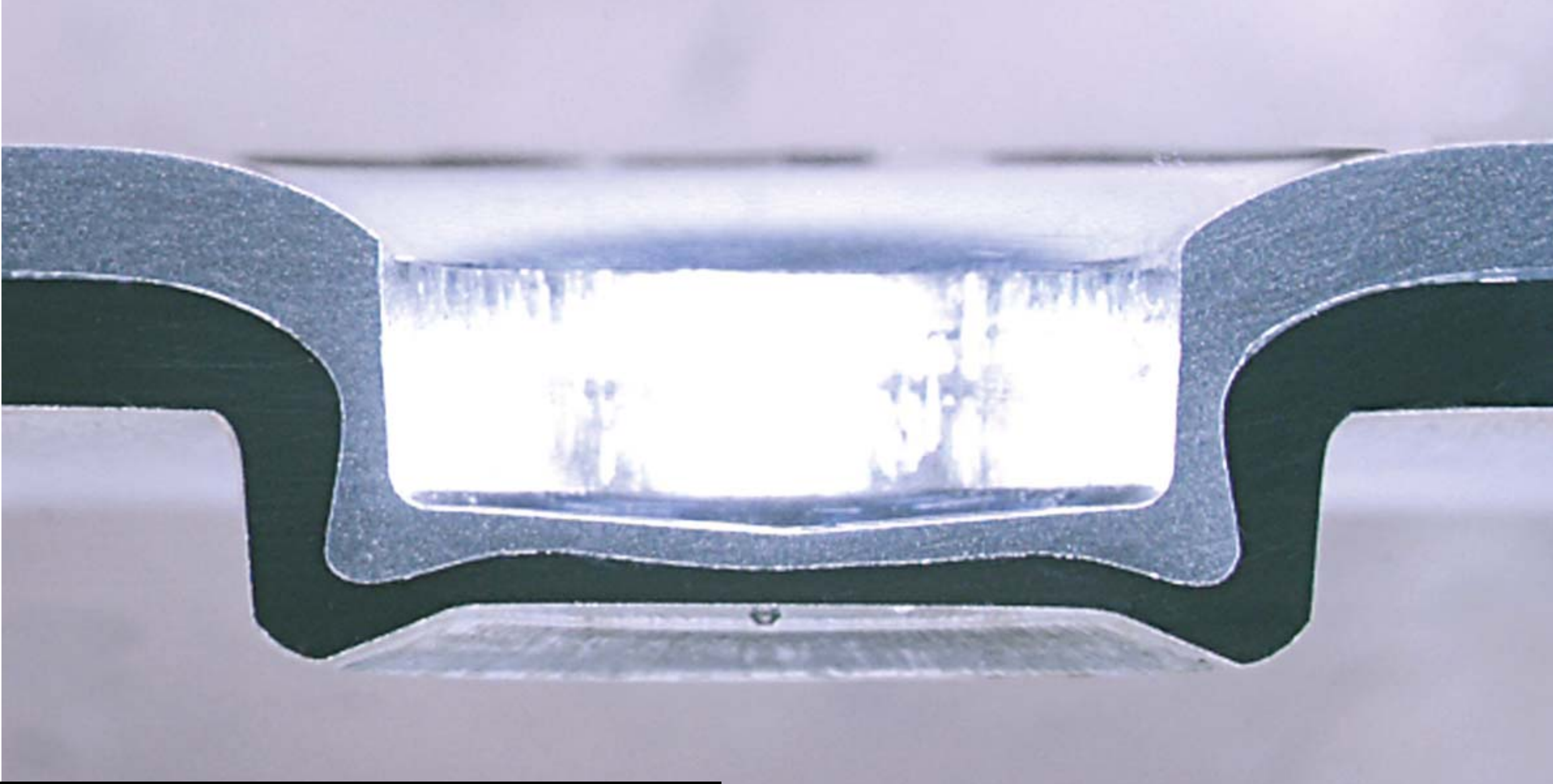

EVALUATION OF SCATTERING PARAMETERS IN MECHANICAL JOINING TECHNOLOGIES

A sensitivity analysis optimizes the design of forming dies by determining the most relevant joining parameters. Furthermore, methods to increase process robustness or monitoring in terms of quality assurance can be derived.

Introduction

Mechanical joining technologies are becoming increasingly important with the trend towards light and multi-material designs in the automotive industry. Providing robust connection techniques will be of particular importance. Thus, rejection rates are reduced and costs are cut in the parts production. This article discusses the example of clinching and its potentials and limits concerning FE-based sensitivity analysis and optimization for the joining by forming technology.

Mass manufacturing processes are subjected to parameter variations, which can cause fluctuations of characteristic result values. Also, in the mechanical joining technology, there are numerous tasks regarding sensitivity analysis, robustness evaluation or optimization. Especially in terms of efficiency and reducing costs, standardization of tool sets for various compounds are great issues. In Kuehne (2007), on the example of the Mercedes S-Class, the potential of such an analysis of different clinching tasks is shown. Such a complex and comprehensive analysis is very expensive, and so, the use of FEM in the process development and process evaluation is significantly increasing. Relating to Held (2009), the ever-growing use of simulation programs at all stages of component manufacturing is caused primarily by the automobile manufacturers to expand the understanding of the process continuously and to exploit cost saving potential.

A sensitivity analysis and robustness evaluation provide, at an early stage of development, the definition of appropriate measures to ensure the process and, thus, the product quality (Will 2005). Therefore, the numerical robustness is of special importance in order to improve properties and to reduce production costs in the virtual development process (Roos 2004). It is essential, particularly in terms of design and quality assurance of mechanical joining, to have proper knowledge of the amount and sensitivity of each influencing parameter variation and tolerance on the joining process. For assessment, sensitivity analysis and robustness evaluation are required. A successful application of a Finite-Element based approach for sensitivity analysis, coupled with an appropriate statistical design of experiments (DOE), have not yet been found in the mechanical joining technology.

Clinching is an important mechanical joining technique, which is standardized according to DIN 8593. Clinching is defined as a mechanical joining process producing a connection between two or more sheets exclusively by a local forming operation. The joining process is divided into three sub-processes (see figure 1). After positioning the sheets in step A, the punch pushes the joining area off the sheet plane. While punching, the sheet material is now pressed down to the die bottom (B). A further punch stroke increases the radial flow of the material between punch and die filling the die shape and realizing the interlock of the sheets (C).

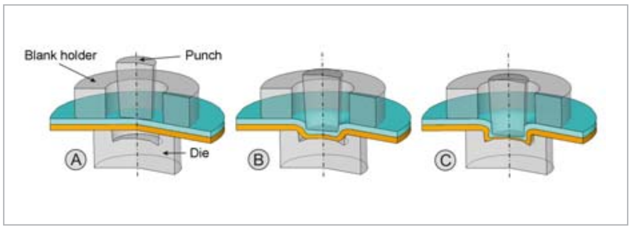

Fig. 1: clinching of round points with rigid dies

To evaluate the affecting parameters, defined result variables are required. For clinching, these are mainly the neck thickness tn and the interlock f (see figure 2) as far as the evaluation of the load capacity of compounds is concerned. The thickness of the bottom tb is seen as a constant parameter in a normal forming process, which is set in advance in the sampling process and can be non-destructively tested using a thickness gauge (Steinhauer 2007).

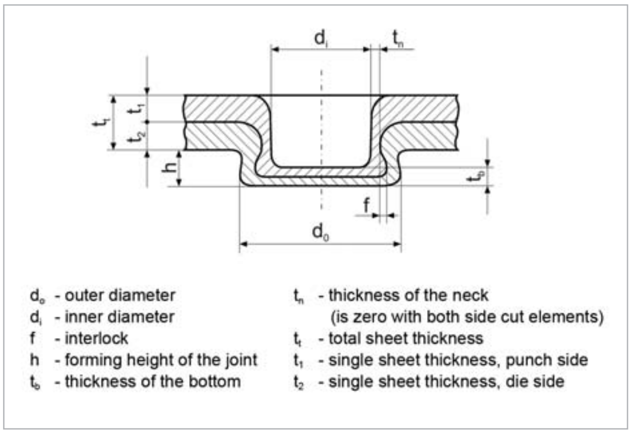

Fig. 2: Relevant geometrical parameter of a clinching joint related to DVS (2009)

The numerical description of clinching is subject of numerous studies and FEM-based projects. In Dietrich (2006), Paula (2007), Lee (2010), Mucha (2011) and other sources, suitable tool geometries to improve the forming of the joint and the joint strength under pull-out tension were numerically, but iteratively identified. Initial findings about the FEM-based optimization of clinching processes based on the Taguchi method and the Response Surface Method were obtained in Oudjene (2008) and Oudjene (2009). However, numerical sensitivity analysis and robustness evaluation with more than two parameters based on statistical design of experiments have not been conducted yet.

In principle, the statistical-numerical analysis of clinching has to be divided into two categories. A key aspect is the provision of appropriate tool and process parameters (design parameters) for an optimal joining. For this purpose, the first type deals with the identification of relevant parameters using sensitivity analysis and a required subsequent process of optimization. The second type of analysis is concerned with the identification and evaluation of process robustness, i.e. result value variations caused by process uncertainties (e.g. friction, material strength variations). Both types of analysis will be considered in the following.

Setup of a stochastic analysis of clinching

For the numerical description of the clinching process, the FEM-software Deform is used, which was developed specifically for solid forming processes. Important for the calculation of forming processes, such as clinching, is the possibility of a re-meshing option. Thus, areas of strong deformation and the resulting geometry variations or distortions can be re-meshed and the new node and element data can be transferred from the previous to the new mesh.

Assuming ideal rotationally symmetrical dies and neglecting any material anisotropy, the problem can be described 2D rotationally symmetrical. The interaction between Deform and optiSLang is assured via appropriate input and output files. Additionally, a script is required, which identifies the result variables of neck thickness and interlock on the basis of geometric features and transfers them to the output file. In advance, the FEM model has to be parameterized.

Subject of the analysis is the material combination EN AW-6016 with a thickness combination of 1.5mm in 1.0mm. Figure 3 shows the Finite-Element Model in the initial state

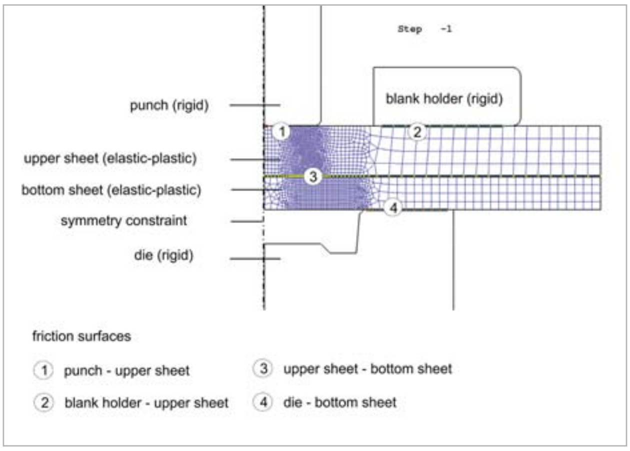

Fig. 3a: FEM-model

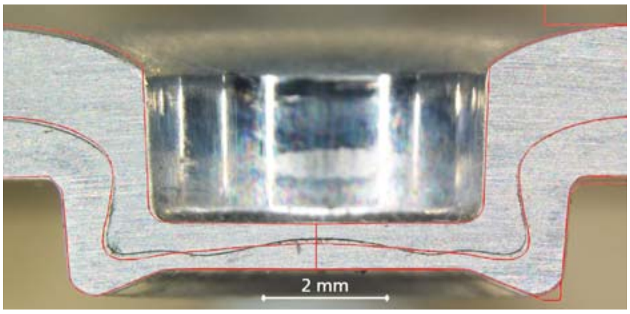

Fig. 3b: Comparison of cross sections experiment and simulation (FEM-result: red line)

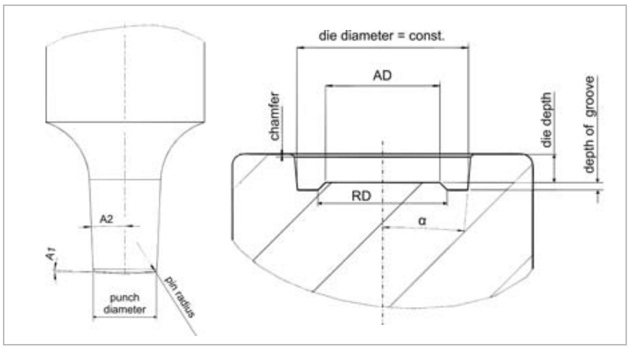

Fig. 4b: Design parameters

and the comparison of cross section of simulation and experiment. An important basis for the numerical calculation of the forming process is the material flow curve, which indicates the flow stress concerning the state of forming. The friction values are based on experience being currently iteratively adjusted for the correlation of joint forming and load in experiment and simulation. This provides a perspective option to optimize friction values with the objective of creating the best possible correlation in the experimental verification of the simulation.

Sensitivity analysis according to design parameters

Design parameters and result values

The design of the clinching joint essentially depends on the geometric shape of the tools, punch and die. Another influencing variable is the blank holder fixing the sheet before clinching and stripping it after the forming process. Due to known proper blank holder adjustments and because of the proven small impact of the blank holder shape and load in a technologically meaningful variation, the parameters of this device are not considered in the analysis. The following listed parameters and their variation limits are subjects of the analysis:

	Parameter	Minimum	Maximum
Die	die depth	1.0	1.8
	groove depth	0.3	0.8
	AD	4.0	6.0
	RD	6.0	7.5
	α	0.0	10.0
	chamfer	0.1	0.5
	RR	0.0	0.5
Punch	punch diameter	4.5	6.5
	pin radius	0.1	0.4
	A1	0.0	5.0
	A2	0.0	6.0

Fig. 4a: variation limits

The relevant result values for joint strength, neck thickness and interlock have already been explained in the introduction. With regard to the dimensions of the required drive and C-frame, the joining force is another important parameter. For assessing the forming and possible damage of the sheet material due to strong deformation, both the joining force and the damage values at critical clinching points can be identified. However, the investigations are focussed on the geometric parameters and the joining force.

Assessment of sensitivity analysis

For the generation of parameter sets to be calculated, the Latin Hypercube Sampling is used. This allows meaningful result assessment already with a set of 100 samples and sufficiently high values of CoP (Coefficient of Prognosis). Here, the CoP was 94% being the indicative value for the forecast quality of the analysis and with the best related meta-model concerning the neck thickness. With 64% of influencing relevance, the die depth is the most important parameter. The variation of the punch diameter affects 19% of the neck thickness variations. For these two most important parameters, the automatic regression analysis identified a functionally polynomial-based correlation between the parameter values and the outcome variable (see Figure 5, top right). However, the 2D plot of the die depth vs. neck thickness shows that the relationship can be described as nearly linear. Here, the neck thickness decreases significantly with increasing die depth.

A similar clear correlation of a parameter can be seen evaluating the interlock (see Figure 6). Here, the punch diameter is the parameter with the greatest influence. Die depth, alpha and pin-radius, each with about 10% relevance, form the second row of influential parameters. Similar to the evaluation of the neck thickness, a nearly linear correlation between the most important parameters and the objective values can be determined also for the interlock. Here, the critical point regarding the proper size of the interlock is having a low punch diameter and little die depth.

The joining force is the third analyzed influencing parameter. With 71% relevance, it is almost exclusively dependent on the size of the punch diameter. As expected, the joining force increases with rising punch diameter.

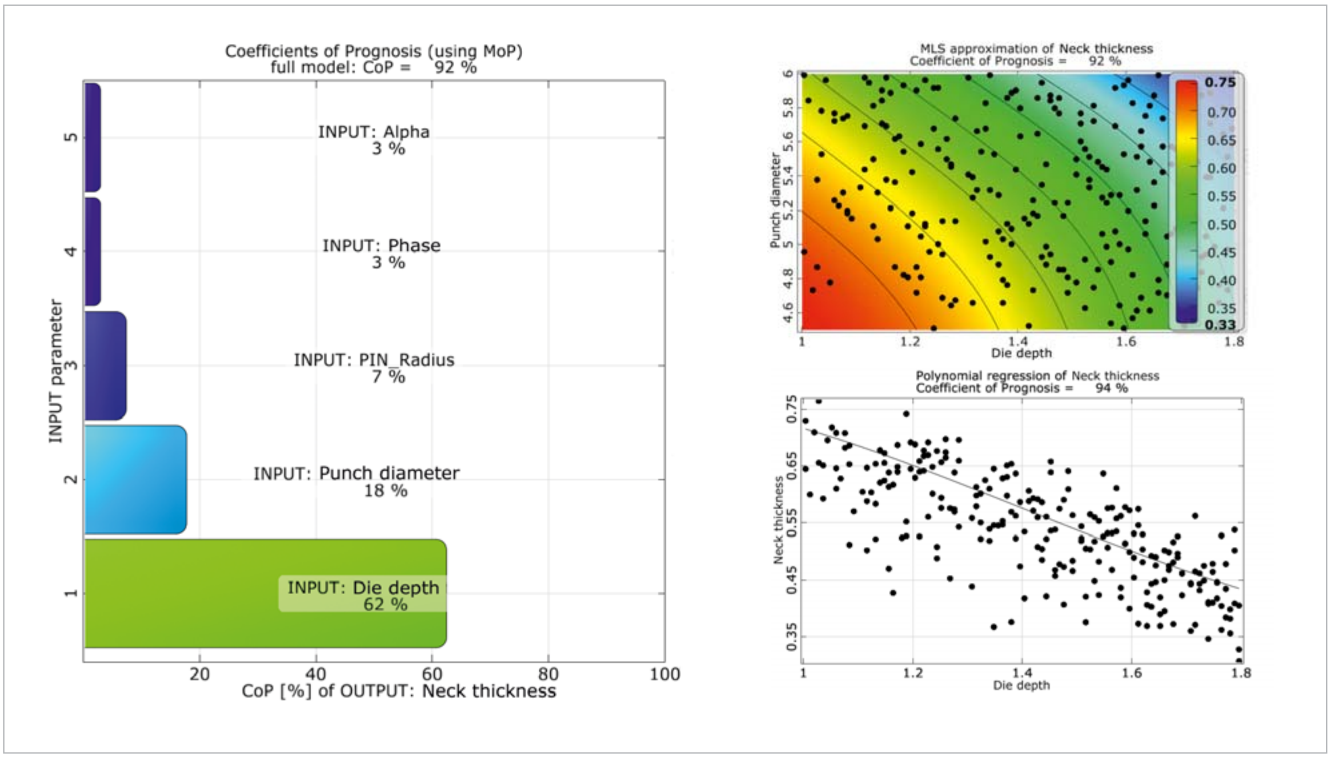

Fig. 5: Relevant influencing variables concerning the neck thickness

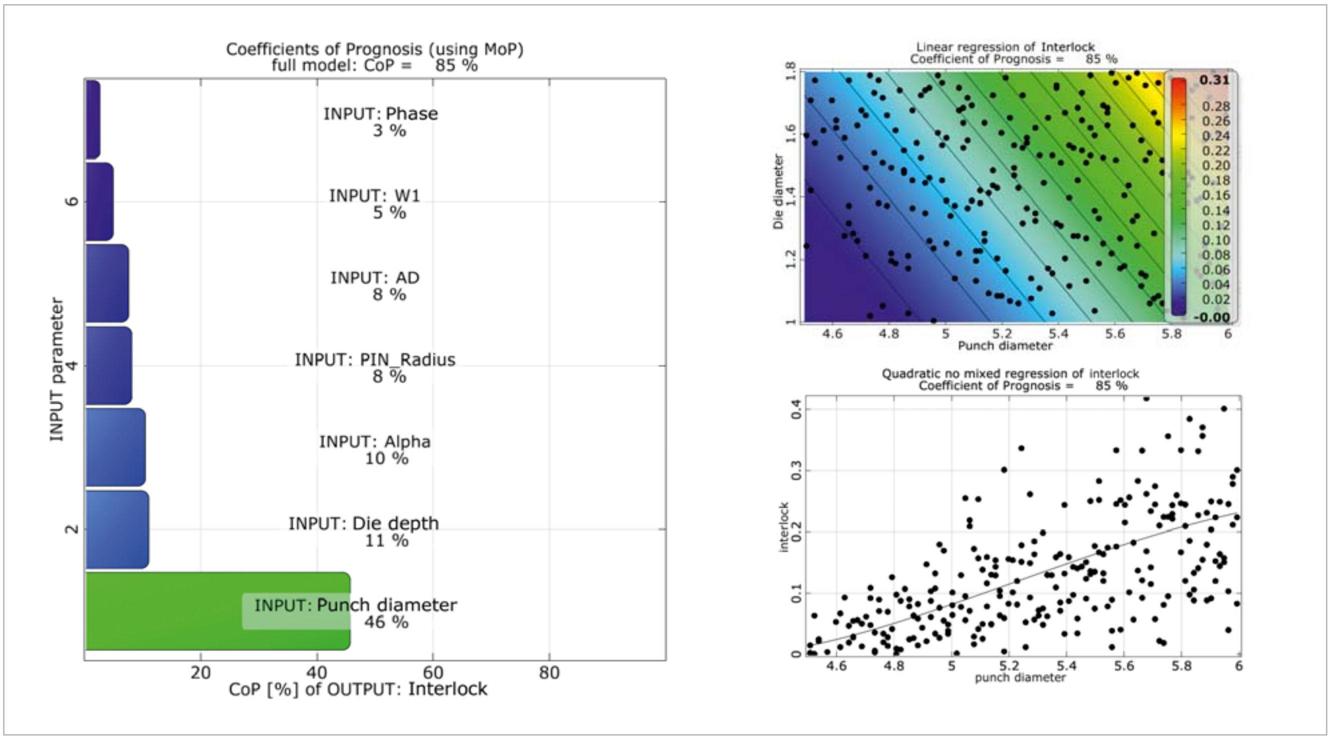

Fig. 6: Relevant influencing variables concerning the interlock

Optimization of the clinching process

Parameter and objective values

Concerning clinching, the objective value to be optimized is the joint strength, which, however, cannot be derived just from the cross section of the calculated joining. Neck thickness and interlock affect the load capacity of the clinching joint. Both values should be high with respect to increased joint strength. However, no clear assessment can be made when a clinching point reaches its maximum load capacity. This is strongly dependent on the load direction as well as on the sheet materials and thicknesses.

Figure 7 shows the possible failure modes after point loading: neck fracture (top), pull-out failure (bottom) and multiple failure (center). To avoid neck fracture, the neck thickness should be maximized. Accordingly, pull-out failure can be avoided in providing the largest possible interlock. In the sensitivity analysis, punch diameter and die depth were

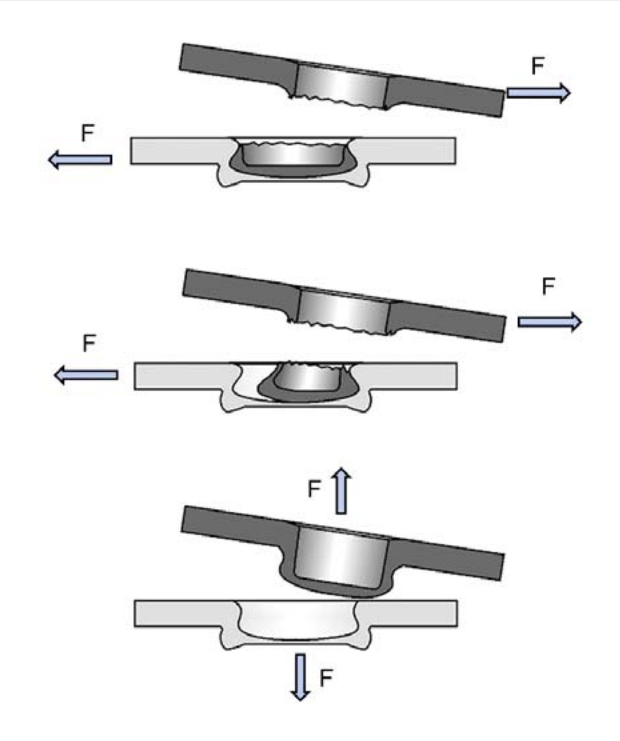

Fig. 7: Failure types after loading the clinching point load according to DVS (2009) neck fracture (top), pull-out failure (bottom) and multiple failure (center)

determined as major influencing parameters concerning neck thickness and interlock. As shown in figure 5 and 6, the value tendencies as a function of these two influencing design parameters are exactly opposite. For optimizing, the parameter AD, i.e. the die bottom diameter, is also considered. The optimization is conducted by using the Adaptive Response Surface Method (ARSM) with maximizing the neck thickness as the objective function. As constraints, a minimum interlock of 0.5 x neck thickness and a maximum joining force of 30kN were defined.

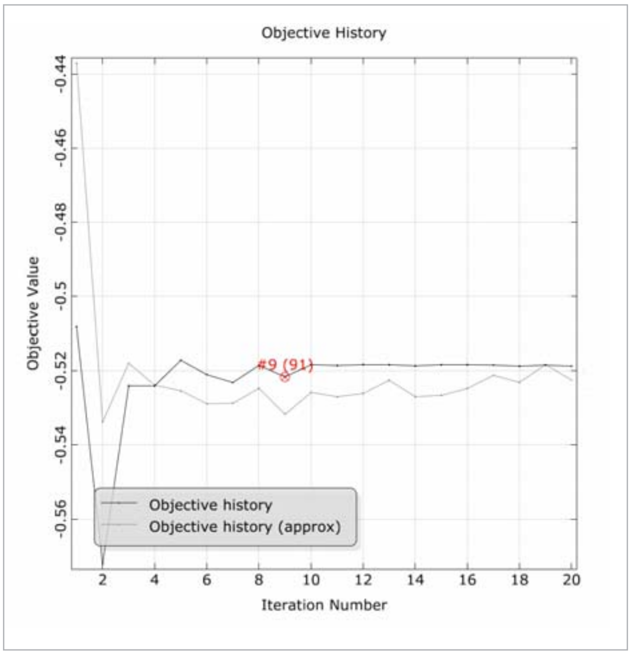

Fig. 8a: convergence of objective value (neck thickness)

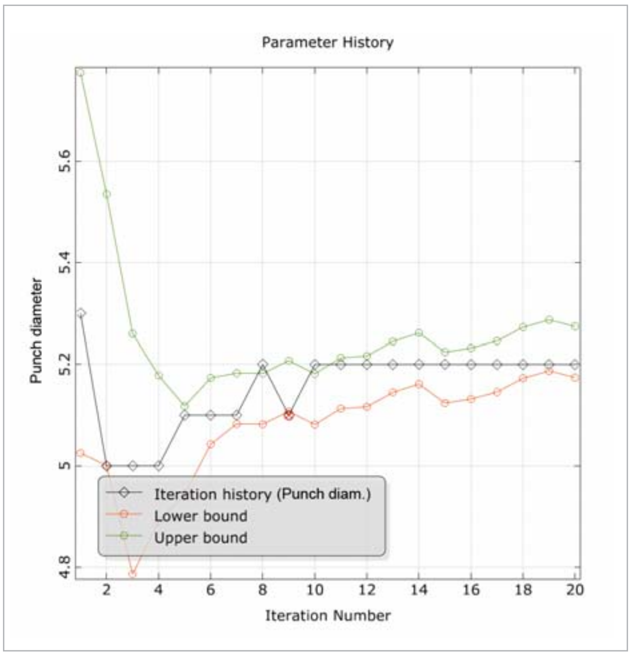

Fig. 8b: parameter punch diameter

Results of parameter optimization

Already after 9 iterations, the best design is determined and the varied parameters converge (Figure 8). Especially for the die depth an optimum (1.6mm) was found quickly.

As already mentioned, a definition of an optimal correlation between neck thickness and interlock is not possible without further analysis. Therefore, in the following optimization, the constraints defining the relation between the interlock and the neck thickness will be adjusted. Figure 9 (right) shows the differences in the cross sections for a quotient of neck thickness/interlock of 0.25 and 0.5. Based on these individual optima, a Pareto optimization can be conducted and, as a result, a range of optimal joining for any neck thickness and interlock is generated.

In addition to the die optimization for individual joints, in practice, alternative joining solutions are increasingly sought for different sheet materials and thicknesses. The aim is to provide a punch and die set for proper clinching of three or more different material combinations and/or thickness combinations. This problem can be also solved by using ARSM. Here, the maximum of all single-neck thicknesses is defined as the objective function (to be maximized). As constraints,

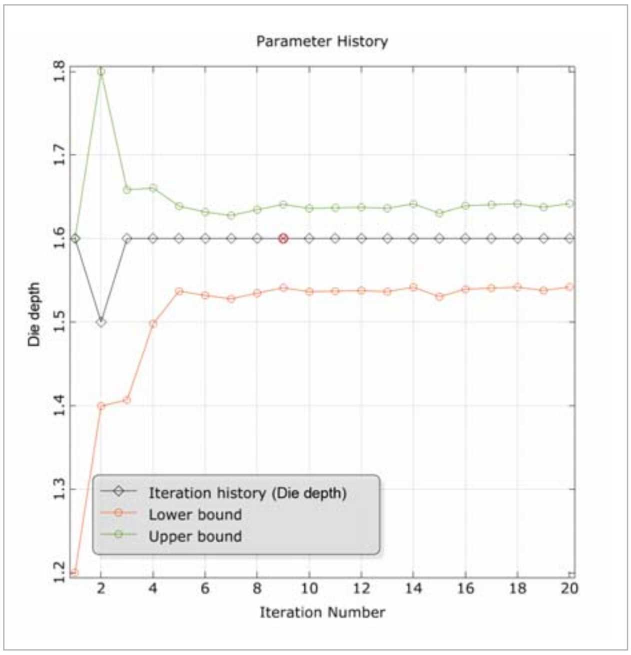

Fig. 8c: parameter die depth

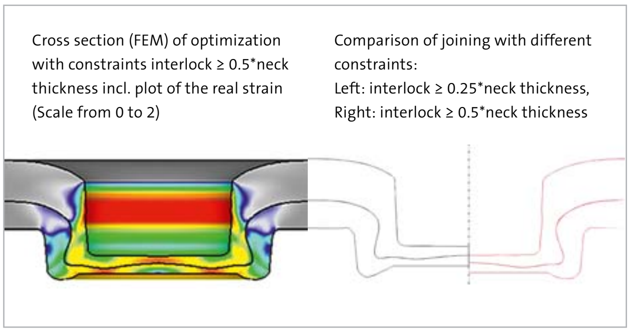

Fig. 9: cross sections of optimal joints with different constraints

cessary. Therefore, a careful determination of parameters (flow curves) is essential. Additionally, realistic coefficients of friction for the four friction pairs have to be determined. In contrast to the sensitivity analysis, a deviation of the prediction accuracy of the FEM always leads to inaccuracies of the optimization results. Furthermore, the implementation of the material damage as a limit or objective function has not yet been possible. For this purpose, adequate damage criteria for clinching and corresponding limits for the sheet materials still have to be investigated.

Sensitivity toward process uncertainties

Parameter and result responses

The clinching process is affected by a variety of process uncertainties. Material properties such as yield strength, tensile strength, braking elongation or the sheet thickness of semi-finished products are typical to be subject of tolerances (Will 2006). Due to changes in the state of lubrication and surface shapes, during the process of clinching, the friction values also vary over a lifetime period of a die set (about 200,000 to 400,000 points). Furthermore, effects of abrasion or adhesion may occur. Here, an assessment of quantity regarding realistic limits and distribution functions is, however, very difficult to determine. A locally varying intensity of deformation or associated pre-hardening of the sheets by previous forming processes (e.g. bending or deep drawing) is also possible.

Figure 11 shows the parameters for clinching disregarding the tool and machine stiffness in the present considerations. Looking closely at these parameter blocks, it appears

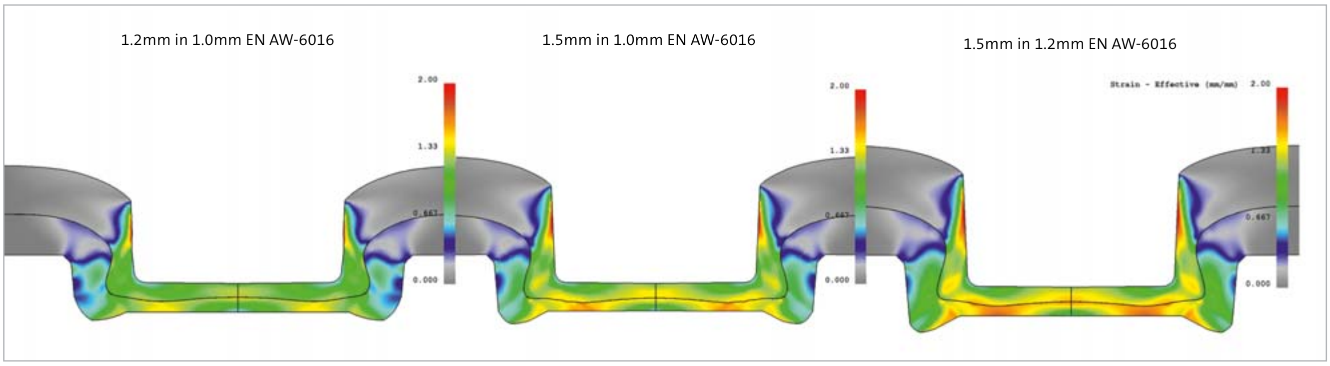

Fig. 10: cross sections of optimized joints; different combinations of sheet thicknesses, constant material and dies

the compliance of an interlock minimum of 0.15mm and a maximum counter-piping of the blanks from the die of 0.2mm were chosen. The cross sections of the FEM at the three sheet thickness combinations in Figure 10 show, impressively, the potential of this approach for tool optimization.

An issue can be seen, however, in the fact that for optimization a precise match of experiment and simulation is necessary. they are resulting in a large number of individual values. For example, there are four frictional combinations: blank holder/sheet, punch/sheet, sheet/sheet and die/sheet. The used parameters and their related scatter ranges evaluated from the analysis are shown in figure 12. As result values, neck thickness, interlock and the joining force are evaluated compared to the design parameters in the same way as in the foregone sensitivity analysis.

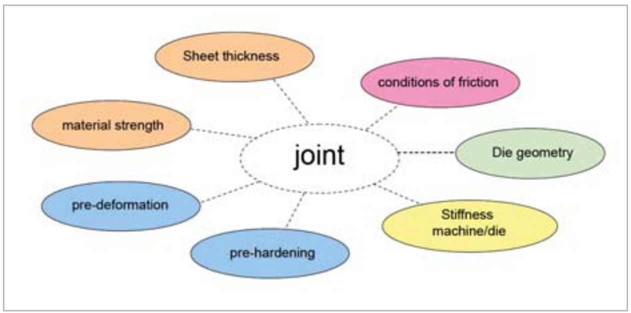

Fig. 11: Selection of relevant process parameters of mechanical joining subjected to tolerances

		Uncertainty	Min	Max
sheet material	upper	thickness in mm	1.36	1.64
		tensile strength in N/mm²	170	240
	bottom	thickness in mm²	0.9	1.10
		tensile strength in N/mm²	170	260
friction factors		punch - upper sheet	0.15	0.45
		blank holder - upper sheet	0.15	0.45
		upper sheet - bottom sheet	0.15	0.45
		die - bottom sheet	0.15	0.45

Fig. 12a: Uncertainties and their variation: limits

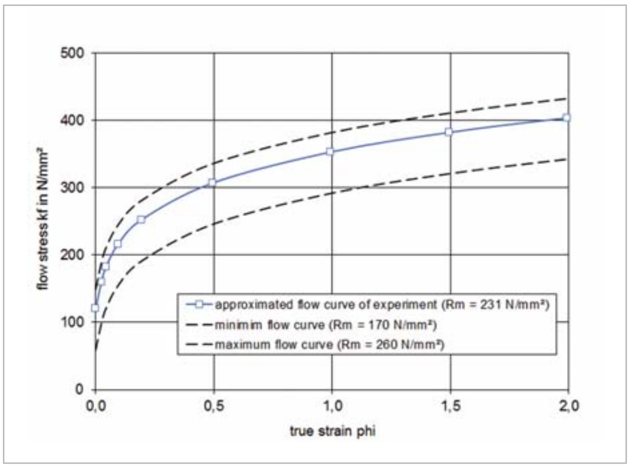

Fig. 12b: Uncertainties and their variation limits: scheme of the flow curve shift

Results of the robustness evaluation

The influence of the neck thickness by parameter variations can be considered as moderate. Values in the range from 0.47 mm to 0.63 mm are expectable.(see Figure 13, right). With a CoP of 97%, the predictive capability of the meta model is adequate. The greatest influence on the objective is affected by the variation of the sheet thicknesses, wherein the variation of the bottom thickness within the accepted scatter range causes more effects on the neck thickness than the variation of the upper thickness. The friction between the two sheets causes a rather small effect. However, a variation of the material strength has virtually no significant effect on the specification of this geometric size.

The critical point in terms of a very small neck thickness (and the associated low joint resistance or an increased risk of cracking during forming) consists in the use of minus-tolerated sheets on the punch-side and plus-tolerated sheets on the die-side. Appropriate strategies to avoid reaching this extreme range may be a limited tolerance width of the sheets or, at least, a check of the sheet thickness.

Even a CoP-value of 89% allows a sufficient prognosis for the evaluation of parameters influences on the interlock. It is also mostly affected by the thickness of the bottom sheet. In contrast, the sheet thickness variation of the upper sheet is of negligible relevance. On the other hand, the formation of the interlock is strongly affected by two friction pairings: the

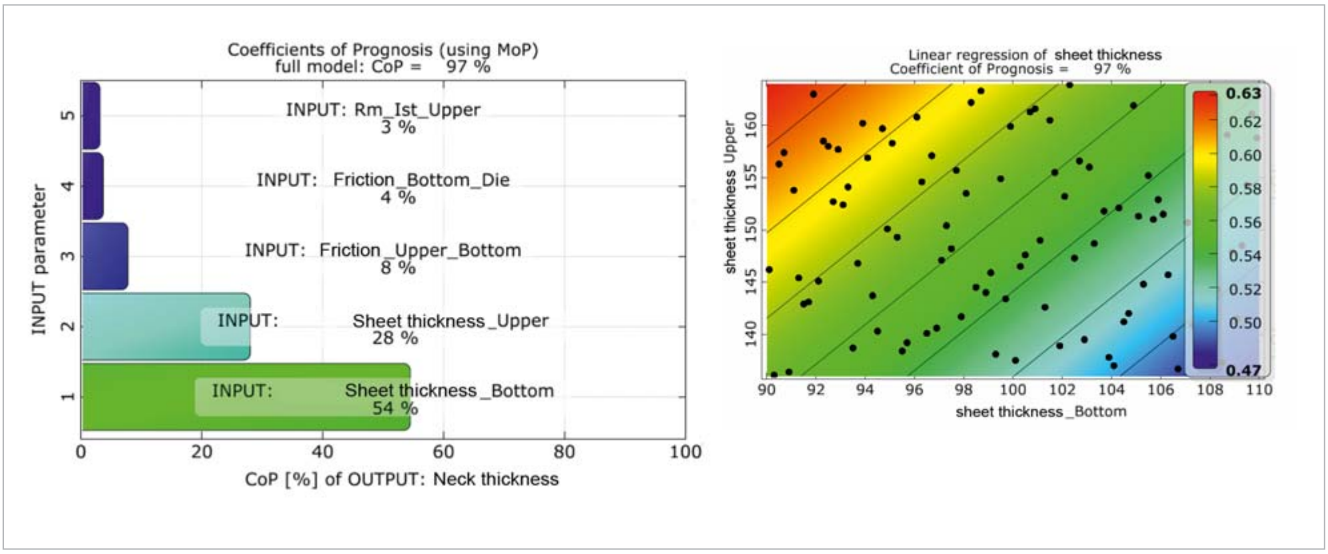

Fig. 13: Relevant influencing variables on the neck thickness

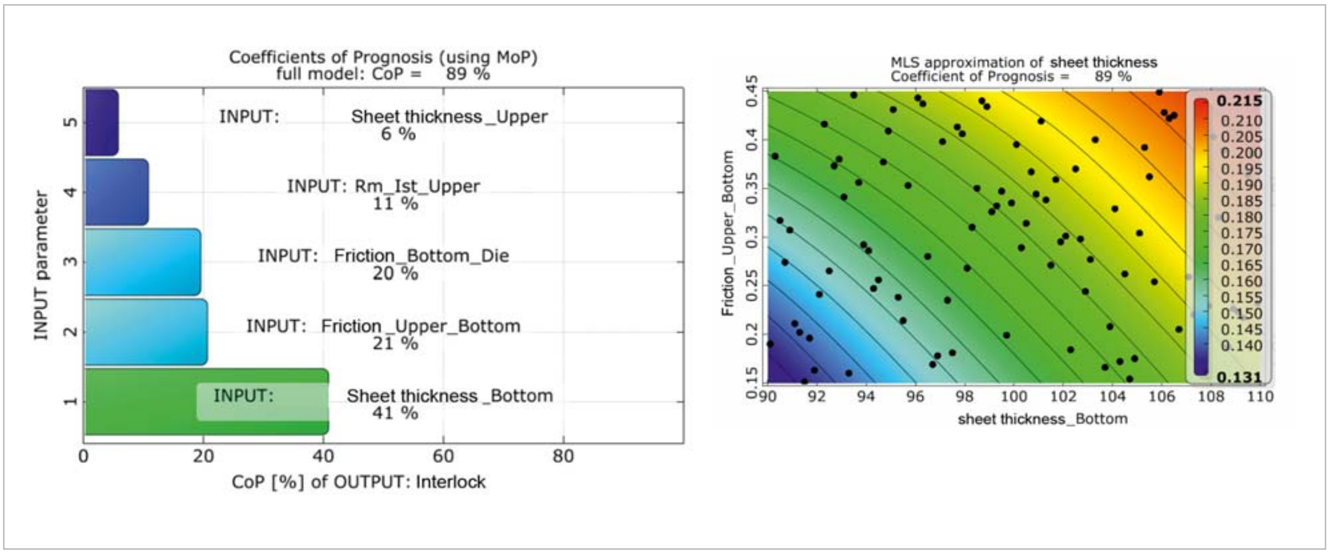

Fig. 14: Relevant influencing variables on the interlock

friction between the sheets and the friction between bottom sheet and die. The tendency of a rising interlock is associated with increasing sheet thickness (bottom) and higher friction between the sheets as well as between sheet and die.

In comparison to the neck thickness, the percentage changes of the interlock due to parameter variations are higher: values of 0.131mm to 0.215mm are to be expected (see Figure 13, right). Here, avoiding a negative tolerance of the bottom sheet, lubrication or lubricant residues on the friction pairings sheet/sheet and die/sheet will lead to less scatter of the interlock. Thus, a robust process can be ensured.

As the sensitivity analysis already indicates, both objectives are affected contrarily by the relevant parameters. Thus, for example, an avoidance of critical values concerning the interlock by ordering exclusively plus-tolerated die-side sheets increases compounds with a low neck thickness. Such changes in the production process are very costly and should be evaluated critically. The analysis of the process robustness allows, however, to gain knowledge about critical parameters and parameter combinations that can be utilized as a basis, for example, to implement a selective control of the relevant parameters as a quality assessment in the development process.

Summary and Outlook

A process chain, being increasingly numerical, especially in the automotive production, requires a profound understanding of the joining processes to improve quality standards and to explore cost saving potential. So far, the various capabilities and applications of FE simulation for sensitivity analysis, robustness evaluation and optimization have not been considered much in the mechanical joining technique. The performed sensitivity and robustness analysis for clinching indicates the potential of the numerically based analysis of clinching processes. From a variety of parameters that affect the joining process, in such studies, the relevant impact parameters are filtered and being provided either for process optimization or an evaluation of the process robustness. The so obtained process knowledge exceeds the previously, often experimentally-generated, understanding and correlation studies. The possibility to assess parameters to such a complex extent and number, never been reached in experiments before, allows to obtain new insights and to find global and general correlations.

Based on these initial studies for clinching, further analysis will be conducted on other frequently used mechanical joining methods. The main focus of further research in the automotive industry is on the increasingly used self-pierce riveting technique. The challenges will be the numerical description of the material separation, the expansion of computing stability and accuracy. As demonstrated in the sensitivity analysis for clinching, mechanical and technological characteristics of the materials, as well as the frictional conditions, are the basic data of the simulation representing the fundamental basis for a realistic numerical analysis. When this data is available, the CAE-based sensitivity analysis and robustness evaluation of joining processes will be a key source of information for method comparison and selection of appropriate joining technologies.

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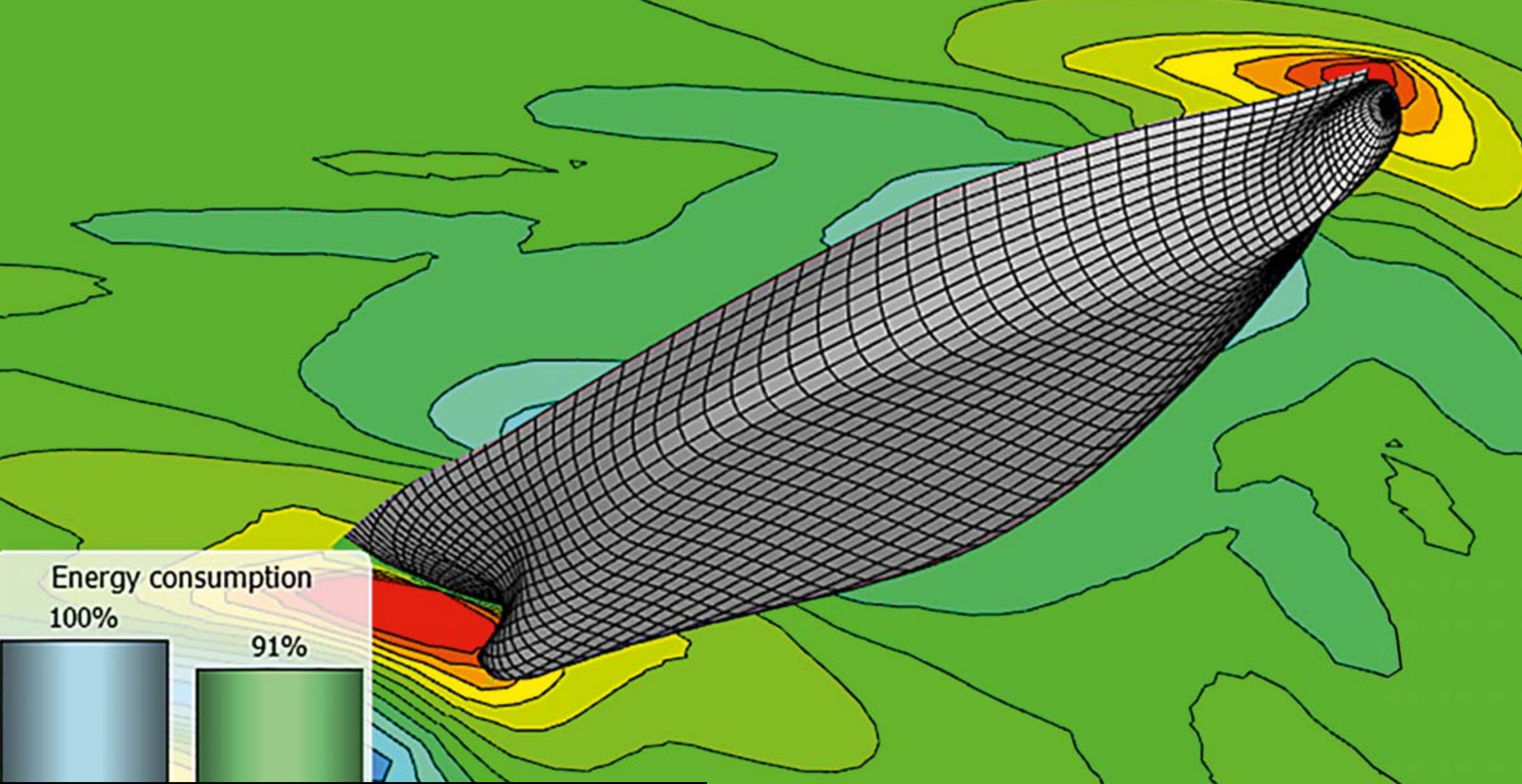


OPTIMIZATION AND ROBUSTNESS ANALYSIS IN SHIP DESIGN

By using optiSLang in combination with FRIENDSHIP-Framework and SHIPFLOW, a ship hull geometry optimization and robustness evaluation were conducted with an automated process chain and a minimum amount of solver runs.

Optimization task

In this presented case study, a given ship hull geometry is optimized by using optiSLang in combination with FRIENDSHIP-Framework and SHIPFLOW. The geometry is initially imported to FRIENDSHIP-Framework and transformation strategies are configured in order to deform the shape automatically by changing a set of design variables. Figure 1 shows the imported geometry in FRIENDSHIP-Framework. The generated design variants are analyzed by using the marine CFD software SHIPFLOW and Dynardo's optiSLang.

In the first stage, some hydrostatic calculations are configured in FRIENDSHIP-Framework in order to keep track of the ship hull's center of buoyancy (CB) and its displacement (V). The CB longitudinal position (XCB), as well as V, are allowed to vary only in a certain range with regard to the baseline design so that they are defined as inequality constraints.
Three different regions of the ship hull are deformed. For global changes of the geometry, a Generalized Lackenby Transformation [1] is applied. It allows shifting the inner part of the hull in a smooth way by entering delta values for XCB and V, such as a change of -1% for XCB and 1.5% for V (note that in marine applications, the change of V is usually defined via the change of the prismatic coefficient CP). When deforming the hull, it is also important to consider so-called hard points which are positions that need to lie strictly within the hull such as points for container arrangements.

Moreover, the stability of the hull needs to be guaranteed for which a characteristic stability value (KM) of the hull is used. It can be received from the hydrostatic calculation for each new design and needs to be larger than a specified minimum value. This minimum KM-value and the hard point positions lead to additional inequality constraints.
For more local changes of the aft part (skeg/transom) and the forward bulb geometry, curve and surface shift functions are utilized. See figure 2 for an example where the bulb is shifted upwards. The amount of the shift is controlled by a user-defined function curve. In this work, the bulb is smoothly moved in x-, y- and z-direction where each direction is configured with a separate shift function.

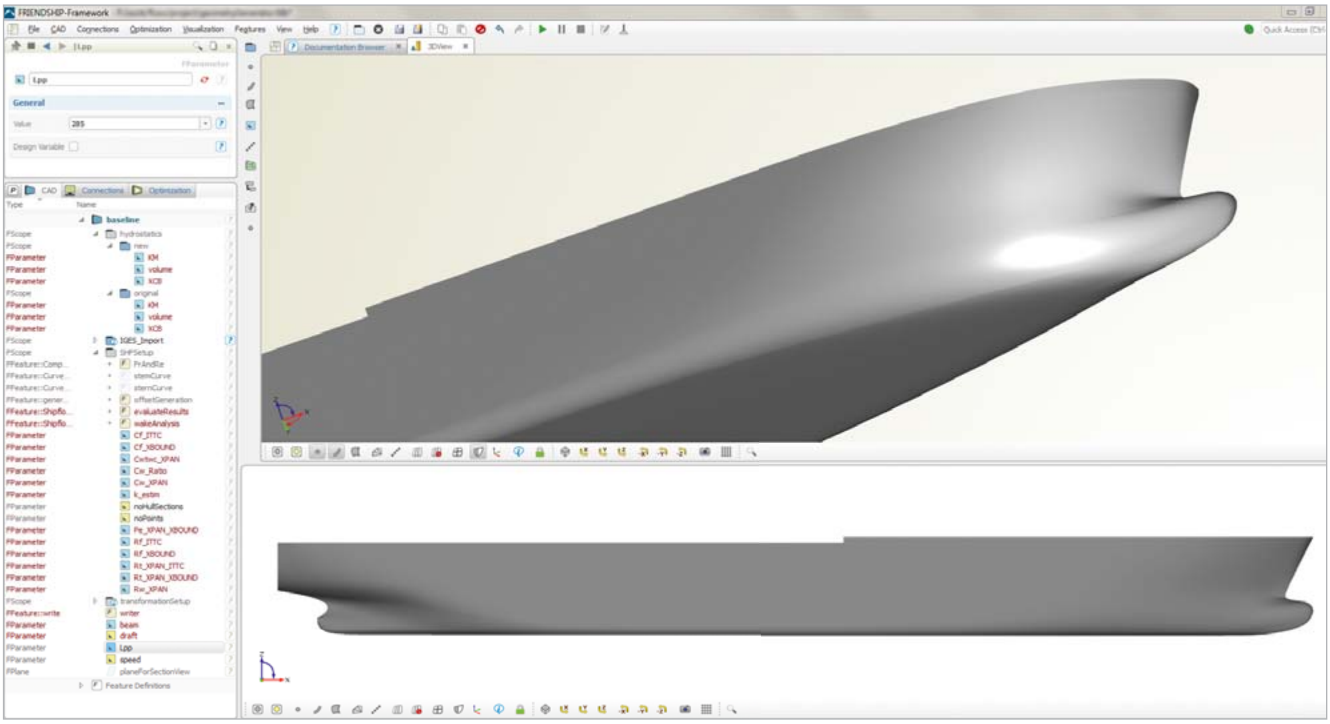


Fig. 1: Ship hull shown in FRIENDSHIP-Framework

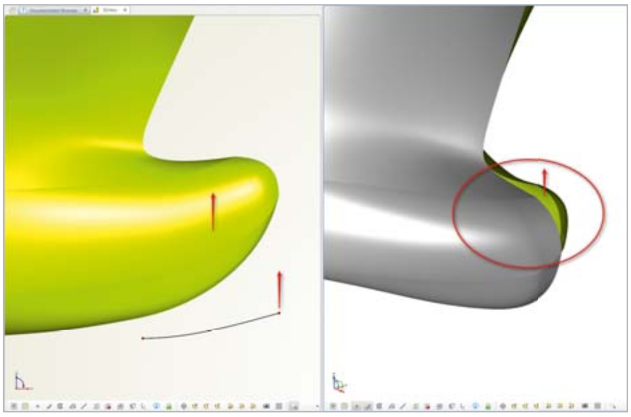
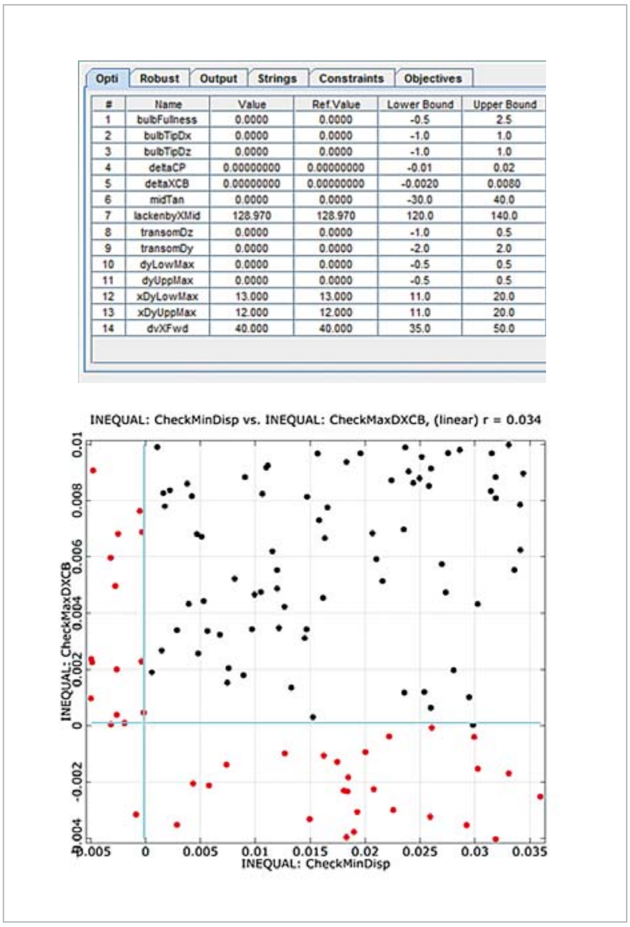


Fig. 2: Upwards deformation of the bulb using a shift transformation that is controlled by a user-defined function curve.

Sensitivity analysis

Defining 14 design parameters (see figure 3 top) with upper and lower bounds, as given in this table, and the performance-relevant responses, the sensitivity analysis is performed using a latin hypercube sampling in three steps to explore the total design space as thoroughly as possible. An extrapolation of the design parameter's bounds can be used in every step to extend the optimization potential. But of course, as a consequence, this results in more samples which are located in the unfeasible design space, as seen in the lower portion of figure 3.

The modification of the parameter bounds is simply based on an extrapolation of the so called Metamodels of Optimal Prognosis (MOP). For example, in case of the violation of the maximal longitudinal center position, the assigned control parameter of the hull's center of buoyancy can be enhanced up to 0.01 (see figure 4).



Opti | Robust | Output | Strings | Constraints | Objectives

#	Name	Value	Ref.Value	Lower Bound	Upper Bound
1	bulbFullness	0.0000	0.0000	-0.5	2.5
2	bulbTipDx	0.0000	0.0000	-1.0	1.0
3	bulbTipDz	0.0000	0.0000	-1.0	1.0
4	deltaCP	0.00000000	0.00000000	-0.01	0.02
5	deltaXCB	0.00000000	0.00000000	-0.0020	0.0080
6	midTan	0.0000	0.0000	-30.0	40.0
7	lackenbyXMid	128.970	128.970	120.0	140.0
8	transomDz	0.0000	0.0000	-1.0	0.5
9	transomDy	0.0000	0.0000	-2.0	2.0
10	dyLowMax	0.0000	0.0000	-0.5	0.5
11	dyUppMax	0.0000	0.0000	-0.5	0.5
12	xDyLowMax	13.000	13.000	11.0	20.0
13	xDyUppMax	12.000	12.000	11.0	20.0
14	dvXFwd	40.000	40.000	35.0	50.0

Fig. 3: Lower and upper bounds to define the box constrains used within optimization

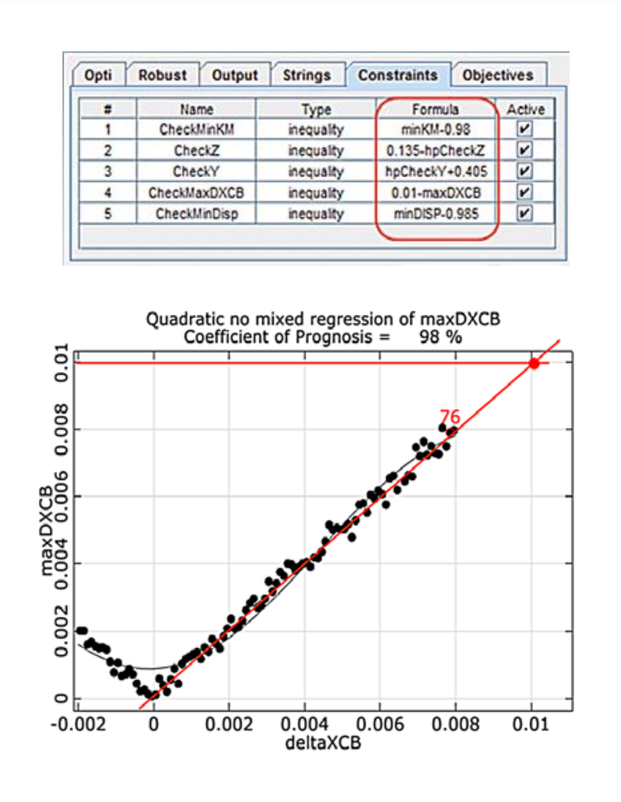


Fig. 4: Extrapolation of the design parameters to make accessible optimization potential

Parameter	**Description**
Design parameters and random variables	
Bulb Full-ness	Global fullness of the bulb geometry i.e. smooth changes to the bulb's width
Bulb Tip DX	Longitudinal position of the bulb tip
Bulb Tip DZ	Vertical position of the bulb tip
Delta CP	Percental change of the prismatic coefficient that allows smoothly increasing or decreasing the hull's displacement V
Delta XCB	Change of the longitudinal position of the hull's center of buoyancy
Mid Tan	Additional control of Generalized Lackenby Transformation, controls the middle tangent of the displacement shift function
X Mid	Additional control of Generalized Lackenby Transformation, controls the longitudinal mid position of the displacement shift function
Transom DZ	Vertical shift of the transom's lower edge in z-direction
Transom DY	Width of the transom, i.e. transom shift in y-direction, 5 additional variables for the skeg part for smoothly shifting the geometry in y-direction
Random variables	
Sref	Wetted surface at zero speed
dens	Water density
visc	Water kinetic viscosity
Lpp	Length between perpendiculars
Re	Reynolds Number
Response values and objectives	
CWTWC	Wave resistance coefficient from transverse wave cut
CW	Wave resistance coefficient from pressure integration
CF	Frictional resistance coefficient
Constraints	
hpCheckY	Hard points check in y-direction (HP: positions that are required to be strictly within the hull)
hpCheckZ	Hard points check in z-direction
maxDXCB	Maximum percental change allowed for longitudinal position of the hull's center of buoyancy
minDISP:	Minimum displacement for modified hull shape
minKM	Minimum KM-value for modified hull shape (KM: characteristic stability value of the hull)

Table 1: Design parameters and random variables

For each new design a CFD analysis is triggered using SHIPFLOW. As a result, the response values of the Table 1 are returned and used for setting up an objective function:

$$Rt = (1.0 \cdot CWTWC + 1.2 \cdot CF)\left(0.5 \cdot dens \left(Re\frac{visc}{Lpp}\right)^2 Sref \cdot Lpp^2\right)$$

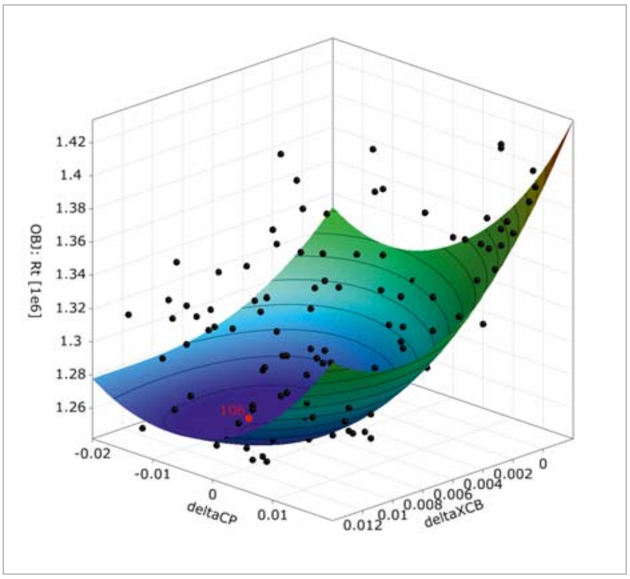


Fig. 5: Surrogate model of the objective function Rt, approximated as meta-model of optimal prognosis in the subspace of the both most important design variables.

Optimization

The constrains, as shown in Table 1, have to be checked during the optimization process to ensure the hard point checks in y- and z-direction, the maximal longitudinal center position and the characteristic stability of the hull. The surrogate model of the objective function Rt, as shown in Figure 5, is

Response value	Initial design	Sensitivity analysis	Evolutionary optimization	Sequential quadratic programming
CWTWC [$\times10^{-4}$]	2.27	1.02	0.766	0.666
CF [$\times10^{-3}$]	1.44	1.43	1.42	1.42
Design evaluations	1	312	1	192

Table 2: Results of the ship design optimization with 506 design evaluations, in summary.

approximated as meta-model of optimal prognosis based on 312 design evaluations of a latin hypercube sampling. This meta-model is used for pre-optimization in the total dimensional design space using an evolutionary algorithm. The resulting best design is used as a starting point for a gradient-based optimization using a sequential quadratic programming algorithm with additional 192 design evaluations. Table 2 collect the results of these optimization steps.

Robustness evaluation

In engineering problems, randomness and uncertainties are inherent and may be involved in several stages, for example in the ship design with material parameters and in the manufacturing process and environment. To evaluate the mean design improvements, their possible deviations and the estimated exeedence probabilities, a robustness analysis is carried out. The histograms of the objective terms as result of the 120 design evaluations show a significant improvement of the weighted objective function with large exeedance probabilities (92% and 95%) in comparison with the initial values of CWTWC and CF. Besides the small mean value shift of the optimized CWTWC value, the given distributions show a robust design improvement of the wave resistance coefficient and the frictional resistance coefficient of the hull shape.

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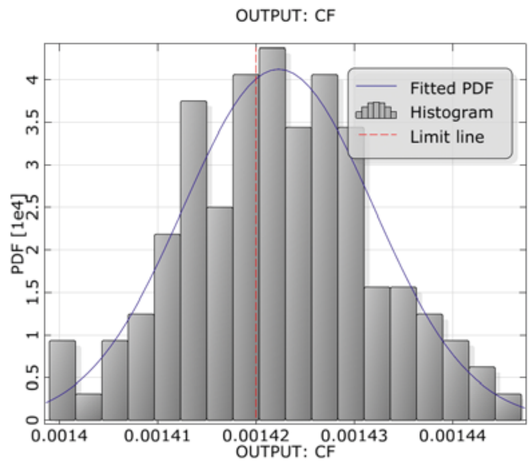
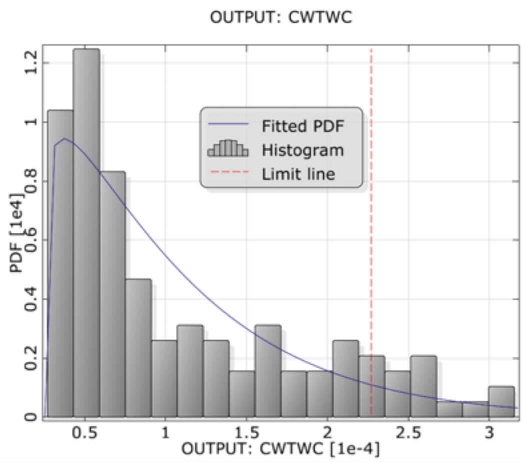


Statistic data			
Min:	0.001399	Max:	0.001447
Mean:	0.001422	Sigma:	9.671e-006
CV:	0.006799		
Skewness:	-0.02388	Kurtosis:	2.831
Fitted PDF: Normal			
Mean:	0.001422	Sigma:	9.671e-006
Limit x = 0.00142			
P_rel =	0.425	P_fit =	0.405673
Probability P(X<x) = 0.95			
x_rel =	0.00144	x_fit =	0.00143822



Statistic data			
Min:	2.708e-005	Max:	0.0003155
Mean:	0.0001095	Sigma:	7.5e-005
CV:	0.6848		
Skewness:	0.986	Kurtosis:	2.757
Fitted PDF: Extreme Typ III (Max) Weibull			
Mean:	0.0001095	Sigma:	7.5e-005
Lower cut:	2.708e-005		
Limit x = 0.000227			
P_rel =	0.891667	P_fit =	0.921784
Probability P(X<x) = 0.95			
x_rel =	0.000265817	x_fit =	0.000258658

Fig. 6: Histograms of the objective terms as result of the robustness analysis.

ANNUAL WEIMAR OPTIMIZATION AND STOCHASTIC DAYS

Dynardo's conference for CAE-based parametric optimization, stochastic analysis and Robust Design Optimization (RDO) in virtual product development.

Our annual conference aims at promoting the successful application of parametric optimization and CAE-based stochastic analysis in virtual product design. The conference offers focused information and training in practical seminars and interdisciplinary lectures. Users can talk about their experiences in parametric optimization, service providers present their new developments and scientific research institutions inform about state-of-the-art RDO methodology. We explicitly do not only invite optiSLang users as lecturers or participants, we also offer everyone who is interested in the topic a platform of exchange with acknowledged specialists from science and industry. You will find more information and current dates at www.dynardo.de/en/wosd.

We are looking forward to welcoming you to the next Weimar Optimization and Stochastic Days.

METHOD OVERVIEW

Process automation and process integration

- Workflow definition via graphical user interface
- Reliable use with help of wizards
- Robust default settings for all algorithms
- Connection of arbitrary complex process chains
- Generate and use templates of process chains
- Parallelization and distribution of design evaluation
- Direct integration of Matlab, MS Excel, Python and SimulationX
- Supported connection of ANSYS, Abaqus, Adams, MADYMO
- Arbitrary connection of ASCII file interfaced solvers
- Full integration of optiSLang in ANSYS workbench
- Python interfaces to optiSLang algorithmic library
- Automatic generation and adaption of user flows via python scripting

Sensitivity analysis

- Classical Design of Experiments
- Advanced Latin Hypercube Sampling
- Correlation coefficients (linear, quadratic, rank-order)
- Principal Component Analysis
- Polynomial based Coefficient of Determination
- Polynomial based Coefficient of Importance
- Metamodel of Optimal Prognosis (MOP) with Coefficient of Prognosis (CoP)
- MOP/CoP based sensitivity indices for important variables

Multidisciplinary nonlinear optimization

- Continuous, discrete and binary design variables
- Gradient based optimization (NLPQL)
- Global Response Surface optimization using MOP with best design validation
- Adaptive Response Surface Method
- Evolutionary Algorithms (EA)
- Particle Swarm Optimization (PSO)
- Stochastic Design Improvement
- Multiobjective optimization using weighted objectives
- Multiobjective Pareto optimization with EA and PSO
- Start design import from previous samples

Parameter identification

- Parametrization and monitoring of response signals
- Signal function library including FFT, filtering etc.
- Sensitivity analysis using MOP/CoP to check identifiability
- Flexible definition of identification goal functions
- Local and global optimization methods to search for optimal parameters

Robustness evaluation

- Continuous and discrete random variables
- More then 20 probability distribution functions
- Distribution fits using measurements
- Correlated input variables using the Nataf model
- Monte Carlo and Advanced Latin Hypercube Sampling
- Statistical assessment of output variation including:
  - histograms with automated distribution fits
  - stochastic moments
  - quantile and sigma level estimation
- Sensitivity analysis with respect to random variables using correlations and MOP/CoP

Reliability analysis

- Definition of arbitrary limit states
- Monte Carlo and Latin Hypercube Sampling
- First Order Reliability Method (FORM)
- Importance Sampling Using Design Point (ISPUD)
- Directional Sampling
- Asymptotic Sampling
- Adaptive Response Surface Method

Robust Design Optimization (RDO)

- Sequential and fully coupled procedures
- Variance based RDO
- Reliability based RDO
- Flexible definition of robustness measures using e.g. mean values, variances, Taguchi loss functions and probability of failure
- Consideration of robustness measures in optimization constraints and objectives functions

Post processing

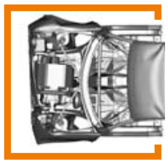
- Statistic post processing including anthill plots, correlation plots and sensitivity indices
- Approximation post processing including 2D and 3D plots of response surfaces and the MOP
- Optimization post processing including Pareto frontier and convergence history of design variables, responses, objectives and constraints
- Show solver output images
- Parallel coordinates plot
- Traffic light plot
- Full interaction of single plots
- Design classification using coloring, selection/deselection
- High quality outputs in BMP, PNG, SVG, EPS and PDF format

CONSULTING, SUPPORT, TRAININGS

Dynardo's consulting team has extensive expertise in the application of CAE-based analysis and Robust Design Optimization in the fields of structural mechanics and dynamics. At seminars and events, we provide basic or expert knowledge of our software products and inform about methods and current issues in the CAE sector.







CAE-Consulting

We offer individual calculation and simulation services in the fields of automotive, mechanical and civil engineering as well as micro-mechanic and process engineering. We support you in all phases of product development: from the first predevelopment and feasibility studies over sensitivity analysis up to the development of the optimal design with robustness evaluation and reliability analysis. Due to the company's combination of software development and consulting, we achieve in various industries a high amount of flexibility referring to special market requirements in the CAE sector.

Support

The main interest of the optiSLang support team is a successful customer. Therefore, we provide technical support by phone, e-mail or online. All requests are processed thoroughly and answered immediately. Besides questions concerning our software products optiSLang, multiPlas, SoS and ETK, also feel free to ask about efficient RDO application and its various methods to solve the CAE-challenges in your particular field of business.

Free information days and webinars

With our free info days and webinars, you can get an introduction to performing complex, non-linear FEM calculations using optiSLang and multiPlas.

Simulations in construction and geomechanics

The participants get an explanation of advanced simulation options in combination with the finite element programs ANSYS and LS-DYNA. Information about comfortable 3D modeling, particularly for complex structural geometries, in linear and nonlinear structural mechanics, in structural dynamics or in multi-physics simulation.

Robust Design Optimization (RDO) with optiSLang and optiSLang inside ANSYS Workbench

This event provides an overview of optimization techniques and appropriate stochastic methods of robustness evaluation with optiSLang inside ANSYS Workbench. Examples show how the software components are used to investigate a design space systematically, to determine sensitivities, to perform optimizations with competing goals and to consider the effect of scatter influences.

Trainings

For a competent and customized introduction to optiSLang, visit our basic or expert trainings explaining the theory and application of sensitivity analysis, multidisciplinary optimization, robustness evaluation and Robust Design Optimization (RDO) in a compact way. The trainings are not only directed to engineers, but are also perfectly suited for decision makers in the CAE-based simulation field. For all trainings there is a discount of 50% for students and 30% for university members / PHD's. You can find an overview of the current training program at our homepage.

Internet library

Our internet library is a perfect source for your research on CAE-Topics and practical examples of CAE-based RDO. There you will find state-of-the-art information matched to all different fields of methods and applications.

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