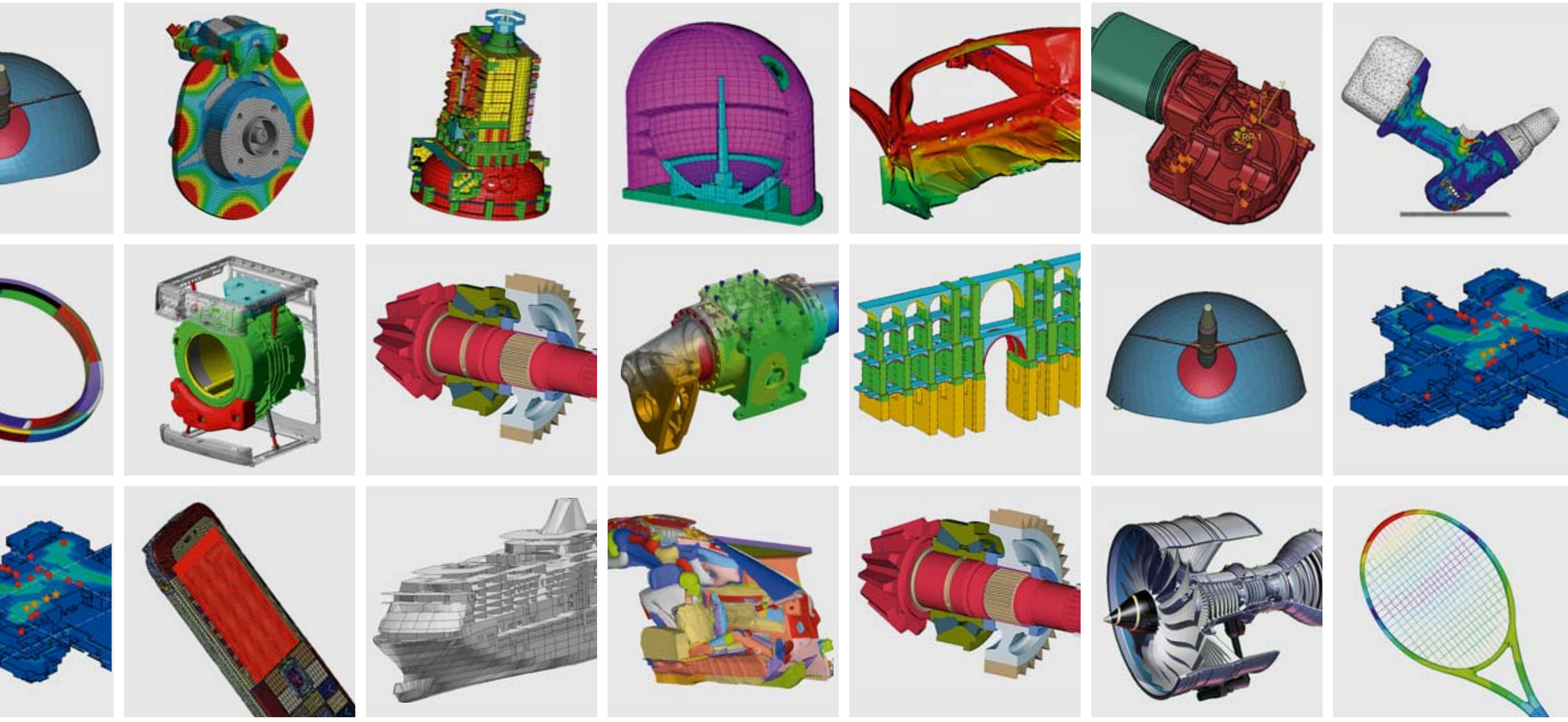
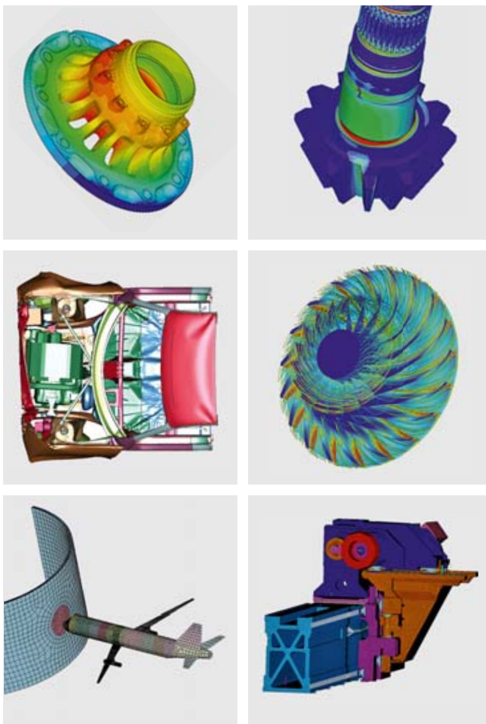




01/2012

Robust Design Optimization (RDO) –
Key technology for resource-efficient
product development
and performance enhancement

# RDO-JOURNAL

optiSLang
multiPlas
ETK
SoS


## DYNARDO ERSCHLIESST SICH NEUE RÄUME

**Dynardo ist in den letzten Jahren stetig gewachsen. Unser lieb gewonnenes Büro im Lutherhof in Weimar hatte seine Kapazitätsgrenzen längst erreicht. Es bestand Bedarf zur Optimierung. Nach langer Suche haben wir in der Steubenstraße 23/25, in zentraler Lage, ein neues Domizil gefunden. Im frisch renovierten Gebäude ist jetzt wieder viel Platz für Ideen, Kreativität und Wachstum.**

**Neue Adresse ab 01.01.2013**
**99423 Weimar**
**Steubenstraße 25**

# NEW SPACES, NEW OPPORTUNITIES

As our company creates new spaces for innovative potential, the CAE-based Robust Design Optimization (RDO) also opens up a lot of opportunities for customers to enhance their product performance and to push resource-efficient development. In recent years, users have made significant progress to successfully integrate sensitivity analysis as well as robustness and reliability evaluations into RDO applications. The significance of RDO methods for resource-efficient product design has been more and more realized and implemented in the virtual prototyping. Users can quickly and easily perform sensitivity studies and RDO analysis by using automated algorithms and, thus, results can directly affect engineering improvements in the development process. A basic requirement for a broad application of RDO is the simplicity of system integration, process automation coupled with a user-friendly automated selection of appropriate algorithms as well as the use of "best practice" defaults. "Easy and Safe to Use" is our main objective being implemented in the new software versions optiSLang inside ANSYS Workbench and optiSLang version 4.x.

Performing RDO means to find optimal solutions by considering a huge variety of input and output variables, optimization variables and objective parameters. In order to manage this challenge, Dynardo has set itself the task of providing efficient methods and software to engineers and to help find the most important parameters and the best possible meta model of prognosis for design optimization. Additionally, Dynardo provides, in collaboration with worldwide distributors, consulting and computing services as well as support and training for our software products optiSLang, Statistics on Structure (SoS) and multiPlas. Thus, we can offer our customers around the world tailor-made solutions at the highest level of quality.

The steadily growing demand for RDO methods on domestic and international markets brought up the idea of publishing an RDO-Journal. With this brochure, we want to inform about multidisciplinary case studies of successful integrations of RDO methods in virtual product development. Practical examples taken from our consulting work explain the methods of solution and make the customer's benefit clear considering enhancement of product performance and resource efficiency.

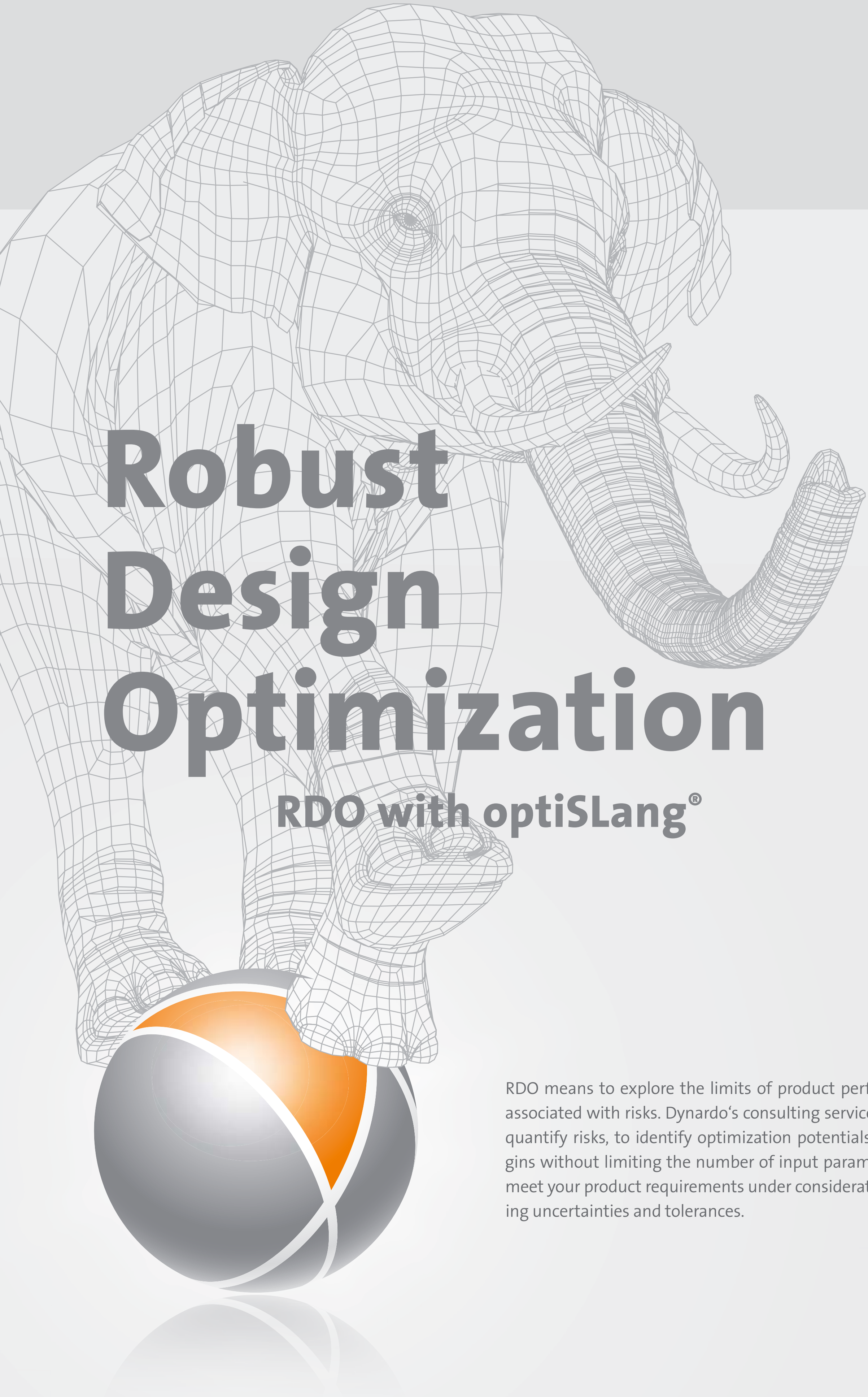
I hope that our journal contains informative and interesting examples for every reader and promotes the advanced approach of RDO methodology.

Yours sincerely

Johannes Will
Managing Director Dynardo GmbH

Weimar, November 2012

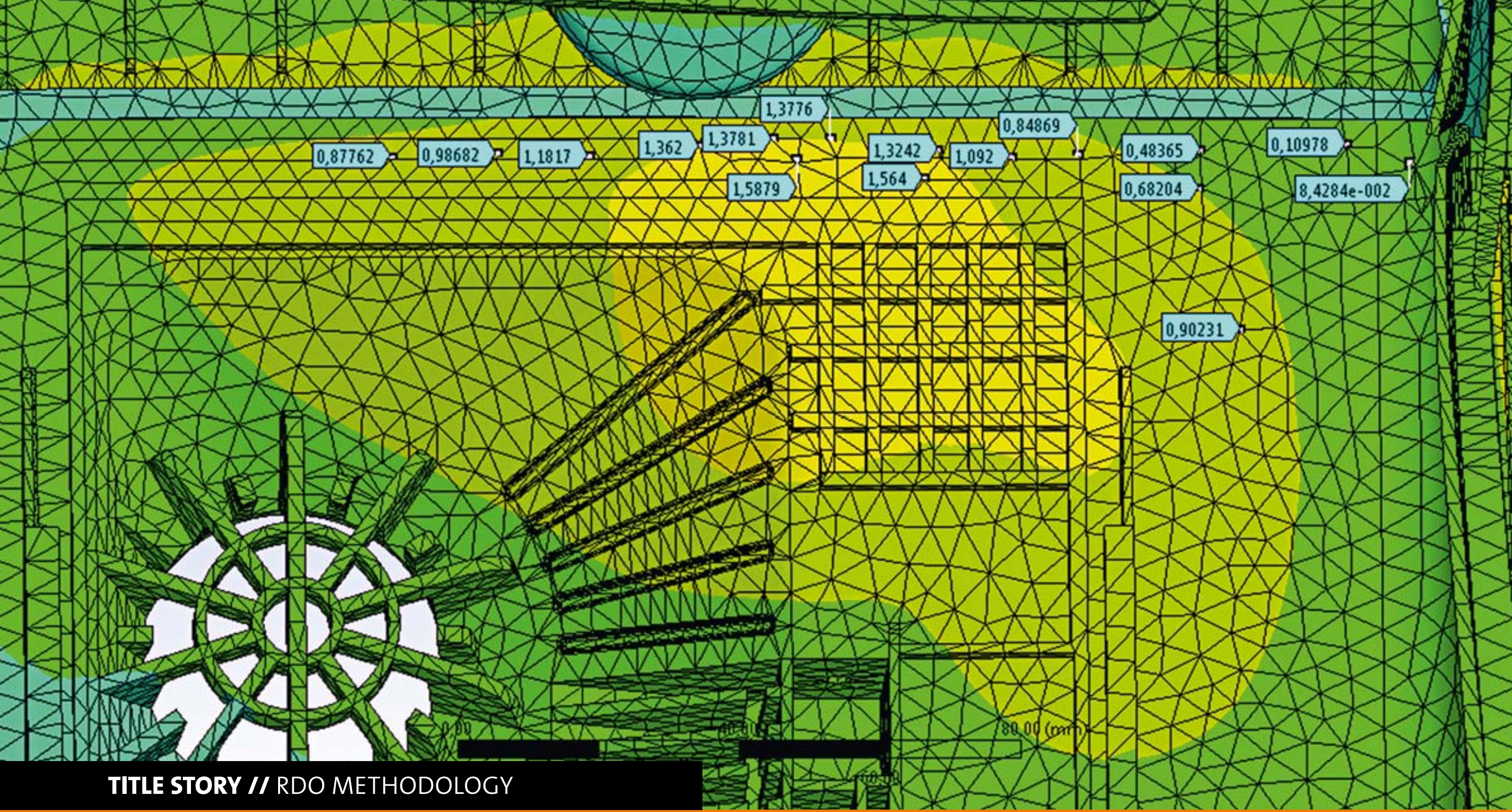
## CONTENT



# Robust Design Optimization

## RDO with optiSLang®

RDO means to explore the limits of product performance, which might be associated with risks. Dynardo's consulting service and software help you to quantify risks, to identify optimization potentials and to adjust safety margins without limiting the number of input parameters. Thus, you can safely meet your product requirements under consideration of all potentially affecting uncertainties and tolerances.






# CAE-BASED ROBUST DESIGN OPTIMIZATION IN THE VIRTUAL PRODUCT DEVELOPMENT

**CAE-based optimization and stochastic analysis are key technologies to improve resource-efficient product development, to enhance product performance and to secure the quality requirements of reliability and robustness.**

The speed of development and introduction of technical innovations, as well as the requirements for the optimization of products, demand more than ever a virtual product development. A distinction has to be made between the construction of designs (Computer Aided Design-CAD) and the calculation or the detection of functionality by simulation methods (Computer Aided Engineering-CAE). Here, CAE-based optimization and stochastic analysis are key technologies to improve product performance while proving the quality requirements of reliability and robustness. At the same time, efficient strategies of Robust Design Optimization (RDO) are required to secure the optimization results and robustness evaluations.

## Variant studies, parametrics, and process automation

For 20 years, CAE-based optimization strategies, ranging from manually generated variant studies of DOE techniques, topology and design optimization to multi-disciplinary optimization of parameters, have been gradually integrated into the product development and the production process. In addition to stand-alone solutions for the optimization of individual disciplines and product requirements, there is now a trend using parametric modeling environments that open up the potential to combine CAD and CAE parametric calculation. Thus, several disciplines and product requirements are connected to each other. Products can be optimized automatically by intelligent variant calculations of multiple disciplines and simulations considering CAD and CAE constraints. As a prerequisite, consistent parameterization as well as integration and automation of simulation processes are a necessity of modern RDO processes. This leads to an increased number of parameters which have to be considered. Tasks with a dozen up to a few hundred parameters become normal and represent both parameters to be optimized and scatters to be considered.

## Optimization and robustness in conflict?

Optimization goals, such as weight reduction and performance optimization are frequently in conflict with robustness and reliability of products. This is nothing new. Of course, at all times, engineers have been concerned about the balance between optimization and reliability. This is illustrated in the example of the Dombauhütten during the

Fields of Application

Consumer Goods Industry

Mechanical and Process Engineering

Energy Industry

Civil Engineering and Geomechanics

Automotive Industry

Aerospace industry

Bioengineering

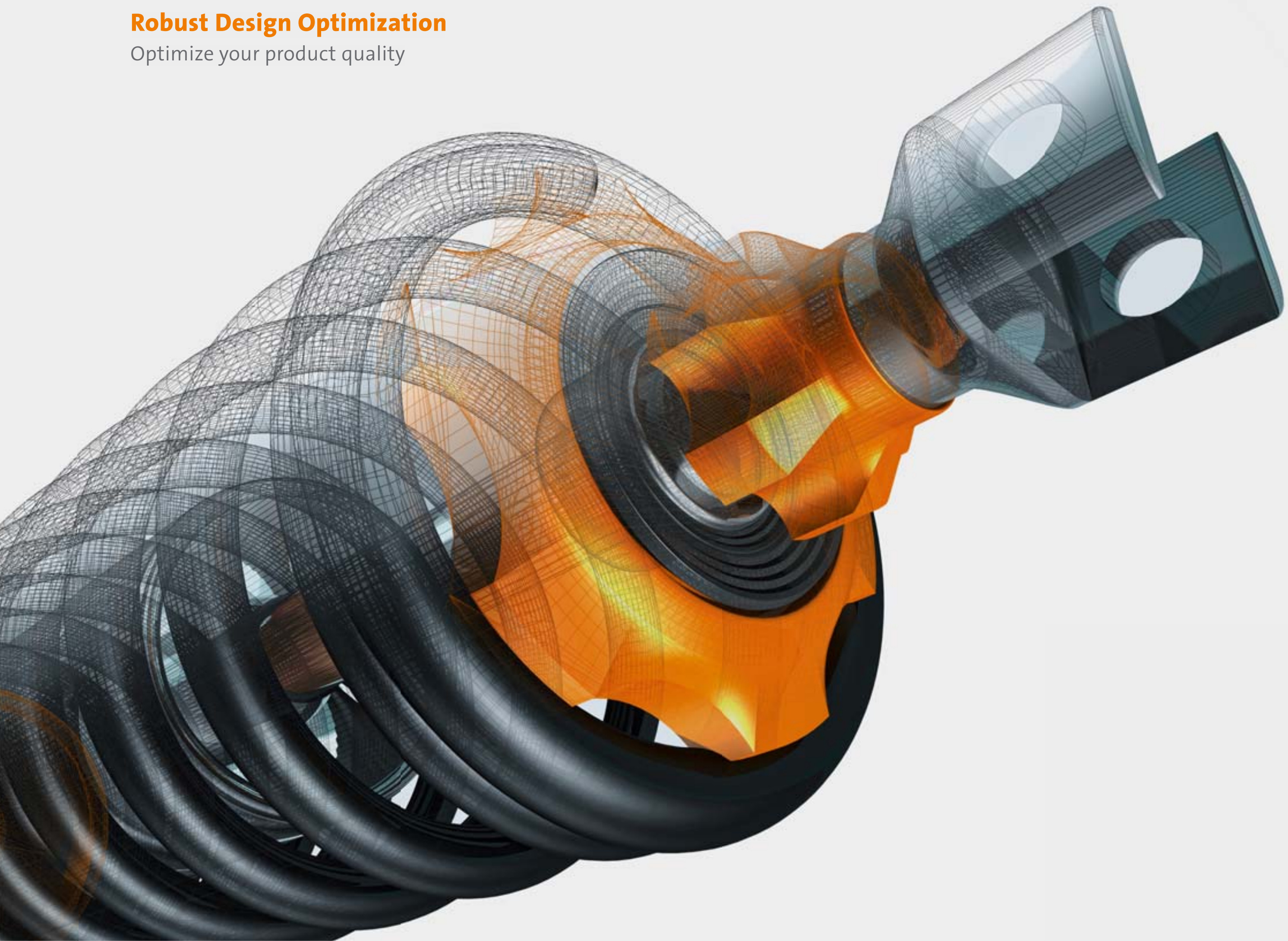
# RDO Methodology

**Sensitivity analysis**
Identify the most important input variables

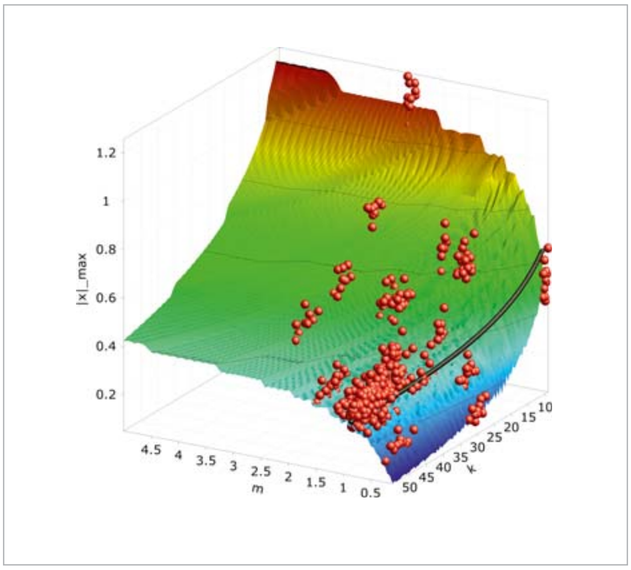
**Multiobjective & multidisciplinary optimization**
Choose the best design for production

**Robustness evaluation & reliability analysis**
Quantify your product quality

**Robust Design Optimization**
Optimize your product quality



Middle Ages. In the Romanesque time, window openings were narrow and arched in a semi-circular shape. From a static point of view, this was very safe. Later, facades became more and more sophisticated and the arcs more risky from a robust point of view. Step by step, the master builder exceeded the known limits of feasible static structures and many churches remained unfinished or simply collapsed. Design rules for masonry structures were derived from these experiences, some of which are still popular today. These safety margins have been established to construct the most sophisticated church buildings. They contain sufficient safety margins considering subsoil uncertainties, geometrical tolerances of the church buildings or material scatters. The implementation of CAE-based optimization follows, in many aspects, these operation methods of engineering to compare different design variants.



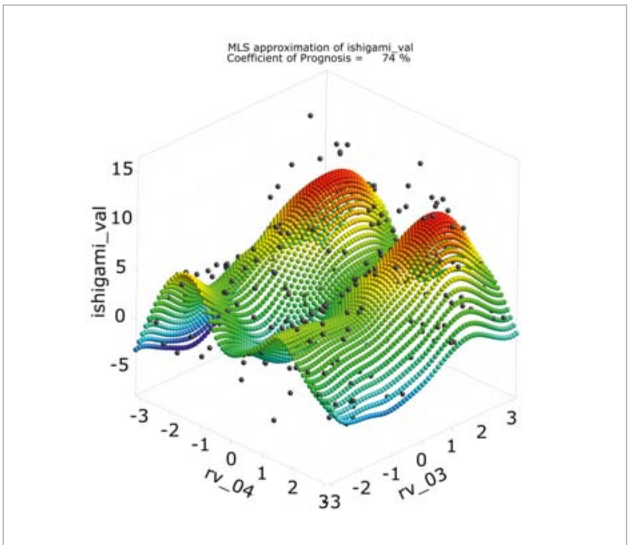

Evolutionary Algorithm solving constraint optimization problem with noisy objective function

## What are the challenges of integrating RDO in the virtual product development?

Of course, the definition of the optimization task (transferring design requirements into objective functions and constraints), the variation space (parameterization of the design space) and the optimization strategy (optimization methods) strongly affect the optimization potential. The introduction of CAE-based stochastic optimization methods requires a significant extension of previous "deterministic" calculation processes. The challenge is to maintain the balance between the definition of the input scatter, the method of stochastic analysis, the estimation of variation and the correlation measures for the evaluation of robustness and reliability.

In order to obtain reliable estimations of outcome variations as a basis of any evaluation of robustness and reliability, all relevant input scatters have to be considered in an appropriate manner. This is an issue concerning the implementation of RDO strategies. It is understood that a detailed knowledge of all potentially affecting variables and an adequate parametric determination of all input scatters appear to be an almost insurmountable obstacle in stochastic analysis. But, waiting for a perfect knowledge will probably lead to no development at all. Therefore, a pragmatic approach is to start with conservative assumptions about all potentially relevant scattering input variables. Thus, for important scattering input variables, the knowledge and the discretization of the definition of scattering input variables can be gradually increased.

Another obstacle for the introduction of stochastic analysis is the fact that a standard deviation or a probability can only be estimated and not (deterministically) calculated. Therefore, the outcome for the user will be an estimation, not a real numerical result. In order to obtain a trustworthy and, thus, a firm estimation which can be used to evaluate product features, often more than one stochastic calculation is necessary. Basically, it must be accepted that the introduction of stochastic analysis for firm evaluation of robustness and reliability within an RDO process demands a significantly large number of nodes (samples of a stochastic analysis) in the region of several hundred or several thousand. Since a single design evaluation already requires a high amount of CPU capacity, it represents a significant challenge to the hardware, and if necessary, to the licenses conducting parallel calculation of designs. Therefore, the challenge in choosing a robust design optimization methodology is to keep a balance between the number of solver calls and the trustworthiness of the robustness and reliability measures. In all RDO methods, for an estimation of robustness measures, it is worthwhile to reduce the amount of real design nodes to a minimum. After a robust design optimization, a final evaluation of the presumptive optimal and robust design with appropriate methods of a reliability analysis is mandatory.

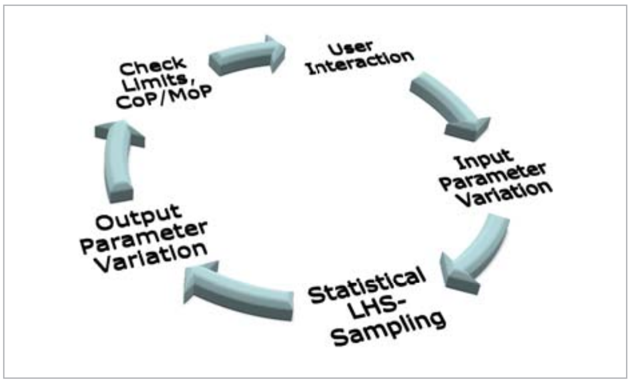



3D visualization of the Metamodel of Optimal Prognosis (MOP)

Due to the large number of sampling nodes in a stochastic analysis, RDO algorithms primarily use meta-models (response surface models) to estimate value variation. The usability of meta-models for robustness evaluation and reliability analysis is discussed controversially in literature. The amount of effort to generate appropriate meta-models depends strongly on the number of important scattering input variables, the non-linearity of the result spaces and the probability level of a robust design. In any case, there must be a final reliability analysis using real design nodes proving the robust design which was generated by meta-models.

## Integration status of Robust Design Optimization (RDO) in the virtual product development

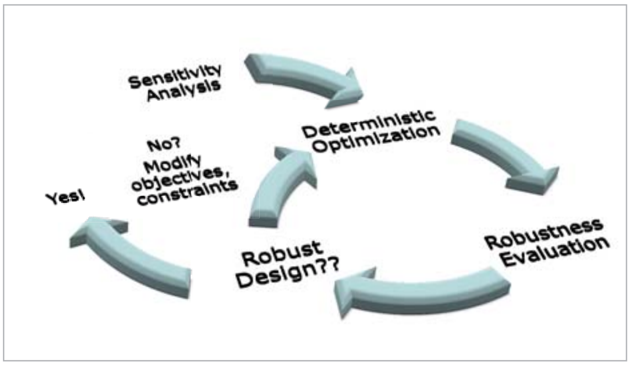
The first important step is to implement a trustworthy robustness evaluation of the most important result values regarding the influence of uncertainties and scatters. By this sensitivity analysis of the uncertainties and tolerances which potentially affect all important result values, a first estimation of variation and variable importance can be conducted.




Process chart robustness evaluation

In order to reduce the number of scattering variables to those being important for the result value variation and to prove the reliability of the estimation of variation values, an iterating approach is often necessary.

In the next step, safety margins are estimated to be considered in the implementation of a deterministic optimization. The generation of an optimized design using preset safety margins is followed by a stochastic analysis proving robustness or reliability. If the safety margins were not sufficient, optimization and robustness steps have to be repeated. This procedure (iterative RDO) is effective if the necessary safety margins are fairly constant in the optimization space. If the safety margins for proving a robust design vary greatly in different areas of the optimization space, it might be necessary to determine the variation of each design in the optimization space. These variation values are used to set constraints and objective functions of a robust design optimization. After that, methods of optimization and stochastic analysis can be automated and combined (automatic RDO). Usually, the effort of an automatic RDO compared to an iterative RDO increases significantly in the course of an analysis.




Process chart Robust Design Optimization

## Dynardo's optiSLang

In Dynardo's software optiSLang, the most efficient methods of optimization and stochastic analysis are integrated for the solution of RDO tasks. With the development of the CoP (Coefficient of Prognosis) and the automatic identification of the MOP (Metamodel of Optimal Prognosis) we provide outstanding algorithms for automatic detection of the most important parameters, automatic detection of the best possible meta model and verification of forecast quality of the MOP. Customers have successfully implemented RDO in their virtual product development. This is also confirmed by the lectures at Dynardo's RDO Conference - the Weimar Optimization and Stochastic Days. In order to implement even more RDO applications as an integrated part of product development and to provide this methodology also for customers without expertise in optimization and stochastic analysis, we have currently developed our "best practice" modular system. In the new software version "optiSLang inside ANSYS Workbench" and "optiSLang v4.0", necessary user input was minimized and automated defaults for variable reduction and the automatic generation of the best possible meta-model were implemented.

## Minimizing application obstacles

A successful integration of RDO methods in the virtual product development make high demands on the user. Parts of the application obstacles can be minimized in commercial software solutions by easy and safe to use RDO modules. However, if the assumptions on the input scattering for a chosen method of stochastic analysis and the reliability of the estimated variation are not in balance, the results of the RDO calculations are unusable. Therefore, it is recommended to introduce CAE-based RDO methods step by step in the virtual product development and to establish the verification of a trustworthy robustness evaluation as the basis of a reliable estimation of the variation of important output variables. The adjustment of the variation values with measurements and experience, as well as the verification of assumptions about scatters, should be permanently reviewed, verified and refined.

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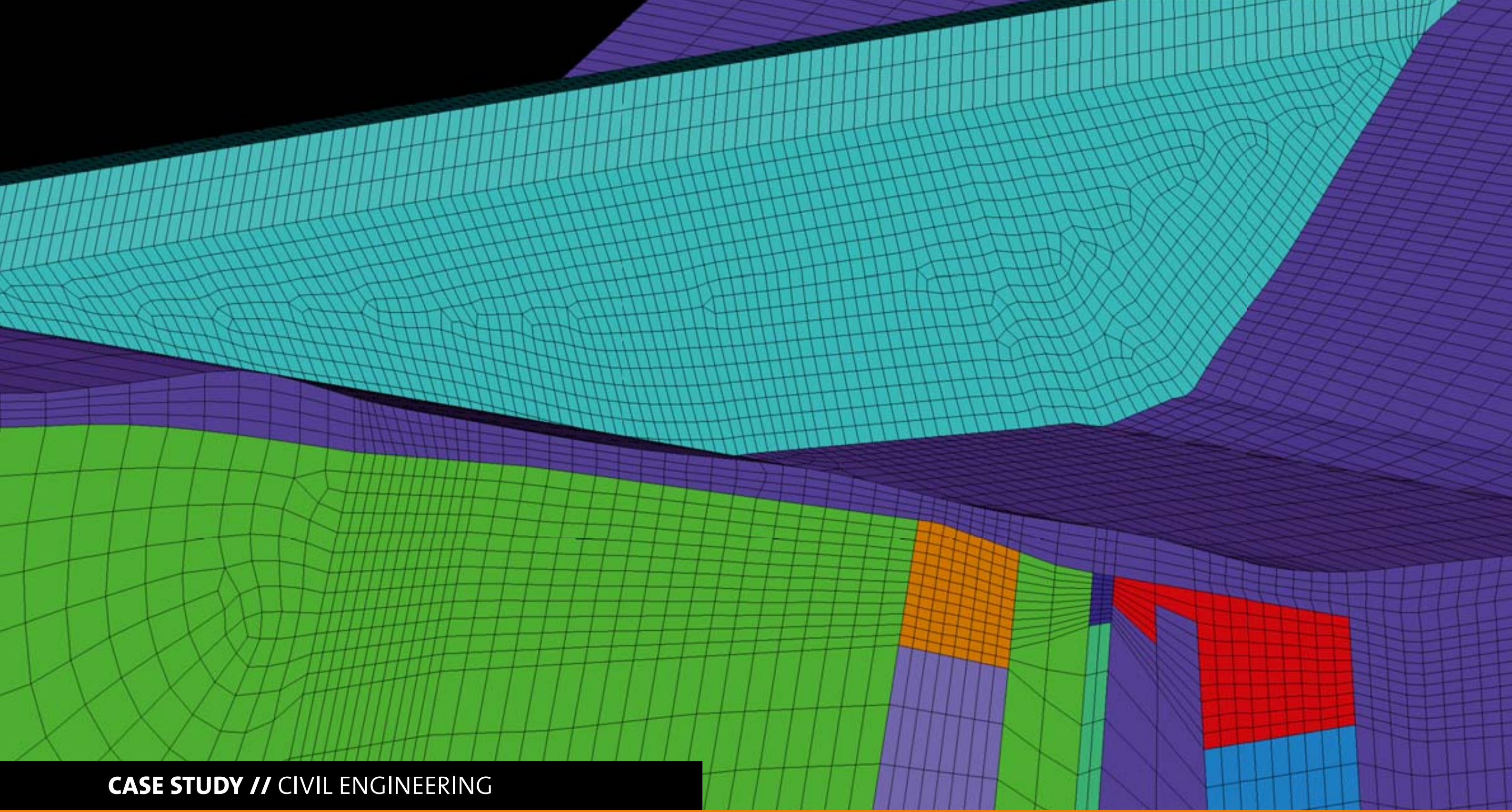




# HRB WALDBÄRENBURG: FIRST RCC DAM EXPERIENCE IN GERMANY

**Thermal and structural analysis with optiSLang help to plan the first Roller Compacted Concrete (RCC) dam in Germany as part of the national flood control programme of the Federal State of Saxony.**

## Project introduction

No RCC dams have been built in Germany to date. HRB Waldbärenburg could be the first one. The RCC dam technology has been chosen as it provides environmental advantages against other design alternatives: essential lower impacts in nature and scenery, shorter time of construction and a better ecological continuity through the dam. Some challenging aspects that need to be faced during the design and construction of the 40m-high dam are the short target RCC construction period (3 months) and the relatively extreme environmental conditions at the site during winter time. The use of a high fly-ash RCC mix concept has been proposed to reduce the heat generated in the concrete mass and to extend the setting time of the mix. A preliminary thermal and structural analysis was conducted in order to analyze the sensitivity of various parameters in the dam design.

## Thermal & structural analysis

The numerical simulations were conducted with the FEM program ANSYS and optiSLang as transient thermal-mechanical coupled analyses on the 3D model of the dam structure and a connected rock section. The non-linear finite element analyses consider the evolution of temperature and mechanical resistance depending on time and location within the dam structure. The calculations were carried out as load history calculations simulating the progress of dam construction in each of the 30 cm thick layers as well as the subsequent five years of operation.

### Methodology

Due to the complexity of the interaction between material parameters and the nonlinear analysis, the FE model was built parametrically. With the help of the optimization platform optiSLang, by conducting a sensitivity analysis it became possible to calculate different variants and to analyze the dependence between the resulting values and the input variables.

The goal of this sensitivity analysis was:

- identify those input parameters which influence mainly the concrete tensile stress forced by hydration
- analyze trends, such as changes in input parameters modifying the concrete tensile stress
- provide meaningful variation ranges for the input parameters

The predictive quality of the calculation results of the sensitivity analysis exceeds clearly those of a single calculation. The evaluation of the results considers particularly the tensile stresses in the concrete due to hydration. For this, at each time step, the current main tension stresses in the dam were compared with the current concrete tensile strength.

**Input data**

Within the sensitivity analysis, 100 designs were calculated using the optiSLang Latin Hypercube sampling. Here, all input parameters were changed in each design to have on optimal resolution of the design space as well as minimum correlation errors in the correlation analysis, which identifies the most import input variable. optiSLang controls the process of modifying the parameter and calling ANSYS to automatically solve the 100 designs as well as the statistical post processing to identify the important parameters.

**Thermal analysis and estimated stress development**

In the transient thermal analysis, influences of the seasonal changes of outside air temperature (reference data from the planned site), the heat radiation, the evolution of heat hydration and the temperature of the fresh concrete were considered. The evolution of heat hydration was calculated as a function of the level of hydration. Here, the maturity function of Arrehnius et al was used. This functionality was implemented in ANSYS using ANSYS APDL programming language.

The analysis of hydration is fundamentally determined by two major time and space dependent physical processes. This is, on the one hand, the temperature evolution and, on the other hand, the evolution of concrete resistance due to hydration. During construction, the concrete is strongly heated by hydration. At the same time, the concrete is cooled by convection on the outside. Therefore, the concrete expands more inside than on the outside causing compressive stresses inside and tensile stresses on the outside. After construction, the concrete reaches its maximum temperature in the core structure (Figure 1) and, by that time, has already reached a much higher resistance than in the heating phase. As a result, the stress conditions reverse during the cooling phase in the subsequent years. Now there is tensile stress within the building structure and compressive stresses on the outside. Figure 2 shows the distribution of tensile stresses directly after the construction of the dam and after 5 years.

## Conclusion

As a result of the sensitivity analysis, it became obvious that the amount of maximum tensile stress on the outside (water- and air-side) of the concrete as a result of hydration especially dependents on:

- horizontal distance between the vertical joints
- start of placing the concrete
- coefficient of thermal expansion

Thus, the major influences are structural and technological parameters. Furthermore, the results show that the maximum tensile stress on the concrete in the inner structure as a result of hydration is particularly influenced by:

- specific heat capacity of the concrete
- heat quantity of the concrete
- coefficient of thermal expansion

It mostly depends on the mixture and quality of the concrete. Only with this degree of diagnostic characterization of the thermo-mechanical analysis it is possible to truly understand the controls on the evolution of the tensile stresses and concrete tensile strength over time. With this approach, a predictive model for the evaluation and design of RCC dams is developed. By use of the predictive model, the RCC design as well as technological aspects can be optimized to provide the required safety levels.

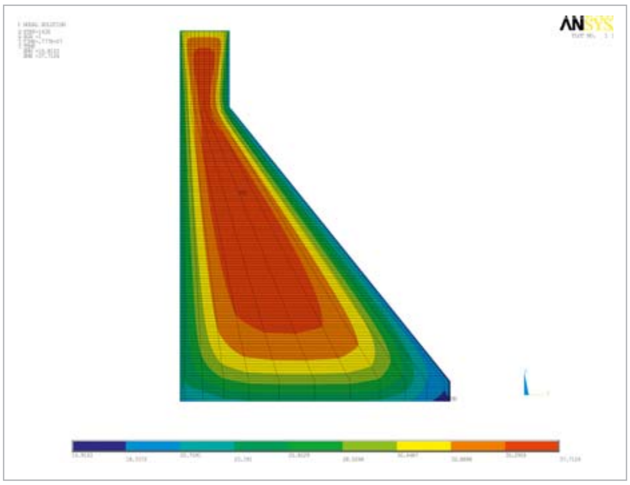



Fig. 1: Estimated temperature distribution after RCC placement

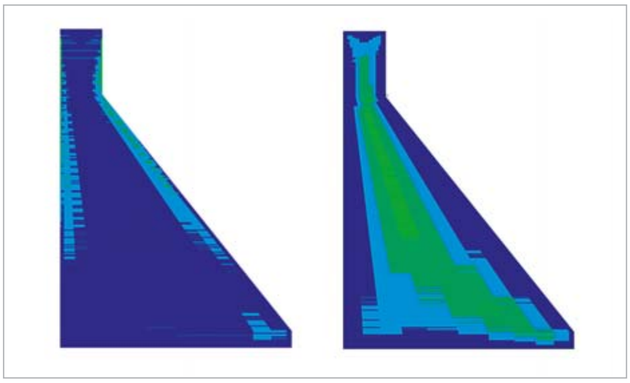
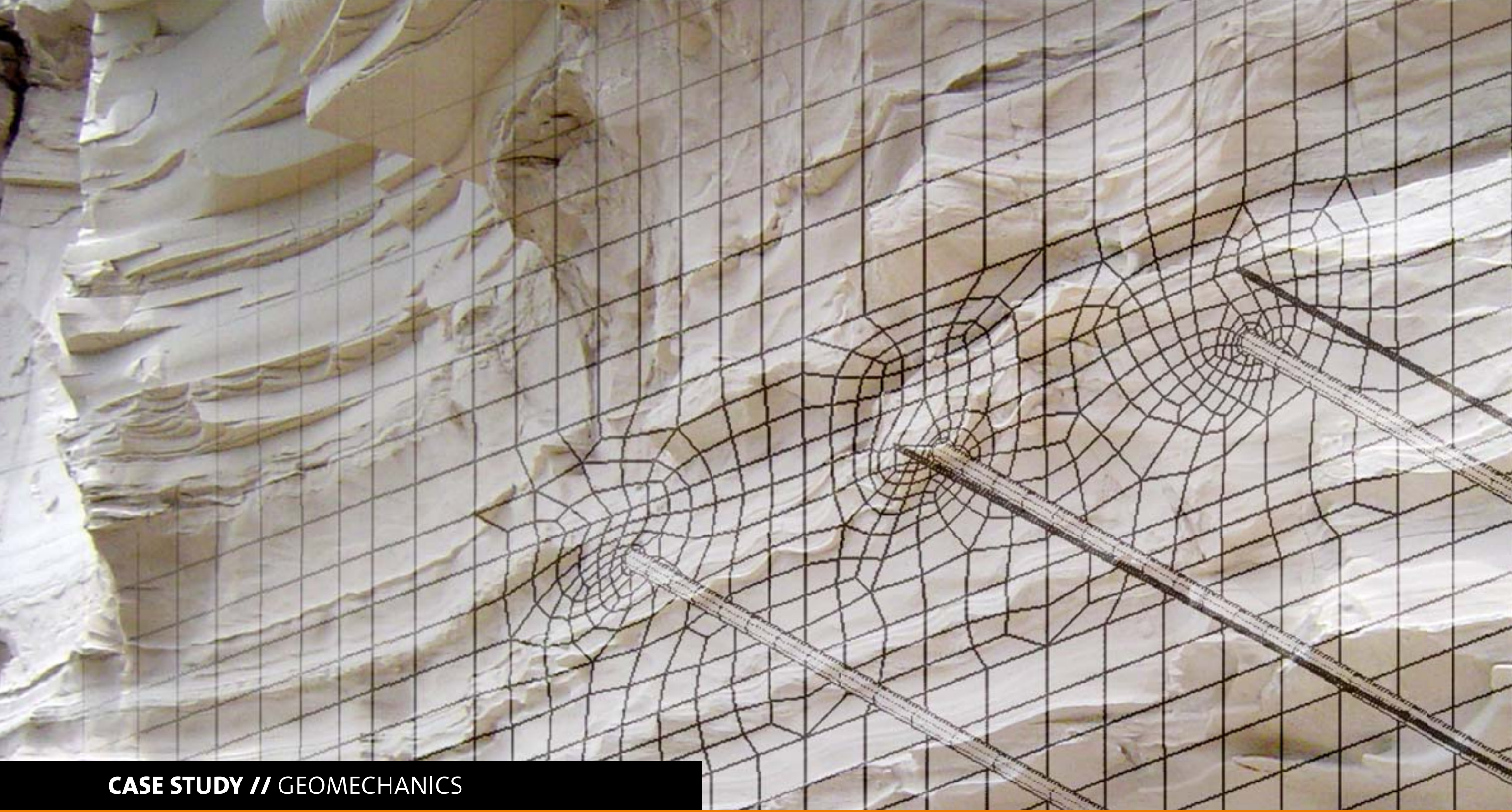


Fig. 2: Distribution of tension stresses, left: after RCC placement, right: after 5 years

**Authors //** B. Lange, F. Hering (LTV, Dam Authority of Saxony, Germany / R. Schlegel (Dynardo GmbH) / G. Leyendecker (IRP Consulting) / F. Ortega (FOSCE Consulting Engineers)



**CASE STUDY //** GEOMECHANICS

# PARAMETER IDENTIFICATION AND ANALYSIS OF UNDERGROUND LABORATORIES

**The DBE Technology GmbH and Dynardo performed an analysis of the Thermo-Hydro-Mechanical (THM) behaviour of claystone in response to artificial heating for the exploration of underground laboratories.**

## Project introduction

In search of suitable disposal sites for hazardous waste in underground laboratories, heating experiments are carried out to investigate thermal-hydraulic-mechanical interactions. In these experiments, the time depending changes of temperature, pore pressure and stress fields can be measured as a result of applying heat energy to rock formations. The DBE TECHNOLOGY GmbH developed, in collaboration with the Dynardo GmbH, simulation models which can be used to understand these interactions within the claystone formation. An important part of this development is the model calibration based on measurement results.

The heating experiment was simulated by the use of a Thermal-Hydraulic-Mechanical (THM) coupled, 3-dimensional finite element analysis with ANSYS and multiPlas. In this case, special routines for poroelasticity theories, thermal-hydraulic coupling and hydraulic-mechanical coupling were developed in isotropic or anisotropic claystone formations and implemented in ANSYS. The optimization software optiSLang was used for the sensitivity analysis and the parameter identification. The complexity of the thermal-hydraulic-mechanical phenomena required a number of about 30 model parameters. Decisive conditions for the successful calibration between measurement and simulation of such a complex task are, on the one hand, high-performance algorithms and filtering strategies for coping with large parameter spaces available in optiSLang, and, on the other hand, the short calculation time achieved by using ANSYS and multiPlas.

## Project aim

The aim of the computational analysis was the Thermal-Hydraulic-Mechanical (THM) coupled simulation of a heating experiment using a 3-dimensional simulation model. It should be proved that the THM interactions within the claystone can be simulated with reasonable accuracy and the simulation results can be compared with the available measurements. Using a sensitivity analysis, the essential interconnections between the measured end results and the input parameters should be identified.

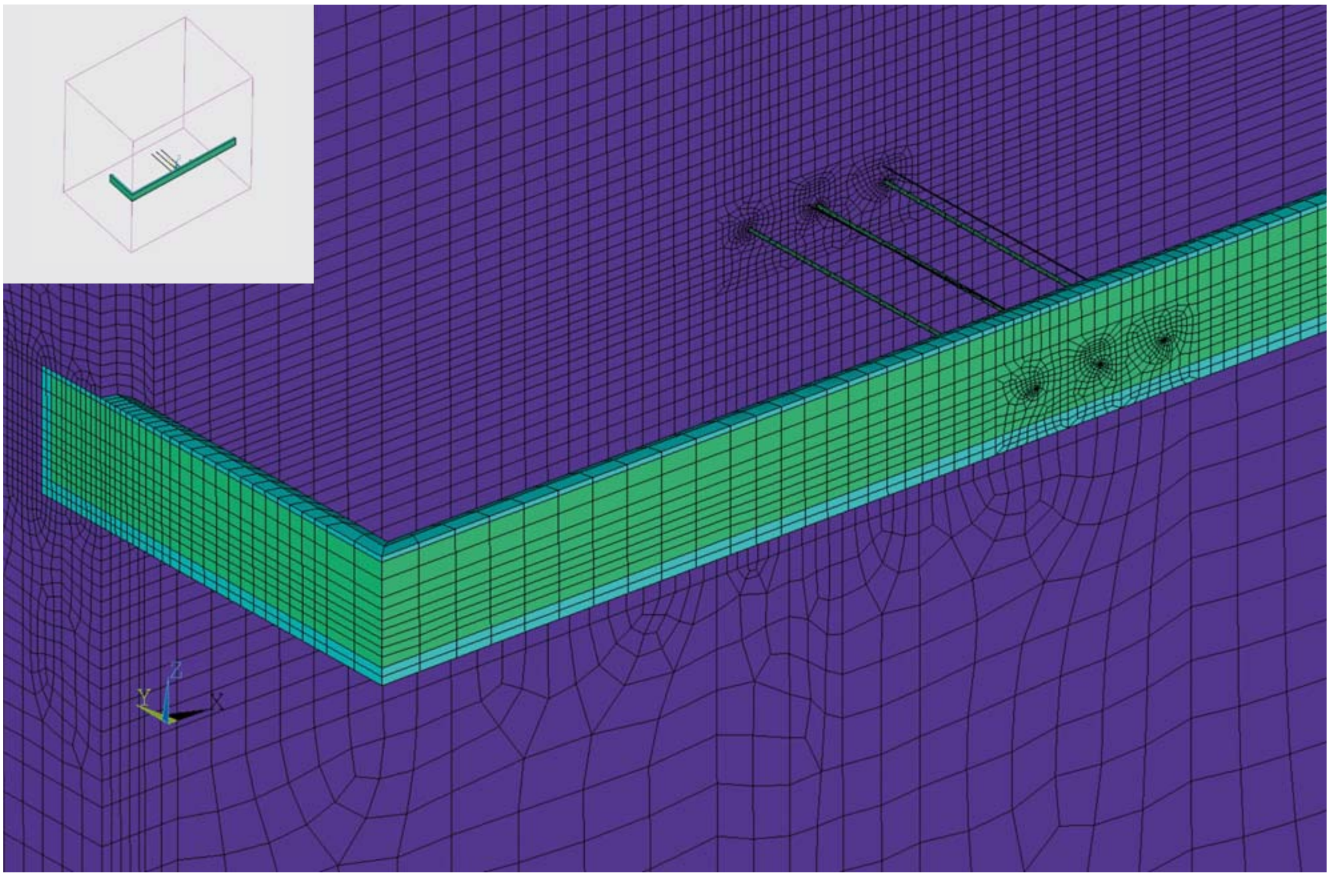



Figure 1: FE-mesh of structure, section

## Finite element simulation of heating experiments in underground laboratory

The heating experiment was simulated using a 3-dimensional finite element analysis (ANSYS and multiPlas). The initial state, i.e. the in-situ stress, pore pressure and temperature conditions, was activated by means of initial material properties and boundary conditions. The excavation of the tunnel was simulated by deactivating the corresponding element areas. Here, the increase of permeability was included in the excavation-damage zone. Subsequently, a nonlinear coupled T-H-M finite element analysis of each heating period of the experiment was conducted. Figure 1 shows a section of the FE model.

The experiment was carried out in three periods with a corresponding increase of temperature output of the three heaters. Figure 2 shows the evolution of the three heating periods.

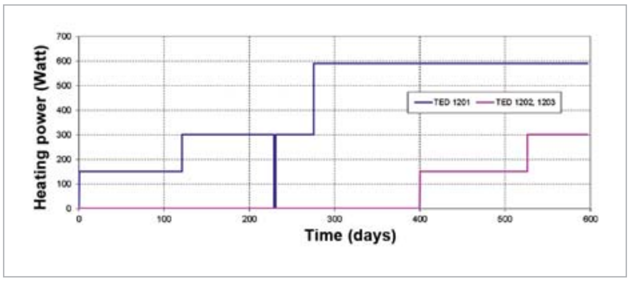



Figure 2: Periods of heating

## Modeling strategy of the claystone

An anisotropic material model containing the coupling of the isotropic Mohr-Coulomb model (rock matrix) and the anisotropic Mohr-Coulomb model (bedding plane) was generated with multiPlas and ANSYS. This model was used for the continuum mechanical modeling of the claystone (Callovo-Oxfordian). The material model considers different behavior of the claystone in the pre and post damage zone. Using optiSLang, the FE model was parameterized.

## T-H-M coupled calculation of the heating experiment

The simulation of the construction process (tunneling) was conducted in the mechanical analysis by deactivation and activation of the corresponding element areas. After deactivation of the claystone elements within the considered section, in a further step, the cladding elements of the tunnel were activated using the parameters of the shotcrete. The elements in the air and heater areas remained deactivated. The fracture sections were adapted to the FE mesh. For the thermal and hydraulic analyses, the construction process was considered analogously. Instead of activating and deactivating, the material properties of the respective elements of claystone to air and then air to shotcrete or heater were modified.

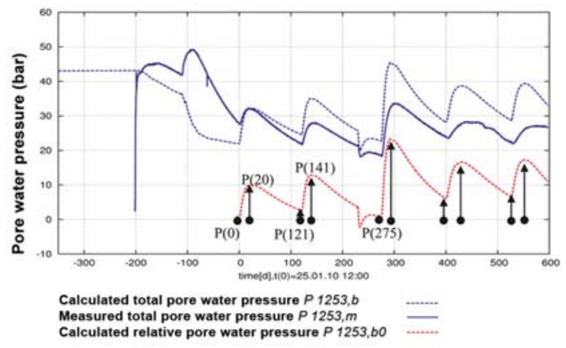



Figure 3: Relative pore water pressures for parameter identification

For the thermal-hydraulic-mechanical simulation, the following non-linear interactions between anisotropic thermal, hydraulic and mechanical material properties were considered:

- T-H coupling: the updating of the pore water pressure due to temperature changes and the temperature dependence of the hydraulic conductivity,
- T-M coupling: the influence of mechanical stress and deformation state by thermal expansion,
- H-M coupling: the updating the effective stress due to pore water pressure changes and
- M-H coupling: the dependence of the hydraulic conductivity in comparison to the stress state and the vector of plastic strains as well as the updating of the pore water pressures due to stress changes

The change of the pore water pressure *P* is due to the changes of fluid volume, volumetric expansion and temperature. The hydraulic conductivity of the claystone is formulated as a function of temperature and the stress-strain state. Here, the anisotropic permeability is dependent on the stress state, the vector of the plastic strain and the orientation of the bedding plane.

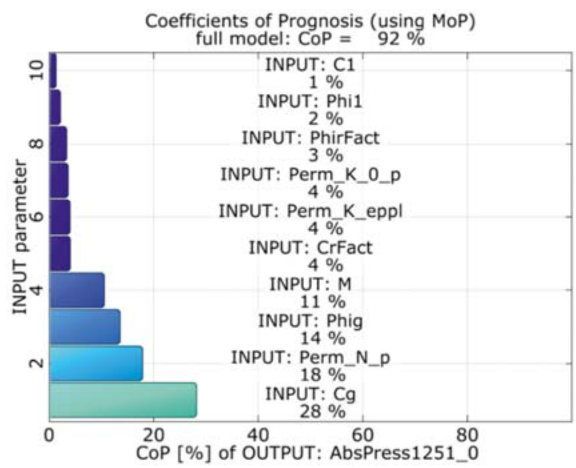



Figure 4: CoP relative pore pressure at time t = 0, the measuring point in 1251

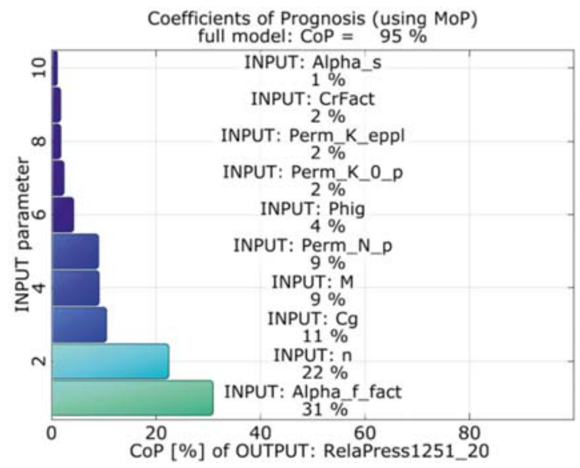



Figure 5: CoP relative pore pressure at time t = 20 days, measurement point 1251

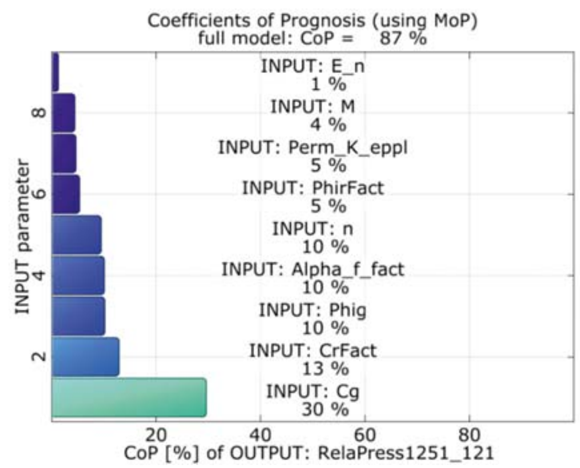



Figure 6: CoP relative pore pressure at time t = 121 days, measurement point 1251

## Sensitivity analysis

In the sensitivity analysis, the material parameters (including the parameters of the coupling dependencies) were varied within physically possible parameter limits. It should be investigated which of the material parameters have a relevant and physically understandable context for a comparison with the experimental results. For the analyzes, data of temperature and pore water pressure from a total of 17 measurement points were available. Due to the many uncertainties of the Tunnel excavation and the installation of the instruments, model calibration and parameter identification were limited to the heating experiment. Here, not the total pore water pressure but the pressure differentials and gradients as results of the heating and applied to the beginning of the heating periods were considered (see Figure 3).

For the sensitivities evaluation of the relative pore water pressures, discrete values at certain times were used. The selection of these response variables made an evaluations of the sensitivity at the beginning and the end of the respective heating phases as well as at the time of reaching the maximum pore water pressure possible. Important results of the sensitivity analysis could be derived from the CoP values (Coefficient of Prognosis), which show the significance of the input parameters. In order to determine the CoP values, the MOP (Metamodel of Optimal Prognosis) is generated by optiSLang showing the best correlation between the variation of response variables and input variables. optiSLang filters out automatically unimportant input parameters. This strategy allows optiSLang, with a minimal number of designs, to identify efficiently the significant input parameters even in large parameter spaces. Thereby, also non-linear correlations are detected.

Figure 4 to Figure 6 (previous page) are examples of the measurement point 1251 showing the CoP values of the input variables for the relative pore pressures at the times t = 0 (start of heating), t = 20 days (reaching the maximum pore water pressure) and t = 121 days (end of the heating phase 1).

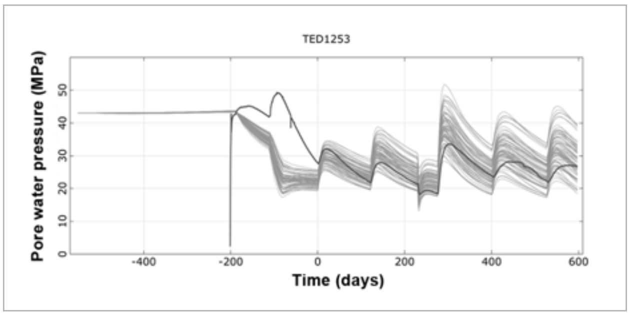



Figure 7: pore water pressure at the measurement point 1253 with a scattering range of the simulation model

Evaluating the CoP values at all measuring points, it can be stated that at time t = 0 (before start of heating), especially the following input variables influence the pore water pressure:

- Perm_N_p, Perm_K_0_p - the permeability function of H-M coupling constants
- CG and phig - strength parameters (cohesion and friction angle) of the claystone
- M – Biot modulus

During the heating phases of the experiment especially the following input variables influence the pore water pressure:

- Alpha_f_fact - factor of the temperature-dependent volumetric expansion of the pore fluid (T-H coupling)
- n - porosity (T-H coupling)
- Perm_N_p, Perm_K_0_p, Perm_N_n, Perm_K_0_n - permeability function of the H-M coupling constants,
- CG and phig - strength parameters (cohesion and friction angle) of the claystone and
- M – Biot modulus

It can be seen that the pore water pressure increase at the beginning of each heating phase, is in particular influenced by the value Alpha_f_fact and n (values of the TH-coupling). The subsequent decrease of pore water pressure values, however, shows a significant correlation to the strength characteris-

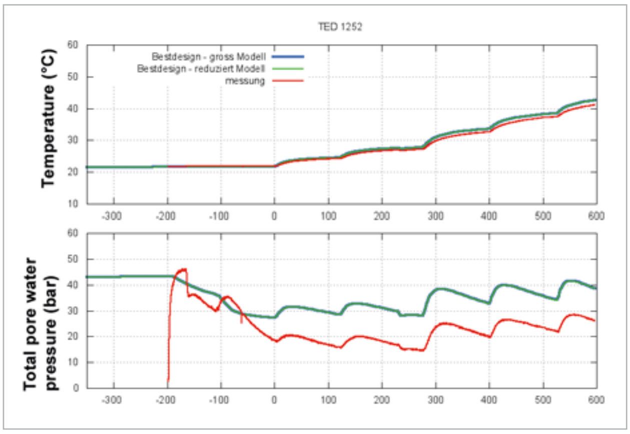



Figure 8a: Comparison of simulation vs. measurement at point 1252 after the parameter identification. Top: temperature curve, middle: total pore water pressure

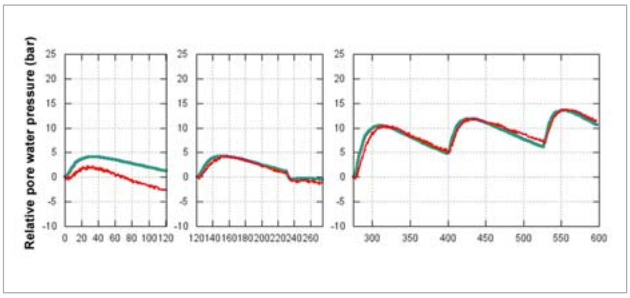



Figure 8b: Comparison of simulation vs. measurement at point 1252 after the parameter identification: Relative pore water pressure of the three heating periods

tics of the claystone (cg and Phig). This is an indication for the pore water pressure decline being particularly caused by stress redistribution, change of permeability and drainage effects. The high total CoP values of the individual response variables of > 85% emphasize the high plausibility of the main physical phenomena by the identified correlation. Furthermore, by comparing the scattering ranges of the calculated values with the time variations of the measurement results (see Figure 7), evaluations about the model quality and adjustability of the numerical model with the experimental results could be made. If the scattering range of the simulation model includes the measured evolution of parameters, a successful comparison within the selected parameter limits is possible. Figure 7 shows the correctness of this evaluation starting from the beginning of the experiment (t = 0).

## Parameter identification

Within the parameter identification, a set of input parameters is determined which simulates decently the time evolution of the measured and calculated temperatures and pore water pressures. Parameters not affecting the response variables in the sensitivity analysis were excluded from the parameter identification. They were taken into account with their reference values. Because the effects of initial disturbances (e.g. from tunnel excavation and installation of heating devices) decline in the course of the test, prognosis quality rises with each heating period. Therefore, the objective function for each heating periods were chosen with different priority factors (0.6 for heating period 1, 0.8 for heating period 2 and 1.0 for heating period 3). For the calibration of measurement and simulation, besides discrete values of the sensitivity analysis (see Figure 3), also the integral differences between the measured and calculated ranges were considered. For optimization, the adaptive response surface method being available in optiSLang was used. The comparison of the measured and calculated time signals of the temperatures and the relative pore water pressures (see Figure 8) shows the very accurate simulation of the used model concerning the observed physical phenomena (thermal-hydraulic and thermo-mechanical as well as thermo-plastic effects) in the heating experiment.

## Conclusions

Based on ANSYS and multiPlas, an efficient THM-simulator was developed. The simulator computes a design completely from the tunnel excavation to the end of the third heating phase in only 32 hours on an ordinary PC workstation with two CPU. optiSlang's high-performance algorithms and filtering strategies for coping with large parameter spaces (advanced Latin Hypercube Sampling, Metamodel of Optimal Prognosis and Coefficient of Prognosis) enabled the efficient determination of significant input parameters and the evaluation of the main physical phenomena. The sensitivity analysis shows very accurately the following main influences affecting the pore water pressure before the start of the heating phase at time t = 0:

- hydraulic-mechanical effects, i.e. permeability due to the stress redistribution and plastic strains in the loosening zones of the tunnel excavation and heater drills
- changing of volumetric strain
- Biot modulus

Changes of the pore water pressure after the beginning and during the course of the heating are significantly influenced by:

- thermal-hydraulic coupling (strongest influence)
- hydraulic-mechanical coupling, i.e. permeability due to stress redistribution, strength characteristics of the claystone and volumetric strain changes

Using powerful optimization algorithms in optiSLang, the most important parameters for T-H-M coupled simulations in claystone (Callovo-Oxfordian) could be successfully identified. The precise simulation results of the measured and calculated differences of pressures illustrated the accurate evaluation of both the rising of the heating gradient of the pore water pressure due to the start of each heating phases and the subsequent declining gradient. The used simulation model and the T-H-M coupling proved to be capable to explain the important thermal hydraulic effects (rising pore water pressure due to temperature increase) and thermo-mechanical effects (decrease of pore pressure due to changes of stress, drainage effects and plastic activities as well as related changes in the permeability).

There are plans to continue using the developed T-H-M simulator for future calculations or other identifications in the field of disposal sites research for hazardous waste in underground laboratories.

**Authors //** M. Jobmann, M. Polster, M. Breustedt
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(Dynardo GmbH)

**CASE STUDY //** TURBO MACHINERY

# ROBUSTNESS EVALUATION AND RDO OF A CENTRIFUGAL COMPRESSOR IMPELLER

**Efficiency enhancement concerning flow and mechanical properties in turbo machinery by performing sensitivity analysis and Robust Design Optimization with optiSLang® and ANSYS®.**

The economy's ever-increasing need of energy and, at the same time, the rapidly declining resources, have made efficiency – and hence Robust Design Optimization (RDO) – one of the most important challenges for engineering at the moment. During energy transformation, in almost every application the turbo machinery is one of the most important parts of the process chain and shows a high potential for optimization. The following case describes the optimization workflow of a highly stressed centrifugal compressor impeller. The project aim was to find a new geometry with improved performance considering its fluid and mechanical efficiency in accordance with sufficient safety margins.

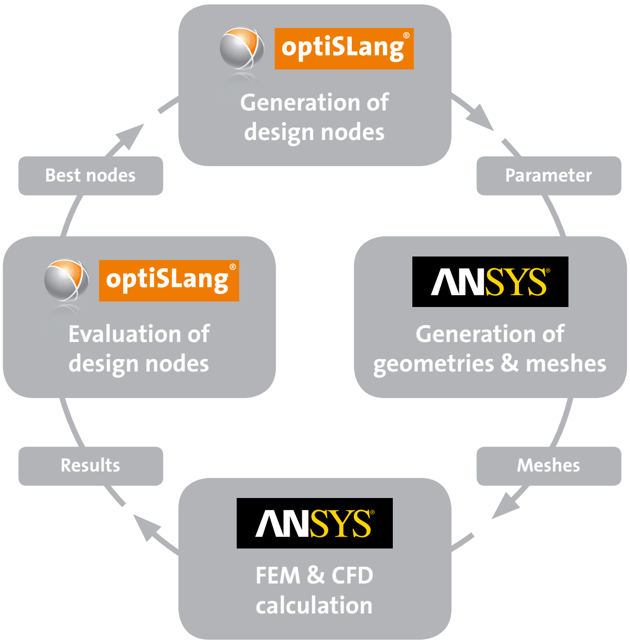
Multidisciplinary optimization, which includes both FEA and CFD simulations, is associated with a significant amount of computation. Therefore, it is essential to find efficiently a design fulfilling both the terms of fluid mechanics and the requirements of structural mechanics complying with sufficient safety margins. In order to reduce the required computational effort, prior to the optimization a sensitivity analysis is recommended. This enables the user to identify the most influential input parameter. Additionally, by this filtering, a reduction of variables for an efficient optimization is achieved.

The use of stochastic sampling methods combined with high-quality meta-models make it possible to detect the parameter space to be analyzed, to determine safely the most important variables and to find the desired optimum with a minimum of solver calls. The software optiSLang developed by the Dynardo GmbH provides all required algorithms in a fully automated workflow.

## Parameterization and sensitivity analysis

Depending on the number of input parameters, using optiSLang's stochastic sampling methods, a "Design of Experiments" (DOE) is created concerning the whole parameter space. The next step is generating a geometry model and the corresponding FEM and CFD meshes out of each design point. In order to ensure a stable and fully parameterized process flow, this step is conducted entirely within ANSYS Workbench. By the use of highly integrated software components, a consistent parameterization and, therefore, a smooth flow of optimization will be ensured. Based on the geometry created with DesignModeler and Blade editor, the network setup of the CFD part is done in Turbogrid and the FEM mesh is generated with the meshing tool within

ANSYS Workbench. After the results of all design points are available, an evaluation is carried out in optiSLang. With a sensitivity analysis using the Coefficient of Prognosis (CoP) and the Metamodel of Optimal Prognosis (MOP), the most influential input parameters are identified and can be used for an efficient optimization.



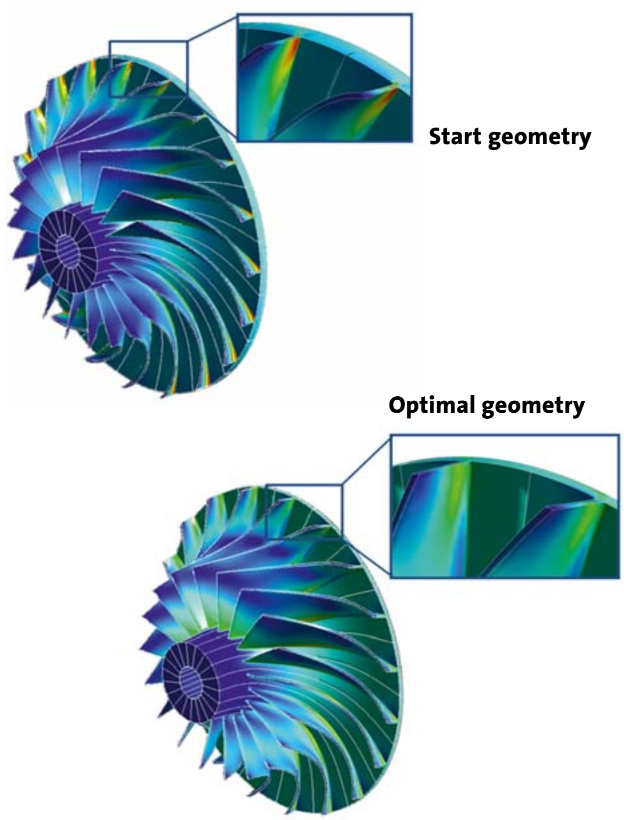

Optimization workflow optiSLang-ANSYS Workbench

## Optimization

A geometry of the compressor impeller generated with a conventional CFD design software is taken as a starting point of the optimization. This geometry already has good flow mechanical properties. Due to a design process concerning only the terms of fluid mechanics, however, the stresses within the impeller geometry are far out sufficient safety margins. Therefore, the aim of the optimization is to lower the stresses in the mechanical analysis to a safe level. At the same time, the good fluid properties have to be remained. Before the previously reduced parameter set is used for optimization, optiSLang offers the possibility to utilize the pre-calculated design points from the sensitivity analysis for a first optimization step. This is done by using the MOP. optiSLang determines, out of a variety of suitable meta-models, and possible subspaces of important parameters, the meta-model, which has the highest prediction accuracy of the result value variation. This is indicated by the CoP. Based on this meta-model, a first global optimization can be run without initiating further solver calls. Only the identified optimum on the meta-model must be validated with an additional numerical calculation. Based on the previously determined design improvements on the global meta-models, further optimization steps can be performed. In this case, an adaptive response surface method is used. In several steps, the parameter space around the previously determined first optimum is adapted. In these parameter spaces, using the meta-models, again design points are calculated and a new optimum is determined.

## Results

The result of the optimization shows the desired properties. Both the three-dimensional plots and the evaluation of flow and mechanical characteristics clearly demonstrate that the aims are achieved very well. By the use of modern automated optimization methods, a stress reduction is possible while retaining good fluid mechanical properties. Here, the combination of optiSLang's stochastic and optimization algorithms with the parameterization and preprocessing capabilities of ANSYS Workbench proved to be a powerful tool. The tight integration of the software components allows a high degree of automation and, thus, a time-and resource-efficient optimization process. With a minimum of required solver calls, even a complex, high-dimensional optimization problem can be efficiently solved.




**Authors //** M. Geller, Ch. Schemmann, N. Kluck
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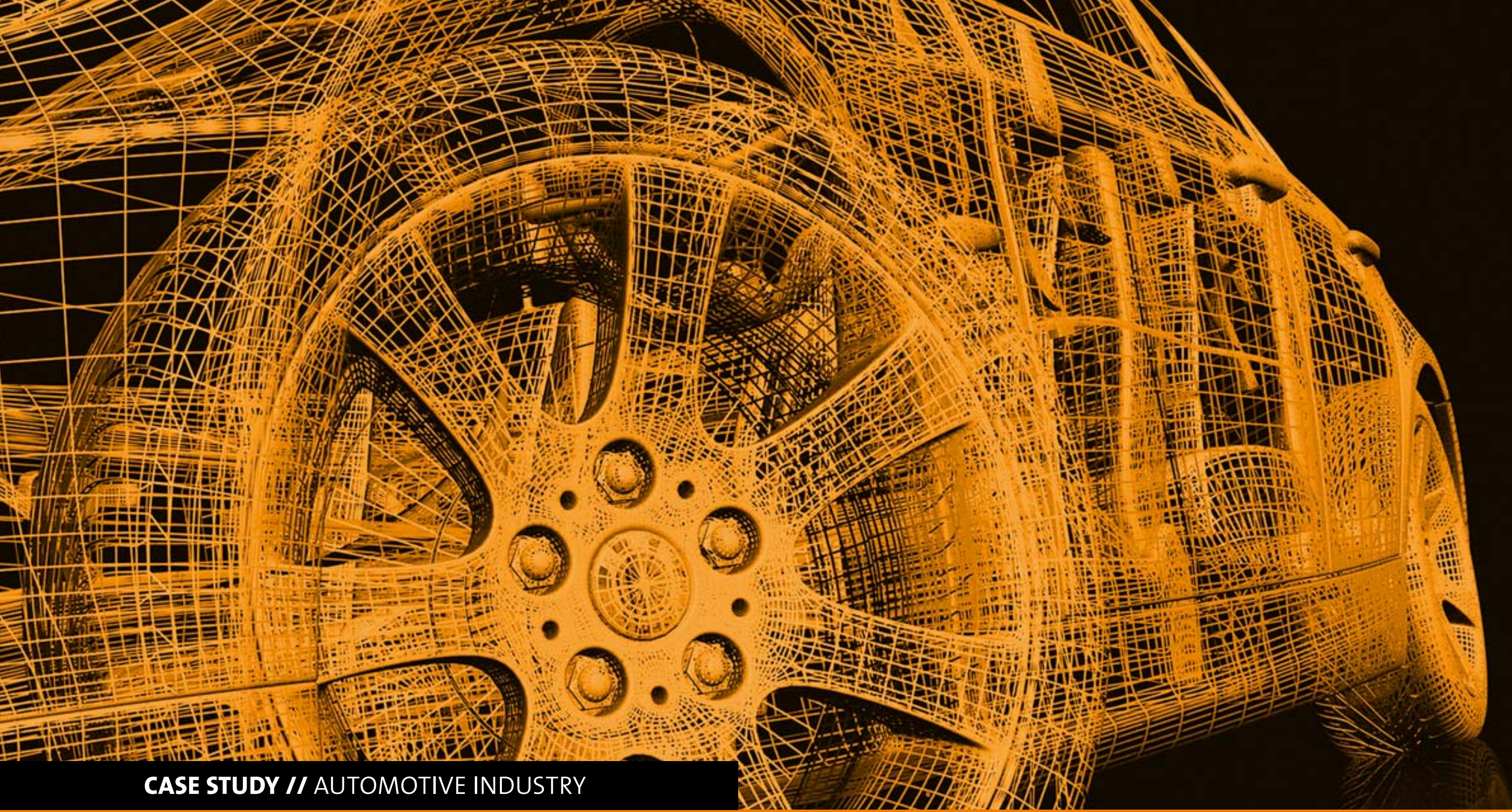


CASE STUDY // AUTOMOTIVE INDUSTRY

# BRAKES WITHOUT SQUEAL

**Most automobile companies are very aware of the unpleasant effect brake squeal has on driving comfort, drivers' fatigue, and thus customer satisfaction. Therefore, avoiding brake squeal is a requirement by drivers and car manufacturers. TRW relies on optiSLang® and ANSYS® to prevent brake squeal by simulations.**

Brake squeal is a friction-induced vibration best explained by a simplified model of a brake assembly. Figure 1 shows a clockwise rotating brake disk and a very simplified brake pad in form of a beam. The beam touches the rotating brake disk with a frictional contact. Without rotation of the brake, any vibration ceases through dissipation at the contact between disk and brake pad. Under certain conditions, however, a rotating brake disk causes instabilities within the brake assembly leading to increasing vibration amplitudes, brake squeal. This moment is shown in Figure 2. The rotating brake disk vibrates upwards in the exact moment the brake pad moves clockwise and therefore within the direction of the rotating disk. The brake pad is picked up by the brake disk through the contact and receives additional energy from the disk. At the maximum deformation of the brake pad the brake disk will vibrate downwards and with loosing contact the brake pad springs back (Figure 3) and the cycle starts again.

## Simulation Process

Development times in the automotive industry are short, and with growing design requirements, engineers need reliable simulations as well as efficient workflows. Simply modifying the design, materials, or testing new brake pad properties shouldn't require any work on the simulation workflow itself. ANSYS Workbench and ANSYS Mechanical allow these modifications in an excellent manner. The single solution steps are shown on the project page of ANSYS Workbench and simply combined to a solution workflow (Figure 4). The starting point for this workflow is given by the materials used in the simulation, a bidirectional CAD interface to import geometries and a robust meshing algorithm.

While classic solutions require a time consuming mesh generation in the contact area between brake pad and disk, ANSYS allows the use of simple nonlinear contact. This contact can not only replace the traditional matrix elements required to define contact between brake pad and disk, but also add more accuracy to the solution. ANSYS uses a nonlinear static contact analysis to solve the contact behavior between rotating brake disc and pads, and sends the pre-stress effects to a subsequent complex modal analysis. Keeping development times in mind, ANSYS allows engineers to choose between short solution times and higher accuracy by running brake squeal simulations as full nonlinear, partial nonlinear, or linear simulations. While being able to respond to needs in timeframe or accuracy by choosing between one of the three solution methods, engineers can also use different complex solvers to solve the complex modal analysis (QRDAMP, UNSYM and DAMP solver). Friction models to define friction between brake pad and disk as a function of brake pressure or rotating velocity of the disk provide the opportunity to add more accuracy to the simulation. In addition, stabilizing squeal damping, a specific brake squeal effect, the influence of gyroscopic effects, and mode tracking options are available within ANSYS Workbench.

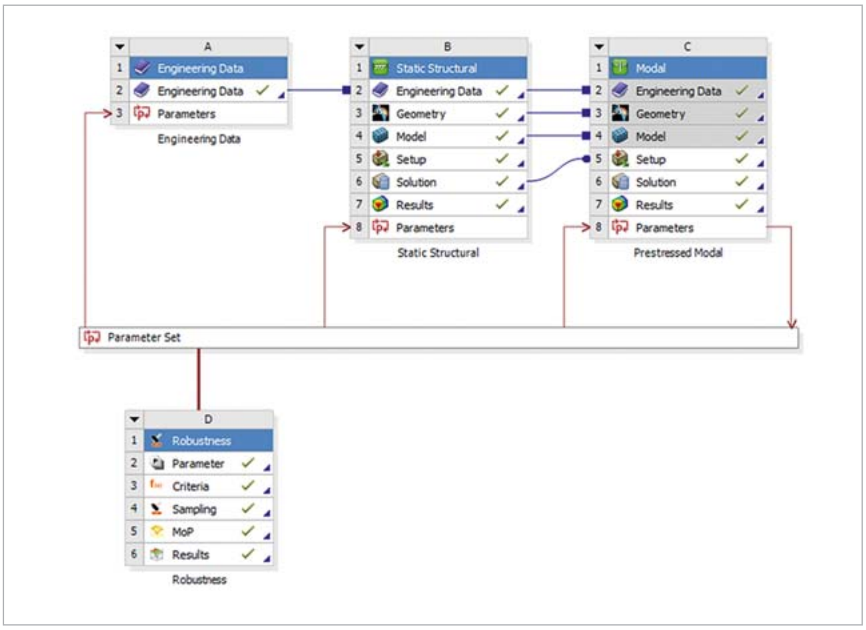



Figure 4: Brake squeal simulation process withANSYS Workbench and optiSLang.

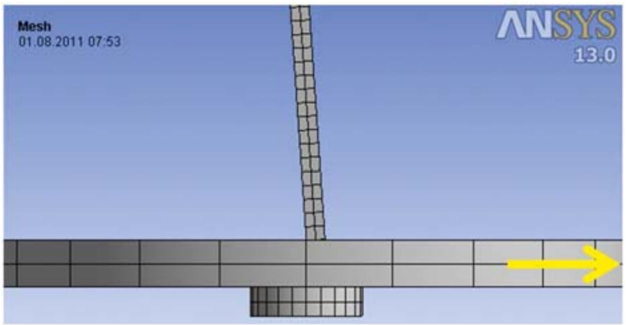



Figure 1: Rotating brake disk

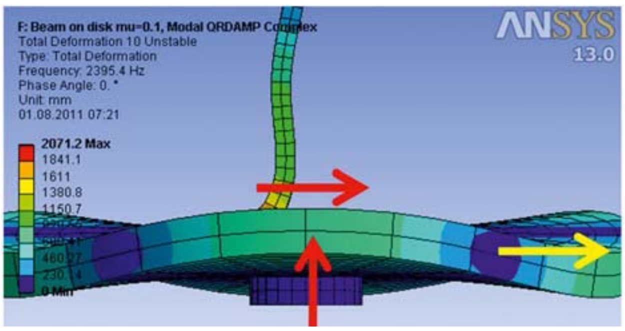



Figure 2: Brake disk picks up brake pad

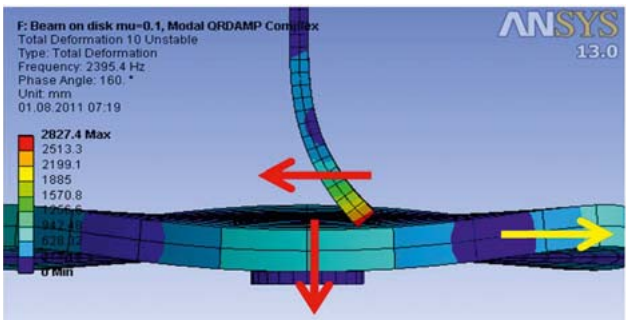



Figure 3: Brake pad springs back

While brake squeal simulations in ANSYS cover all areas from fast results to detailed and highly accurate solutions, ANSYS Workbench provides another important piece of the brake squeal puzzle. The parametric environment includes all important variables from friction coefficient to material properties and CAD design. The user simply defines a new set of material properties, a new friction condition, or brake pressure and updates the simulation.

Brake squeal is not simple to understand. Improving the design of a brake assembly, as well as analyzing the assembly with all uncertainties of its later working environment, is an important part of brakes squeal simulations. optiSLang inside ANSYS Workbench allows simulations including uncertainties as well as design improvements. Variations within brake friction and pressure, the material properties of the brake pad, or manufacturing tolerances are included in the simulation and provide new information to design engineers.

Eye-opener by unexpected brake squeal are avoided and brakes improved. The combination of efficiency and technology integrated within one environment leads to more comprehensive and reliable brake squeal simulations.

You see: That your brakes are not squealing is not just luck, it is a result of good and detailed engineering.

**Author //** M. Moosrainer (CADFEM GmbH)/
**Image Title //** © fotolia.com: 3ddock

CASE STUDY // CONSUMER GOODS INDUSTRY

# DIVERSITY OF VARIATIONS IN VIRTUAL PROTOTYPING OF TENNIS RACKETS

**Robustness evaluation and optimization of HEAD tennis rackets with multiple input and objective parameters using optiSLang® and ANSYS®.**

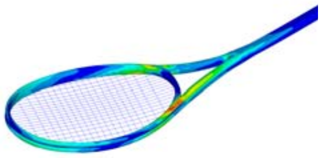
## Optimization task

When HEAD engineers first began using simulation, they evaluated a single design iteration, made changes based on the results, and ran a new simulation. It took approximately one week to evaluate the performance of each iteration. The process of design optimization of tennis rackets considers various input parameters. Different fibers, FAWs (Fiber Area Weight), angles and different component compounds and placements yield a large number of possible variations. In addition, a sufficient amount of optimization variables and objective parameters (e.g. stiffness, strength, impact behavior, production costs) are taken into the consideration. This can result in up to 20 million combinations. If one were supposed to build and test a prototype per day, it would take 2750 years for 1 million combinations! By conventional means, in real prototyping, such a computational effort for a sufficient number of designs and quality evaluation can not be realized. The optimization potential remains unused to a large extent.

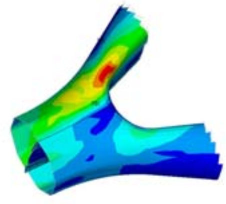
## Methods of solution

Today, HEAD engineers frequently use Dynardo`s optiSLang as a nonlinear optimizer to generate design iterations and run ANSYS Mechanical simulations automatically in a batch process to identify the optimal solution. Thus, engineers evaluate approximately 1 million design concepts in about a week to improve the design of a composite structure.

The typical goal of an optimization is to find the lightest structure with the highest stiffness and strength that meets other design constraints. Using optiSLang, large amounts of multidisciplinary non-linear optimization variables (layer thickness, angle, material ...) can be considered and evaluated with different priorities (weight, balance ...). The parameterization of layout and geometry is realized in ANSYS. Running a sensitivity analysis, optiSLang identifies the relevant input and output parameters, quantifies the forecast quality with the help of the Coefficient of Prognosis (CoP) and chooses the best Metamodel of Optimal Prognosis (MOP). Based on this identification, the number of design variables are decisively reduced and an efficient optimization can be performed. Thus, a robustness proof of the optimal design as well as the avoidance of over-engineering reliability goals become an integrated part of the optimization procedure. The meta-model is used for global optimization in order to determine, depending on the desired objective functions and constraints (e.g. scattering material values), the "optimal" design for "real prototyping". Based on the determined design improvements using global meta-models, further optimization steps can be conducted. For this purpose, optiSLang provides a variety of algorithms. These include, among others, classical gradient-based algorithms, adaptive response surface methods or nature-inspired optimization methods such as evolutionary strategies or genetic algorithms.



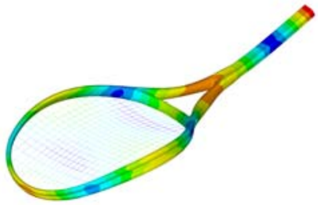
First bending mode of a strung tennis racket in tension.



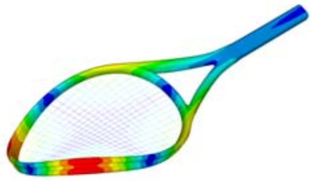
Shaft area of a tennis racket under bending load. The stress level is too high, so engineers reinforced the design.

## Costumer's benefit

The ability of prognosis is the key to efficiency. Thus, a "no run too much"-philosophy can be implemented minimizing solver runs. Additionally, the evaluation of prognosis allows to distinguish between physical and numerical effects on the change of output variables. For example, it is possible to quantify the influence of meshing if geometry changes. If permissible limits are violated by scattering output variables, optiSLang identifies safely (statistically provable) the responsible scattering input parameters. The design optimization of the racket does not have to be limited to a few parameter (CAE + CAD) any longer. The full optimization potential can be explored. Furthermore, oversizing is minimized by the implementation of specific variations. The ability to identified automatically the most important parameters made it possible to analyze such a large number of design alternatives and to optimize performance to a level that would never have been possible in the past.



Second bending mode of a strung tennis racket



Torsion mode of a tennis racquet illustrating how a non-center hit introduces torsion.

With the help of optiSLang, design concepts have been frequently identified that are such a departure from traditional engineering practices that the team would never have thought them applicable. HEAD has developed a challenging series of quality tests that measure stiffness and strength, which every racket must pass before entering the market. For example, the racket must withstand a drop test onto concrete without any damage.

First bending mode of a strung tennis racket in elongation. Hitting the ball at the blue node line on the strings does not excite this mode. This is the sweet spot of the racket.

The combination of optiSLang's stochastic and optimization algorithms with the parameterization and preprocessing capabilities of ANSYS Workbench enable engineers to quickly and easily evaluate each proposed design from a quality standpoint, all from the early stages of the product development process. Simulation and Robust Design Optimization (RDO) have played a significant role in the dramatic improvements that HEAD has achieved in the performance and durability of its tennis rackets. The detailed and accurate design information provided by optiSLang and ANSYS combined with the experience of HEAD engineers has made it possible to produce extremely lightweight designs that can withstand the enormous forces generated by string tension as well as the impact of the ball on the racket during the serve.

**Author //** Stefan Mohr (R&D Manager, Predevelopment)/
Publication by courtesy of HEAD Sport GmbH


# ANNUAL WEIMAR OPTIMIZATION AND STOCHASTIC DAYS

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

Our annual conference aims at promoting the successful application of CAE-based optimization and CAE-based stochastic analysis in virtual product design. The conference offers a good mixture between additional education, qualified workshops and practical oriented lectures. It provides a vital exchange between scientific and industrial application. Customers talk about their experiences in applying parametric optimization and stochastic analysis. Service providers present their innovations 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 would be happy to welcome you or interested colleagues to the next Weimar Optimization and Stochastic Days.

# 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 to optiSLang users by phone or by e-mail where every support request is processed thoroughly and promptly. We do not only answer questions concerning the handling of optiSLang, but we also give hints for an efficient application of its various methods to solve our customers challenges.

## Free information days and webinars

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

**Simulations in construction and geotechnics**

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 optimization with competing goals and to ensure the function of scatter influences.

## Trainings

If you are looking for a competent and custom-made introduction to optiSLang, visit our seminars which explain the theory and train the application of the methods of multidisciplinary optimization, robustness evaluation and robust design optimization in a compact way. Thereby, the areas and limits of applying the different methods in optiSLang to customers tasks are discussed. The well balanced ratio of lectures and exercises is 50% each. Hence, the seminars are not only directed to engineers in the whole CAE-based simulation area, but are also perfectly suited for decision makers in CAE, too. For all trainings there is a discount of 50% for students and 30% for university members / PHD's. You will find an overview of all seminars on the next page.

**Infos //** www.dynardo.de/en/trainings
www.dynardo.de/en/consulting

## optiSLang basics

The training introduces the topic of sensitivity analysis, multidisciplinary optimization, robustness evaluation, reliability analysis and Robust Design Optimization (RDO) with optiSLang. The seminar is suitable for CAD engineers and decision makers in the whole CAE-area (FE, CFD, MKS) with emphasis on non-linear optimization and stochastic analysis. It gives a good overview of state-of-the-art optimization methods and reliability analysis. The exercises with optiSLang illustrate the workflow management and process integration. This basic workshop is a prerequisite condition for the successful participation on other seminars.

**3 days**
**09.00 a.m. - 05.00 p.m.**
**1.500 Euro (excl. VAT)**

**The fee includes a 1-month test licence of optiSLang.**

## Update training: optiSLang inside ANSYS Workbench

The update training deals with features of the new version optiSLang inside ANSYS Workbench and its possibilities regarding multidisciplinary optimization, sensitivity analysis, robustness evaluation and RDO.

**1 day**
**09.00 a.m. - 05.00 p.m.**
**500 Euro (excl. VAT)**

## Design of Experiments (DoE) and sensitivity analysis with optiSLang

The training communicates the theory and application of methods for Design of Experiments and sensitivity analysis in optiSLang. The fields of application for different methods, such as stochastic sampling methods, variance based sensitivity analysis, and correlation analysis will be discussed. The participants will learn about metamodelling and how to conduct a principal component analysis as well as a prediction analysis.

**1 day**
**09.00 a.m. - 05.00 p.m.**
**500 Euro (excl. VAT)**

## Model validation with optiSLang

The validation of a numeric simulation model by real measure data is an important task in CAE-based dimensioning of structures and systems. The adjustment of measurement and simulation is the basis for trustworthy simulation results and a predictable model. The model validation is often bonded with the troublesome setting of numerous model parameters. The seminar provides a systematic approach for model validation through sensitivity analysis and multiobjective and multidisciplinary optimization. The solution method is shown with the help of examples and it is documented in detail. The suggested model validation can be integrated as a standardized process into virtual product development.

**1 day**
**09.00 a.m. - 05.00 p.m.**
**500 Euro (excl. VAT)**

## Statistics on Structure

Engineering structures or parts are naturally subject to random scatter: manufacturing tolerances cause random structural properties; random loads cause scatter of stresses and strains. Typically, such scatter cannot be characterized by single parameters, but rather is spatially distributed on the structure. Analysis of the spatial characteristics of scatter and of the statistical relations of the spatial distribution to the random input parameters gives important insight to the robustness of the structure and allows formulating quality requirements.

Statistics on Structure (SoS) is a tool for analysis and assessment of spatially random properties of structures. The seminar provides a brief overview on the theoretical background and demonstrates the usage of SoS and the post-processing options by help of application examples.

**1 day**
**09.00 a.m. - 05.00 p.m.**
**500 Euro (excl. VAT)**

## Increasing product efficiency through CAE-based optimization strategies

The energy efficiency debate brought an old issue back to the agenda: Can existing products be optimized or is a whole new concept or design necessary? The seminar will introduce CAE-based parametric optimization strategies for the different problems of design improvements including potential studies, global optimization and RDO. Practical examples will show the possibilities of product enhancement concerning performance and resource efficiency.

**2 days**
**09.00 a.m. - 05.00 p.m.**
**1.000 Euro (excl. VAT)**

**The fee includes a 1-month test licence of optiSLang.**

## Parametric simulation

This online seminar gives an introduction of the features in optiSLang and the workflow of parameter generation. The instructions include how to set up a sensitivity or a robustness analysis. The instructor introduces methods of multidisciplinary optimization and the workflow of a reliability analysis will be discussed.

**Online Seminar 4 hours**
**310 Euro (excl. VAT)**

## Optimization, reliability analysis and robust design with optiSLang and ANSYS Workbench

The seminar provides an introduction to the mode of operation and the range of application of optimization processes in virtual product development. The focus will lie on optiSLang and ANSYS Workbench, which are two of the leading software products in the area of optimization, robustness analysis and robust design optimization.

**2 days**
**09.00 a.m. - 05.00 p.m.**
**1.150 Euro (excl. VAT)**

**The fee includes a 1-month test licence of optiSLang.**

## FEM in civil engineering and geotechnics

For a realistic evaluation of safety and reliability, for the investigation of building physics problems or to simulate earthquakes and other disaster situations, numerical calculations in civil and geotechnical engineering have been firmly established. In this context, the seminar introduces the workflow of FE-simulation with ANSYS and LS-DYNA and their application in civil engineering and geotechnics. Furthermore, material models for non-linear simulation of material will be discussed. The seminar answers questions about how to evaluate optimally historic and modern buildings using stochastic analysis and how to set up an optimization workflow.

**1 day**
**09.00 a.m. - 05.00 p.m.**
**575 Euro (excl. VAT)**

## multiPlas

multiPlas is a material library which provides the material models for FEM calculations in ANSYS in the field of civil engineering and geotechnics. The software contains efficient, realistic material models for masonry, soil, rock, sand, concrete, reinforced concrete, steel, wood, mortar and stone.

The seminar introduces the material models based on elasto-plastic flow criterion with associated and non-associated flow rules. Methods of FEM calculations in ANSYS will be discussed. With the help of practical examples, the instructor will explain efficient and robust algorithm for the proceeding of single and multi surface plasticity in multiPlas. In this context, special features will be discussed, such as the interconnection of isotropic and anisotropic yield conditions which can be combined in numerous ways by the user.

**1 day**
**09.00 a.m. - 05.00 p.m.**
**500 Euro (excl. VAT)**

# 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

# STATISTICS ON STRUCTURE (SoS)

**Statistics on Structure is DYNARDO's post-processor for the visualization of statistical data on finite element structures to analyze the spatial distribution of variation and correlation as well as to detect "hot spots" of variation.**

## Why SoS?

Any structure possesses some natural randomness due to material scatter or manufacturing tolerance. For CAE-based robustness evaluations, engineers need to evaluate statistical data on finite element structures in order to locate "hot spots" of variation and investigate the cause of scatter by performing correlation analyses.

## Statistics

The following statistical measures can be plotted on the FE structure.

- Descriptive statistics (like means, standard deviations, coefficients of variation or quantiles)
- Single designs and design differences
- Statistics of eroded (failed) elements
- Quality capability statistics
- Input/output correlation and Coefficient of Determination
- Minimum, maximum, range

## What is SoS?

SoS reads structure discretizations (nodes, elements) and related results of structural computations with randomly simulated input. Based on these data, statistical measures are determined and visualized directly on the FE structure.

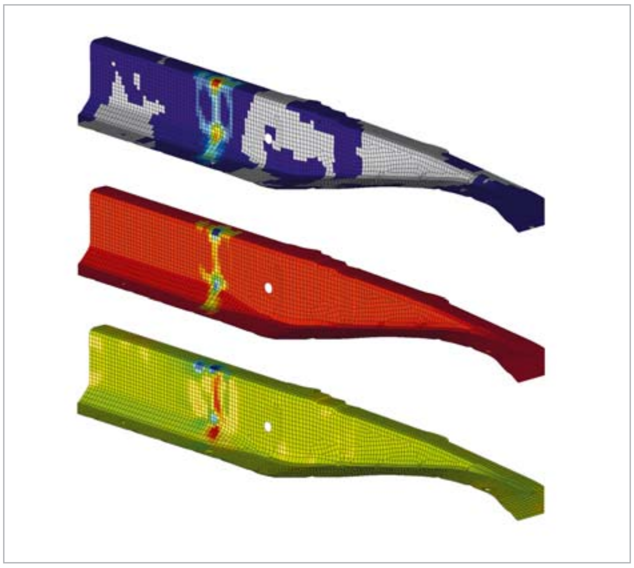
**Visualization**: Visualization of the statistical data is based on an interactive multi-window concept. Numerous possibilities are available for evaluation and documentation, and exporting of data for further analysis.

**Data smoothing**: The imported mesh can be reduced by SoS. Structure-related data is transferred to the new mesh by interpolation, which leads to smoother representation of data.

**Random field projection**: Based on random field methodology, data are expanded by a series of scatter shapes scaled by random amplitudes. The contributions of the series components to the total variation are ranked. With the identification of the most important scatter shapes, the user can visualize different "mechanisms" of randomness. Export of the sample of amplitudes to optiSLang allows for correlation analyses with respect to the random input variables.

**Eroded elements**: Elements which failed during the previous structural analyses, e.g. in a crash analysis, are detected. The statistics of failed elements within the sample can be evaluated and visualized.

**Interfacing**: The reference structure and structure-related response data can be imported from several common FE programs. Samples of input data may be read from an optiSLang binary file or as a text file. For further correlation analysis, samples of selected output data and random amplitudes are exported as optiSLang result file.



Example from crash simulation: Standard deviation of plastic strain (above) and first two scatter shapes

## Your benefit

SoS helps you to visualize and understand sources of scatter, assess the robustness of the structure and formulate quality requirements. By introducing SoS in the virtual product development process using stochastic analysis, you can:

- Locate "hot spots" of high scatter directly on the structure,
- Analyse the most relevant shapes of imperfection or scatter,
- Evaluate the influence of varying input on the structure's performance,
- Identify correlations between input data and structural results or mode shape amplitudes.

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