

Robust Design Optimization of Opto-Thermo-Mechanical Systems

S. Kunath, Dynardo GmbH,
S. Steiner, LightTrans International UG
H. Schüler, CADFEM GmbH

A coupled opto-thermo-mechanical simulation of an objective lens system in a casing was conducted. Its optical performance due to thermal effects and a mechanical deformation induced by the lens casing was evaluated. The optics and thermo-mechanics of the domain have been considered separately as well as in a coupled simulation using the Robust Design Optimization approach. The results indicate that the optimization in separate domains can be totally misleading concerning the optimization potential and it is therefore crucial to couple the physical domains in order to obtain optimized results for the real (=coupled) system. With this methodology an overall insight of the important parameters within the design process can be obtained. This can be used to reduce the thermo-mechanical effects on the optical performance.

Motivation

The application of modern simulation software allows for an enormous reduction of development times and costs of optical systems due to the replacement of physical experiments. In this manner, the determination of thermo-mechanical effects on optical systems is of high importance as these effects can dramatically reduce the system's optical performance. Thus, for the optimization of optical systems knowledge of the impact of the thermo-mechanical effects is necessary to match the demands under real world conditions. To shorten development cycles of optical systems with thermo-mechanical effects a fully automated approach including design understanding, optimization and tolerance/robustness analysis is needed.

The coupling of several physical domains is still a new and demanding field that is not yet a practice of daily life for simulation engineers. Some software tools like ANSYS strongly support the coupling between domains but optical simulation is not yet included. Therefore, we developed our own solution for coupling ANSYS Mechanical with LightTrans VirtualLab Fusion by means of Dynardo optiSLang.

Methods and Results

In this article, we present the coupling of optical and thermal-structural simulation models. As an illustrative example, we have modelled the collimation of a diode laser beam by an objective lens in the optical design software LightTrans VirtualLab Fusion (Figure. 1). The lens system collimates and refocuses an astigmatic laser diode. The 6 radii describing the curvature of the 3 lenses as well as the distances between the lens surfaces and between the lenses have been varied. The considered optical output parameters are the wavefront error (results are not shown), divergence angle in x and y direction as well as M^2 value to evaluate the system's performance. In laser science nafe.ms/2tsEpUS, the parameter M^2 , also known as the **beam quality factor**, represents the degree of variation of a beam from an ideal Gaussian beam nafe.ms/2tsCpvK.

The casing of this optical system causes stresses and deformations. Furthermore, deformations caused by an inhomogeneous temperature field are occurring. These

stresses and deformations have been investigated using the multiphysics simulation software ANSYS Mechanical (Figure. 1). This approach allows coupling of the temperature field and the deformation field of the structure. The investigated lens system contains a power supply near one of the lenses. The generated heat from the power supply causes an inhomogeneous temperature field which has an influence on the refraction index of the lenses. The temperature fields as well as the deformations caused by interference fits between the lenses and the casing have been analyzed. The thickness of the objective casing, the length of the objective, internal heat generation, heat transfer coefficient and the ambient temperature have been varied.

The influence of the thermo-mechanical effects on the optical performance has been investigated using the Robust Design Optimization (RDO) software optiSLang of Dynardo (Figure. 2). To do so, a first step is the coupling of the different physical domains represented by different software tools:

1. This means we need to "talk" to the tools (software integration).
2. Afterwards, workflows including several tools, pre- and postprocessors can be designed. These can be part of more complex workflows that can be run in loops or parallel running flows. These flows define the order and kind of operation that is computed. The main challenge was here the transfer of simulation results from one domain to the other.
3. Once such a workflow is designed, it can be automated and used for further analysis of the simulated design.

These analysis possibilities within the RDO approach include:

1. Model calibration to match experiment and simulation
2. Sensitivity analysis to understand your design
3. Optimization
4. Robustness analysis
5. Coupled RDO: The optimizer is considering the robustness as well as the optimization criteria. With this method an optimized and robust design in terms of input tolerances is obtained in a fully automated manner.

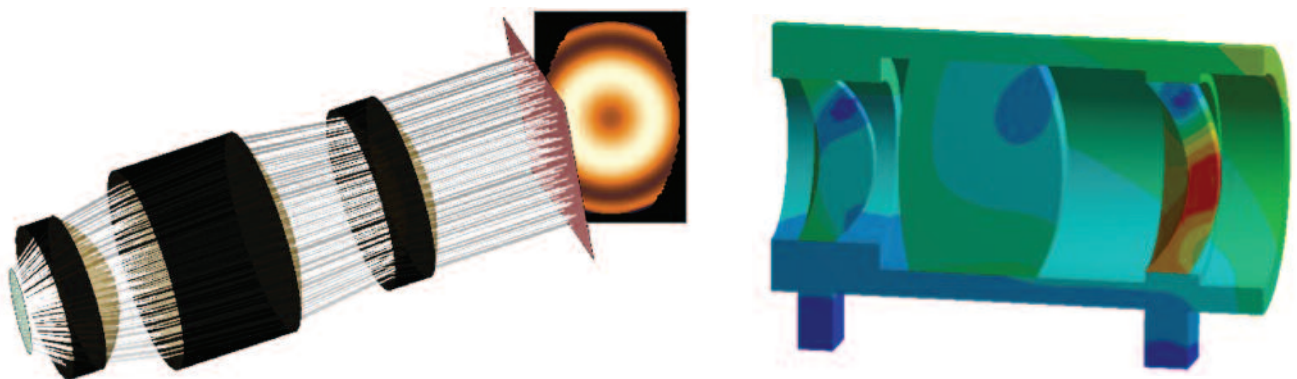


Figure 1: Optical simulation model of the collimation of a diode laser beam by an objective lens consisting of 3 lenses (left side) and deformation of the thermo-mechanical simulation model of the casing of the objective and its lenses (right side).

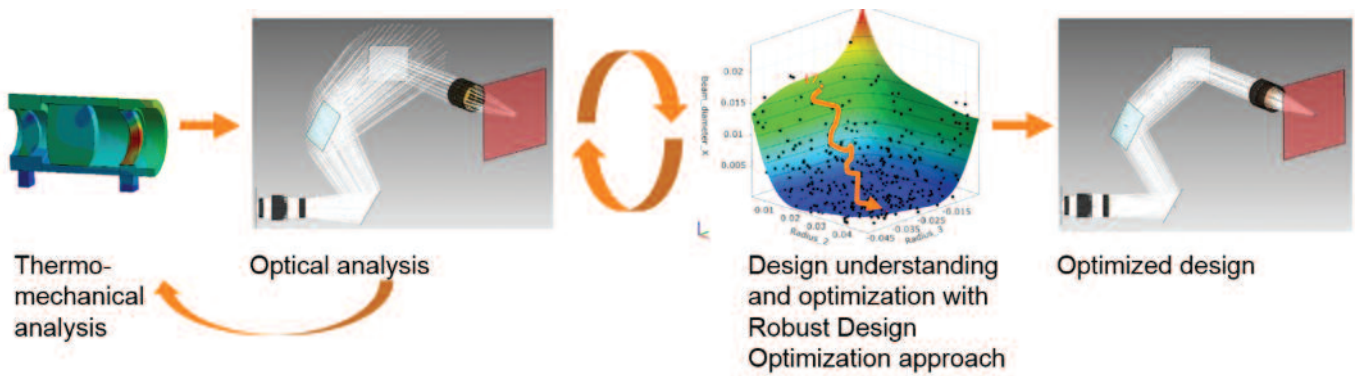


Figure 2: Automatable loop of an opto-thermo-mechanical simulation which is used for optical design optimization. First, the optical lens design geometry is exported to the thermo-mechanical simulation tool. A mesh is generated and a thermo-mechanical analysis is performed. Afterwards, the deformed structure is given back to the optical analysis that computes the optical performance of the optical system. Performing this loop several times for several parameter variations generates a metamodel for design understanding and subsequent optimization.

The coupling of several physical domains is still not yet a day-to-day practice for simulation engineers. Therefore, several levels of expertise exist in this field. Four innovation steps for optical design are defined here with number 0 the status quo for most designers:

0. Improve the optical design with optical design software but no support of further optimization tools.
1. Application of advanced RDO tools for optical design improvement
2. Application of advanced RDO tools for thermo-mechanical design improvement
3. Application of advanced RDO tools for opto-thermo-mechanical design improvement

In the following, we will focus on innovation steps 1-3. To improve the optical design, first, the influence of the design parameters on the responses and objectives is explored by means of sensitivity analysis. For the Design of Experiment, 100 designs with Advanced Latin Hypercube Sampling were

sampled. Based on the corresponding simulation results, the Metamodel of Optimal Prognosis (MOP) for each of the considered outputs has been built to describe the relationship between the input and output parameters. Based on these metamodels the sensitivities have been computed and illustrated in a Coefficient of Prognosis (CoP) matrix (Figure. 3). The results indicate that the distances have a rather small influence whereas the impact of the lens radii on the divergence angle in x and y direction dominates. Radius 2 and 5 have the highest influence on the M^2 value in x and y direction. The objective functions can be defined free of conflict based on the obtained information from this sensitivity analysis. Figure. 4 shows that the most appropriate way to define the objective function is to use two separate objective functions:

objective 1: minimize Divergence_Angle_Y+Divergence_Angle_X;

objective 2: minimize $[M^2_X-1]^2 + [M^2_Y-1]^2$.

The optimal M^2 value is 1 and the divergence angle should be minimized in x and y. With this approach, the optimization procedure will be most efficient and the result is a Pareto front (Figure. 5). The best design can be selected from the front: Either a lower divergence angle is of interest but the M^2 is increased or vice versa.

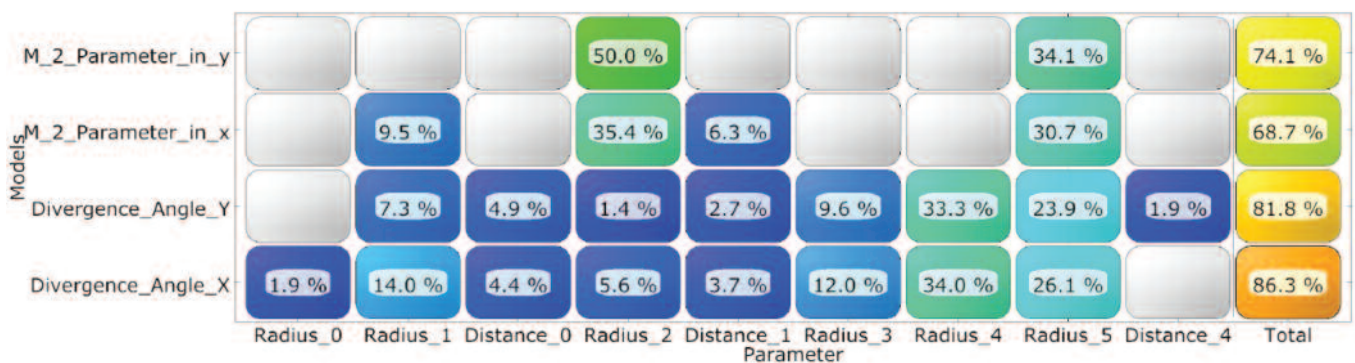


Figure 3: COP matrix as a result of the sensitivity analysis of the optical simulation: The output parameters are represented by rows whereas the inputs are illustrated in columns. The percentages indicate the impact of the inputs on the output variation and the total value represents how good the underlying model can predict designs that have not been used to build the model.

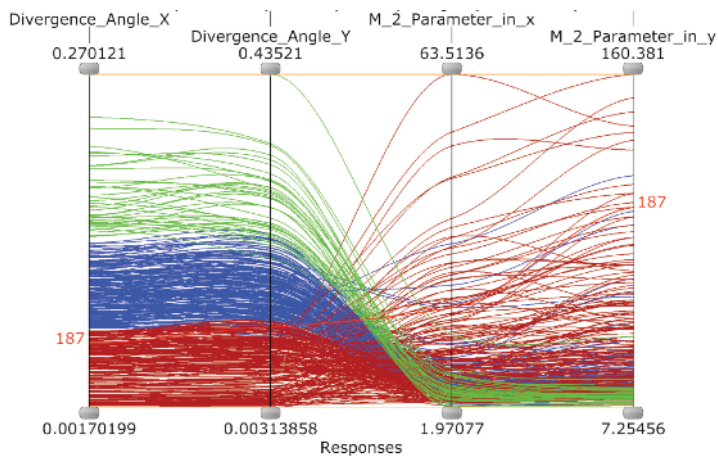


Figure 4: Parallel coordinates plot as a result of the sensitivity analysis of the optical simulation: Each line represents one design. Output parameters and their variation ranges are illustrated vertically. The activated design 187 has a low divergence angle in x and y as well as a low M² in x but a higher than average value for M² in the y direction. A cluster analysis for divergence angle in x direction colors the designs corresponding to the clusters. In that way, it shows that higher divergence angles correspond to lower M² values which means there is a conflict between the output parameters when both should be minimized.

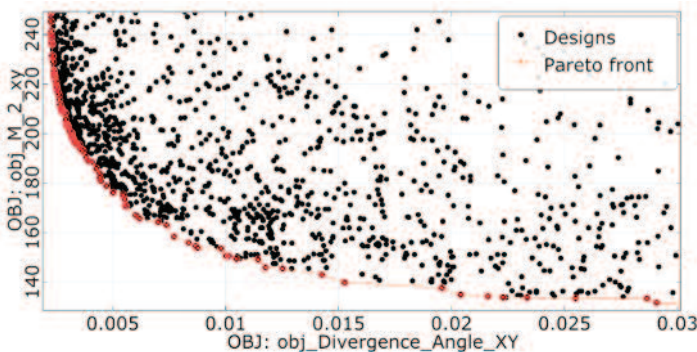


Figure 5: Pareto plot with the two objectives: divergence angle and M². Both objectives form a front of best designs that cannot be further improved because of the conflict between the objectives.

A subsequent robustness analysis of the best design was performed. With this method, the robustness (expressed as output variation) against varying input tolerances and environmental (noise) effects during the manufacturing process and in operation can be quantified. As robustness criteria we defined the Coefficient of Variation (CoV = standard deviation / mean value) of divergence angle and M² in x and y direction not to exceed 20%. Additionally to the inputs used for optimization, the distance between the light source and the first lens ("distance before") as well as the lateral shift of the light source in x and y direction was considered. The scattering of the inputs was defined (Figure 6) and a robustness analysis was performed using 100 designs sampled with Advanced Latin Hypercube Sampling. The results of the analysis are illustrated in Figure 7. The design is not robust because the CoV exceeds the limit of 20% for the divergence angle and M² (for M² data not shown). The lateral shift and distance before have been identified to have the highest impact on the robustness of the design.

In this case there are two ways to improve it:

1. Analysis of causes: Minimize the scattering of the inputs that are mainly responsible for the robustness of the design.
2. Coupled Robust Design Optimization: Run a new optimization with robustness analysis in one loop by using robustness criteria as constraint or objective function

To illustrate the second innovation step (Application of advanced RDO tools for thermo-mechanical design improvement) we performed a sensitivity analysis of the thermo-mechanical design in the same manner as described before. The results are shown in Figure 8. The third lens in the 3-lens system showed the strongest deformation (Figure 1 right side). Therefore, the maximum stresses and deformations have been considered for this lens only as it was expected to have the highest influence on the optical performance. The maximum thermal deformation of this lens is influenced by all inputs besides the ambient temperature. In contrast, the maximum total deformation including thermal and mechanical effects is only influenced by the thickness of the objective. This is because the mechanical effects are much stronger than the thermal effects. Thus, very small impacts on the thermal deformation will not be detected by the metamodel (MOP).

Name	PDF	Type	Mean	Std. Dev.	CoV
Distance_0		NORMAL	0.00200701	2.00701e-05	1 %
Distance_1		NORMAL	0.000967461	4.83731e-05	5 %
Distance_2		NORMAL	0.00600046	6.00046e-05	1 %
Distance_3		NORMAL	0.00448916	0.000224458	5 %
Distance_4		NORMAL	0.00108139	1.08139e-05	1 %
Distance_Before		NORMAL	0.0036915	0.000184575	5 %
Lateral_Shift_X		NORMAL	0	1e-05	100 %
Lateral_Shift_Y		NORMAL	0	1e-05	100 %

Name	PDF	Type	Mean	Std. Dev.	CoV
Radius_0		NORMAL	-0.00679898	3.39949e-05	0.5 %
Radius_1		NORMAL	-0.00390681	1.9534e-05	0.5 %
Radius_2		NORMAL	0.0210514	0.000105257	0.5 %
Radius_3		NORMAL	-0.00873955	4.36978e-05	0.5 %
Radius_4		NORMAL	-0.00504888	2.52444e-05	0.5 %
Radius_5		NORMAL	-0.0070837	3.54185e-05	0.5 %

Figure 6: Definition of scattering input parameters for the robustness analysis including type of distribution, mean value, standard deviation or Coefficient of Variation (CoV).

Within the third innovation step (Application of advanced RDO tools for opto-thermo-mechanical design improvement) we performed a sensitivity analysis of the opto-thermo-mechanical design. The deformations of the thermo-mechanical design obtained in the previous sensitivity analysis have been exported and transferred to the optical simulation via scripting. The results of the coupled domains have been analyzed.

Figure 9 illustrates the influence of the mechanical input parameters on the optical outputs. Surprisingly, the impact of the thickness of the objective's casing is reduced compared to the pure thermo-mechanical analysis (Figure. 8) and the ambient temperature is dominant for all output parameters. This is rather interesting because, usually, the engineer would expect that the main effects of the thermo-mechanical analysis will also have a main effect on the optical performance.

We found out that this is not the case here, because we analyzed only the maximum values but not the distribution of the deformations over the lens surface in the thermo-mechanical analysis. Therefore, the effect of the lens tilting due to the thermo-mechanical load was invisible within this analysis; only the maximum deformation situated at the middle of the lens was considered.

In contrast, for the optical design analysis the deformation over the whole surface was transferred which explains why different effects dominate here. This illustrates, that it is crucial to couple several physical domains to get an overall insight of the important parameters within the design process. This knowledge can be used to reduce these thermo-mechanical effects on the optical performance and to improve the design much more efficient than by analyzing separate domains.

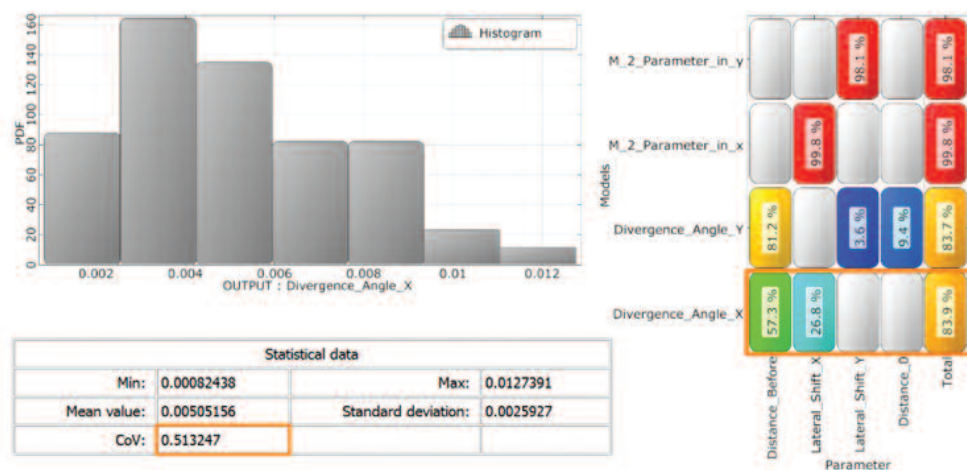


Figure 7: Results of the robustness analysis: The histogram shows the distribution of the divergence angle. The table shows that the Coefficient of Variation is 51% which means that the design is not robust. The main impact on the robustness is the lateral shift and distance before (right side).

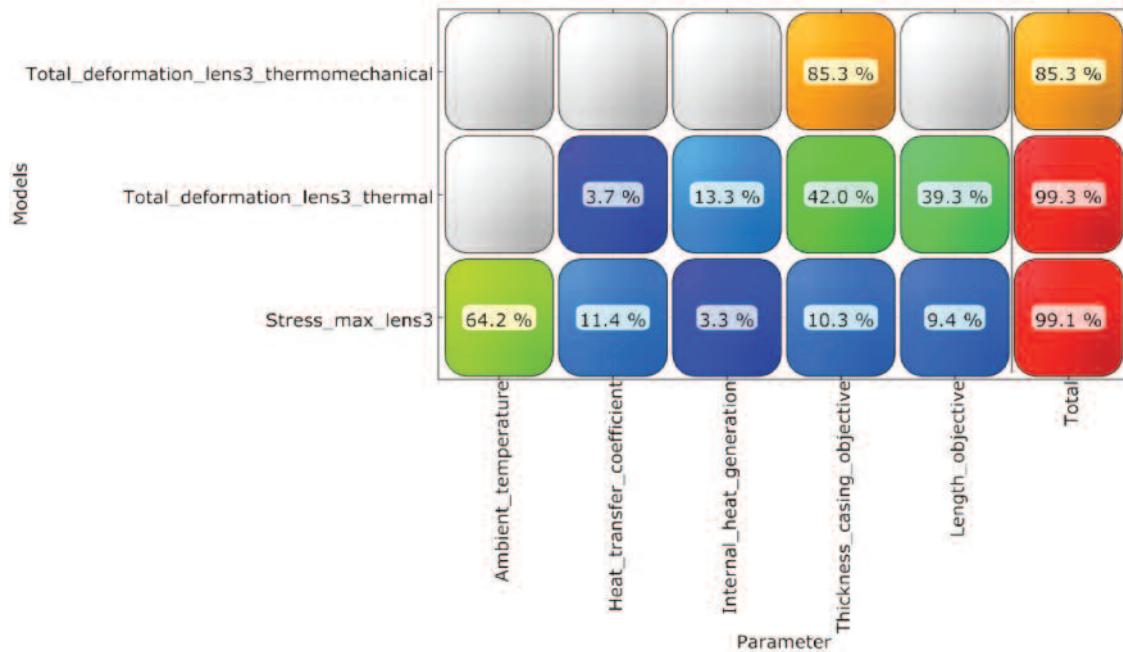


Figure 8: COP matrix as a result of the sensitivity analysis of the thermo-mechanical simulation: All input parameters have an influence on the maximum stress of lens 3 but only the thickness of the objective casing influences the total thermo-mechanical deformation of lens 3.

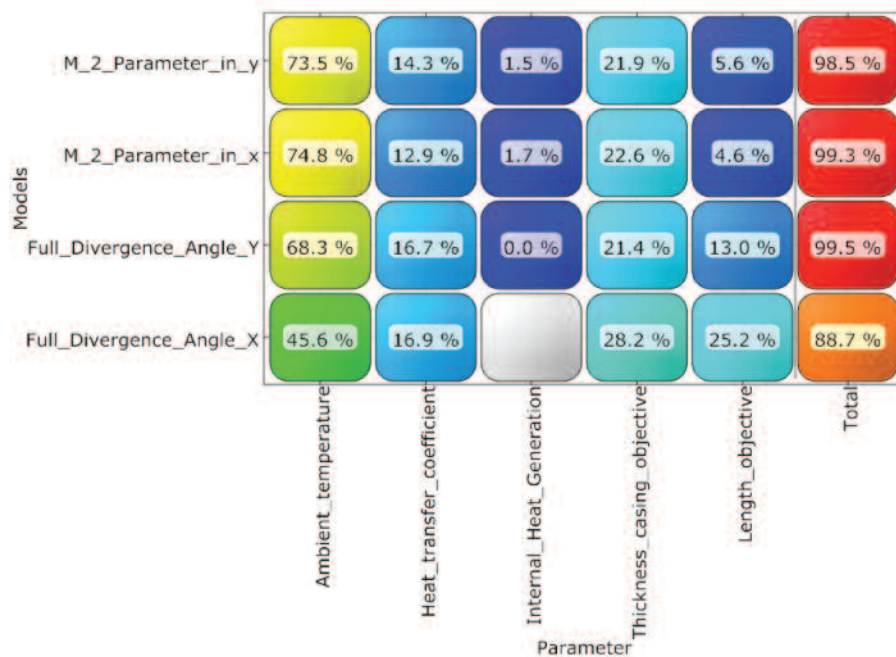


Figure 9: COP matrix as a result of the sensitivity analysis of the opto-thermo-mechanical simulation: The ambient temperature is mainly influencing all output parameters whereas the impact of the thickness of the objective casing is reduced compared to the pure thermo-mechanical simulation.

"Readers interested in the topic of Robust Design Optimization should look forward to the NAFEMS publication "Robust Design Optimization in Virtual Product Development" by Johannes Will, Thomas Most, Stephanie Kunath. This publication will shortly be shipped to NAFEMS members and be on general sale." ■

Stephanie Kunath studied Pharma-Biotechnology at the University of Applied Sciences Jena. Afterwards, she did her PhD at the TU Dresden at the faculty of mechanical engineering in the area of biosensors development and optimization based on miniaturized optical detection. Thereafter, she did a postdoc at the Université de Technologie Compiègne, France, where she optimized biosensorical elements and systems applying the methodology of Design of Experiments. Since 2014 Stephanie has worked for for Dynardo where she is responsible for new software applications and research projects.