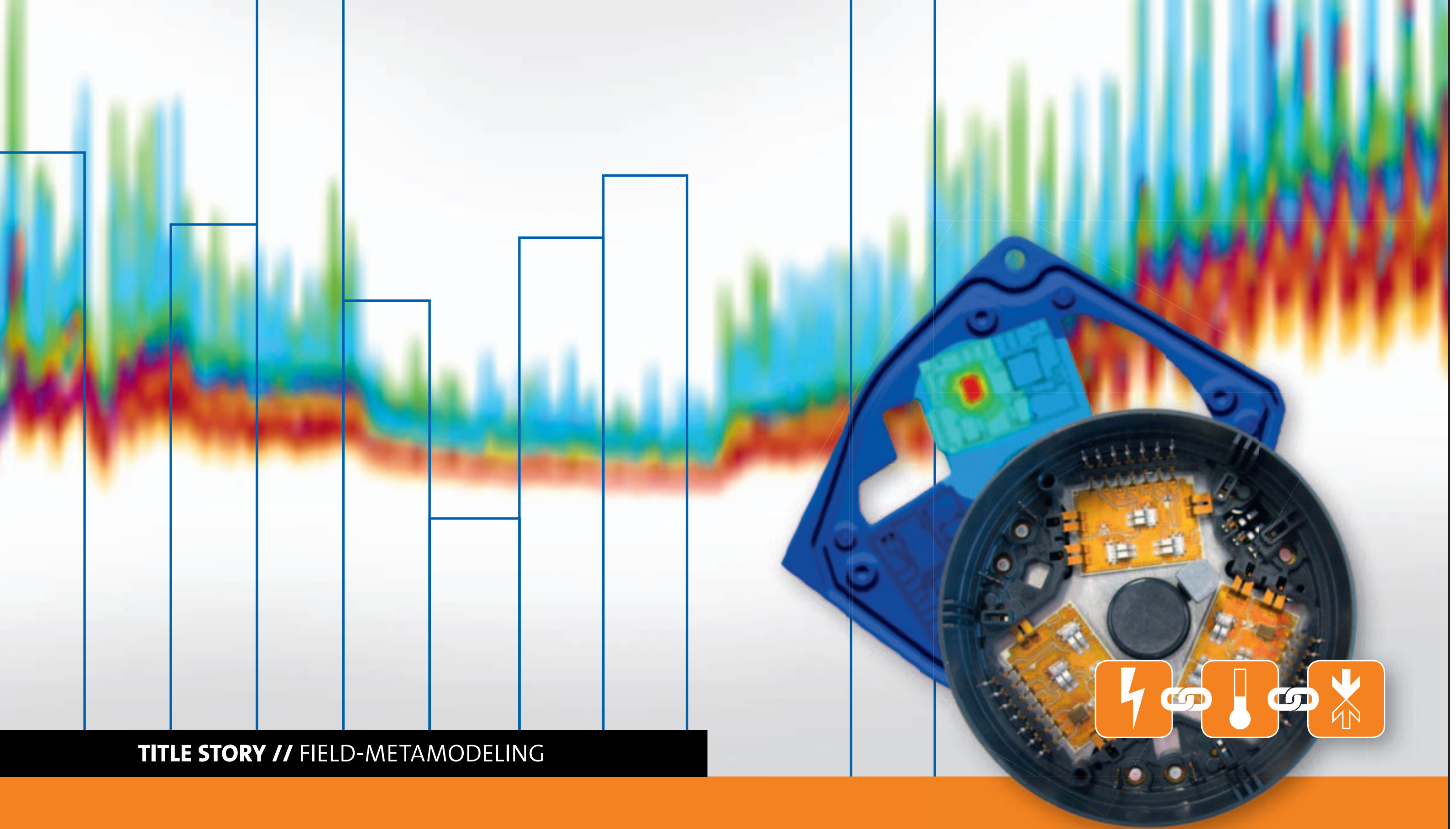

TITLE STORY // FIELD-METAMODELING

FIELD-METAMODELING FOR TRANSIENT ELECTRO-THERMAL-MECHANICAL APPLICATIONS

At Robert Bosch GmbH, metamodeling was applied as an alternative to electro-thermal-mechanical FEM simulation in order to accelerate the assessment of temperature fields or contact stresses.

Introduction

Electronic circuit boards are used in a wide variety of engineering applications. In the automotive industry, for instance, they can be found in electronic power steering assemblies. This case of application was also used as a test vehicle for the method that is described in this article. Other examples are battery load control circuits, motor control or safety devices like traction control and ESC. These circuit boards are constantly exposed to environmental influences like changing climate conditions (humidity), hazardous chemical conditions, vibration and mechanically and thermally induced stresses.

The goal in predictive engineering is to assess mechanical designs with respect to real world load cases. It should be possible to create and validate engineering designs with a verification of operational readiness during the full product lifetime.

One area of interest in that regard is the fatigue analysis of aluminium bond contacts during load cycle operations. Here, transient input signals originating from the bus system, e.g. steering or brake controls, as well as changing environmental conditions, lead to mechanically and thermally induced strain. Due to deviating stiffnesses and thermal coefficients of expansion at the electrical contact area (see Fig. 1), the aluminium bond contacts might fail, which is not acceptable in safety-critical applications.

State of the art in computer aided design is the fully coupled FEM analysis using design platforms, such as ANSYS Workbench, to model the thermo-mechanically coupled electric circuit board under different loading conditions. For the broad range of real-world load cases, it needs to be considered that, during the design phase, fully coupled transient simulations have been infeasible yet. Using the FEM method, only temperature-based lifetime models are applied in industrial applications, due to the large computational demand. The next evolution is a design assessment based on a full thermo-mechanical coupling (see Fig. 2), but in order to use this approach effectively, much more efficient solution techniques need to be developed.

This article demonstrates how a fully coupled transient electro-thermal-mechanical FEM simulation can be replaced by metamodeling technology. First, the field solution quantities are expressed using shape decomposition techniques. Based on a design of experiment, the resulting shapes of the design space are then used to generate a field-metamodel that can be applied to very rapidly compute new transient field responses, like temperature fields or normal contact stresses. The results are then implemented into a rain-flow counting routine to make design decisions based on the complete transient field response in almost real-time (see Fig. 3).

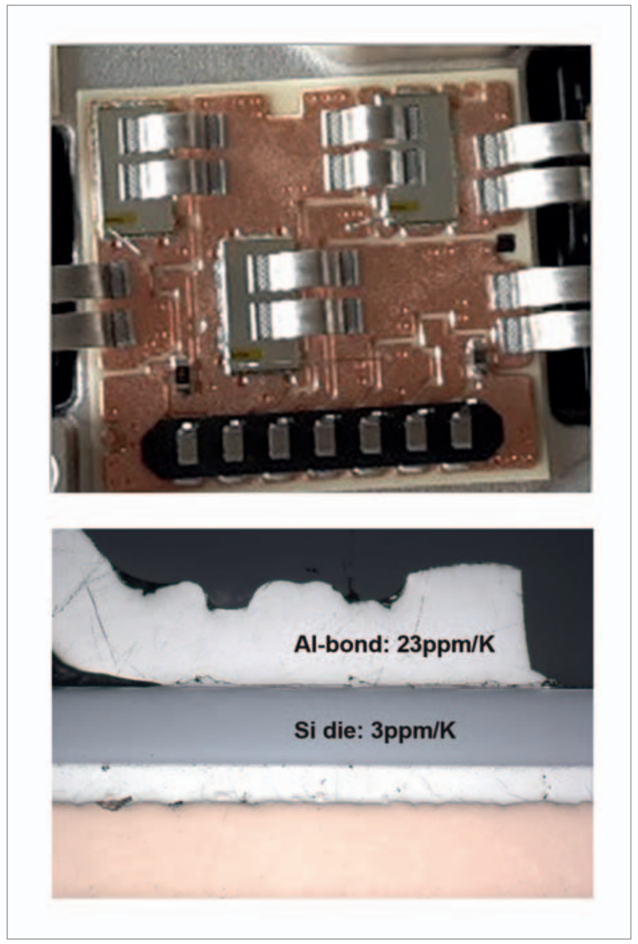

Fig. 1: Circuit Board with electric aluminium bond connections

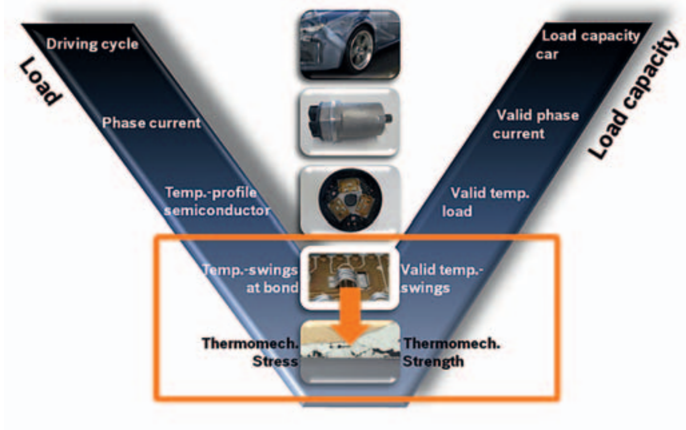

Fig. 2: Next step in lifetime modeling from temperature-based to thermo-mechanical models

Methodology

Field-Metamodeling

Scalar based metamodels are used in engineering as handy surrogate models. Due to their good mathematical foundation and ease of application, they are widely accepted in the engineering community. These surrogate models are not only applied as a replacement for the complex and error prone large-scale simulation models, but also for gaining a general knowledge of the non-linear correlation of the corresponding input and output parameters. Metamodels can be used to gain engineering knowledge and often give the design engineer the key insight into what really influences the design response.

Field-metamodels are a natural multi-dimensional expansion to the idea of scalar based metamodels. Instead of the simpler one-dimensional scalar input-output response correlation modeling (e.g. nodal stress at a time instant, scalar integral quantity, maximum deflection, as well as

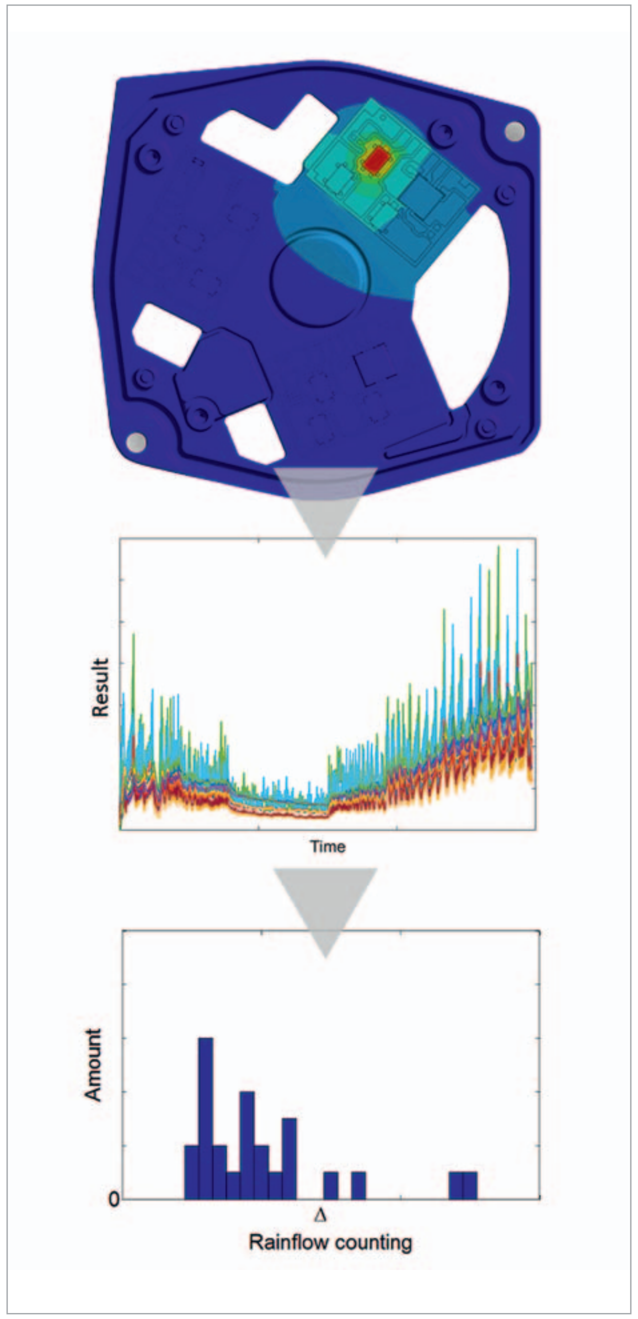

Fig. 3: Rainflow counting for field result quantity

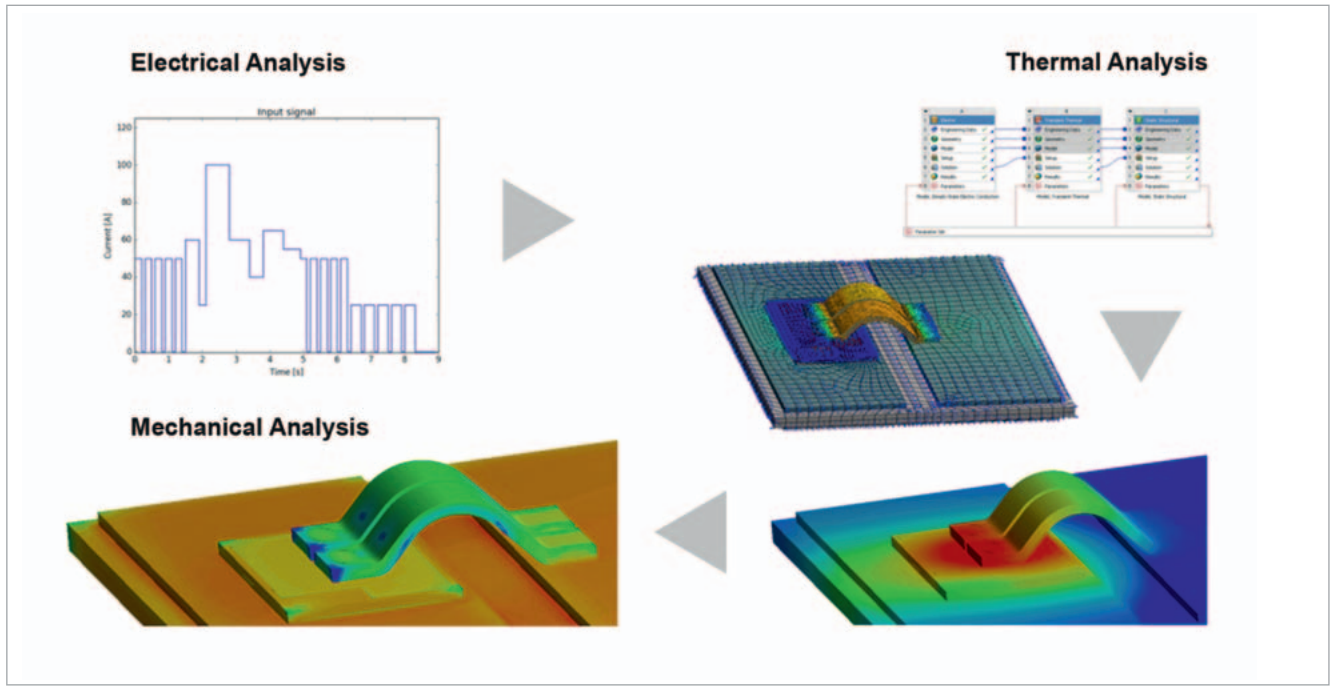

Fig. 4: Coupled transient Electrical-Thermal-Mechanical ANSYS Workbench model

stress for a complete domain) the field-metamodel generates a surrogate model for the full field response. The method is based on a Karhunen–Loève like decomposition of the field quantity in the parametric design space, which is later daisy-chained by using non-linear models.

In the current example, the full temperature and stress fields are expressed with this type of model. As an advantage of this approach, the design engineer does not need to pin-point one specific location of interest, before he builds the surrogate model. Furthermore, changing locations of interest during a transient analysis, e.g. hot spot analysis, becomes much more feasible.

Sensitivity Analysis

Fig. 4 demonstrates the underlying FEM simulation workflow generated in ANSYS Workbench. An electrical input signal is applied in an electric field simulation. The eddy currents act as source terms for the transient temperature computation. This data is subsequently fed into a thermo-mechanical stress strain simulation.

The resulting field-metamodel is based on a parametric scan of the underlying design space. It is important to note that electric loading leads to different temperature fields, depending on the load history. Therefore, a transient parametrization has to be generated to capture these effects. The input space consists of environmental conditions, e.g. ambient temperature and the electric loading signal, for which an appropriate partitioning scheme was devised. Afterwards, an Advanced-Latin-Hypercube sampling is used to generate a design of experiments that captures the underlying design space of the fluctuating current input signal. The parametric agglomeration of input to field-output data finally builds the foundation of the field-metamodel.

Transient field surrogate model

The basis of the field surrogate model is a shape decomposition of the quantity of interest. Fig. 5 visualizes the first three expansions of the normal stress field of the aluminium bond contact surface. Any response field of the underlying design space might be decomposed into such prototype shapes. Together with the information of the input parametrization of the design of experiments, a surrogate model can now be built. The resulting metamodel can now be used to generate field responses for new input sets and to

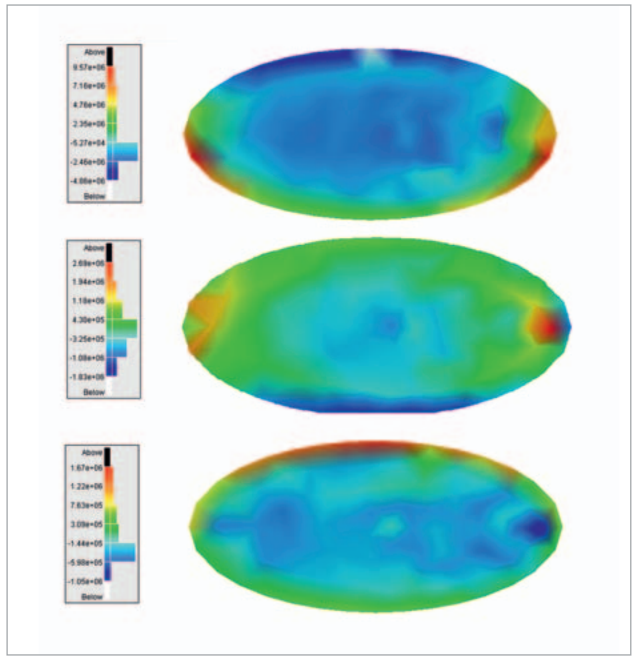

Fig. 5: First three shapes of metamodel stress field decomposition in normal direction for the bond contact surface

visualize the non-linear input-output correlation, much like their scalar companions. Additionally, a multi-dimensional Coefficient of Prognosis (CoP) value is available for the domain, which demonstrates the model approximation quality at each location of the model (see Fig. 6).

The input parametrization of the design of experiments results in a scalar input to multi-dimensional field output mapping. In the beginning, it was stated that the history of the applied loading affects the outcome of the experiment. Put differently, the current input signal and the temperature

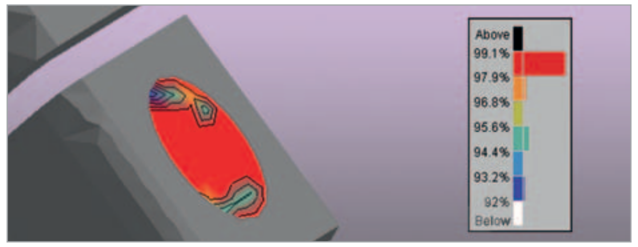

Fig. 6: Field-CoP values for metamodel of stress field in normal direction for the bond contact surface

field at each position affect the next temperature approximation. Therefore, the temperature is not only considered as an output, but also as an input. The above-mentioned decomposition technique is therefore applied to the temperature state at each beginning of a parametrized load step to generate a unique field decomposition. The enlarged design space is then used to generate a field-metamodel, which is not only based on the scalar input quantities, but it also relies on the temperature field information on the full domain at the beginning of each load step.

optiSLang custom input integration

The resulting field-metamodel can be used inside of standard optiSLang workflows. A custom input integration was developed (see Fig. 7) to allow users to enter text-based load cycle data and generate a full field response, which is based on the transient approximation as defined above. The choice of custom integration interface also allows non-experts to use these surrogate models. Thus, they can make engineering decisions without having expert simulation knowledge. Results can then directly be stored using simulation data manage-

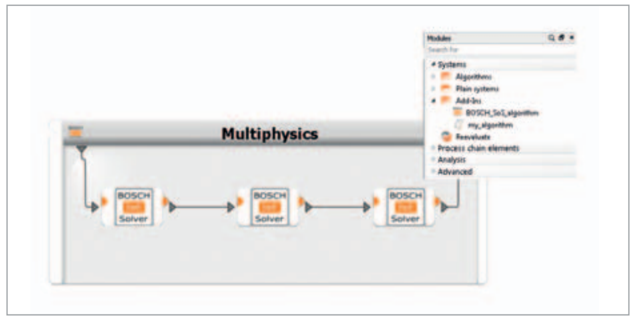

Fig. 7: Use of custom algorithm integration node in optiSLang for an easy use in user defined workflows

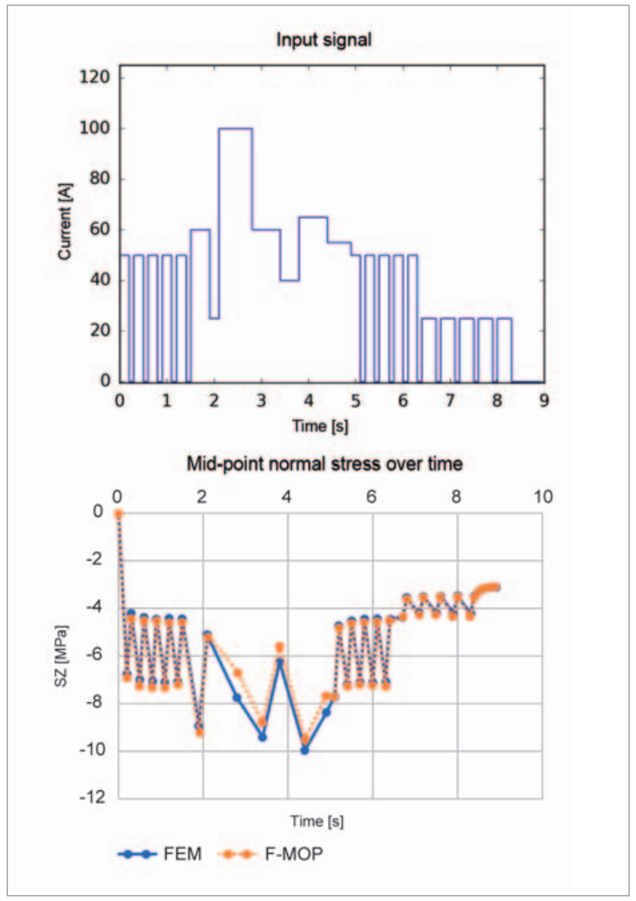

Fig. 8: Comparison of transient stress field solution at bond contact surface using FMOP-surrogate model to full FEM model

ment technology to ensure traceability and to make them available to other stakeholders like circuit board designer and project management.

Results and discussion

The field-metamodel technology has been effectively applied in the design of electric circuit boards. Fig. 8 shows how the normal stress on the inside of the bond contact surface changes as a function of a varying input current load signal. The output of the transient surrogate model (dashed line) matches very closely the response of a fully coupled FEM simulation (continuous line). For this specific example, the computation time could be reduced from around 25 hours for the FEM model to approximately two minutes using the field-metamodel. For longer profiles, FEM will no longer be feasible and the benefit of the metamodel will be even bigger.

The surrogate model can be used to fully replace a complex FEM simulation, while significantly reducing the computational demand. With this approach, thermo-mechanical analysis as the next step in lifetime-based modeling becomes reality. It furthermore demonstrates that real-time or almost real-time digital twin applications are practical and feasible.

Authors //
K. Riester (Robert Bosch GmbH), S. Klonk (Dynardo GmbH)