Meta-Modeling With OptiY®
Winning Mathematical Surrogate Models from Measurement Data or Complex Finite Element Analysis

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Outline

1. Objective
2. Theoretical Basics
    - Gaussian Process
    - Visualization of the Adaptive Gaussian Process
3. Practical FEA Example
    - Electromagnetic Actuator
    - Characteristic Diagram *F=f(i,s)* and *Psi=f(i,s)*
    - System Simulation using Characteristic Diagrams

Objective

Simulation of a Real Product or Process

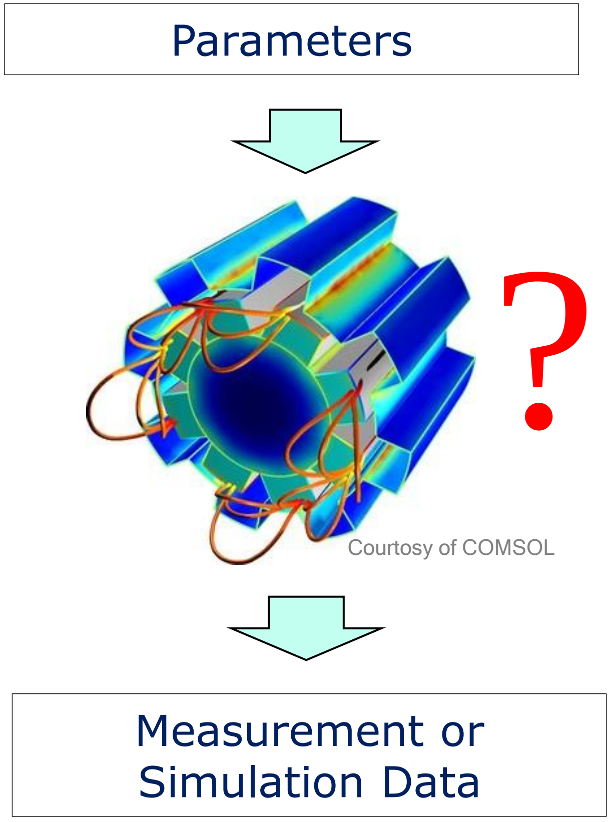
- Relationships or work principles are unknown
- Up to now only measurement data exist
- What should be modeled?

Complex Finite Element Model

- Long computing time: hours or days
- Control: loops of simulations
- Test scenarios: many simulations required
- Technical feasibility of system simulation?

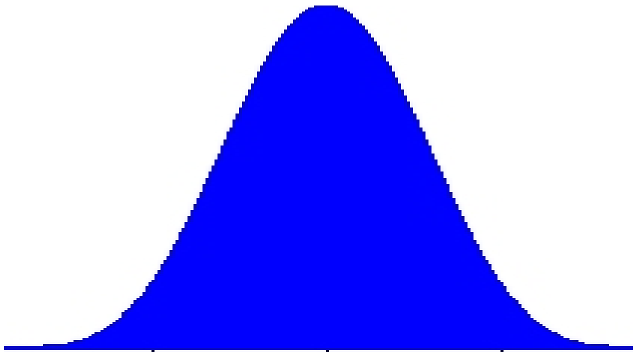
Current Solutions

- Model reduction to network elements
- Mathematically describable relationships only
- Search for suitable model structures and parameters
- Parameter validation required
- Time-consuming and cost-intensive



Gaussian Process

- Polynomial f(**x**) of p^{th} order for global adaptation
- Stochastic process Z(**x**) for local adaptation



$$
\begin{aligned}
Y(\mathbf{x}) = \; & f_0 + b_{11} x_1 + b_{12} x_1^2 + \ldots + b_{1p} x_1^p \\
& + b_{21} x_2 + b_{22} x_2^2 + \ldots + b_{2p} x_2^p \\
& \ldots \\
& + b_{n1} x_n + b_{n2} x_n^2 + \ldots + b_{np} x_n^p \\
& + Z(\mathbf{x})
\end{aligned}
$$

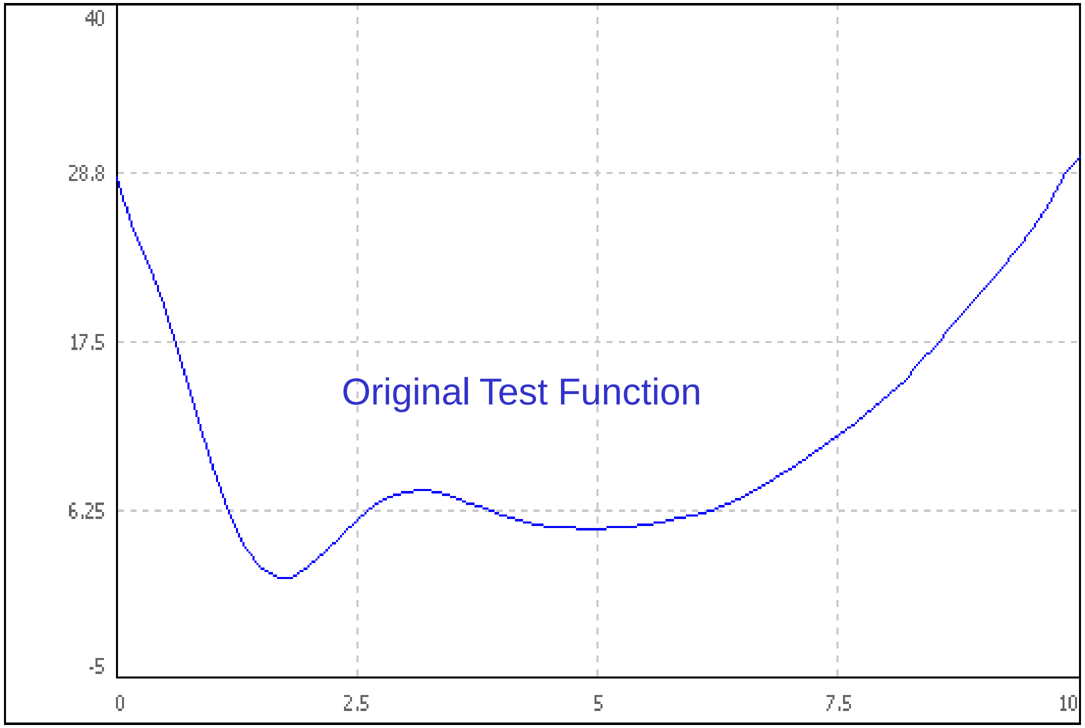
Correlation Function R**(x)**

- Multivariate Gaussian distribution (normal distribution)
- Interpolation between calculated points
- Interactions between individual parameters

$$R(x_i, x_j) = \sum_{k=1}^{n} w_k^2 (x_i - x_j)^2$$

Visualization of the Adaptive Gaussian Process

$$Y = (X-5)^2 - 15 \cdot e^{-(X-1.5)^2} + 5$$



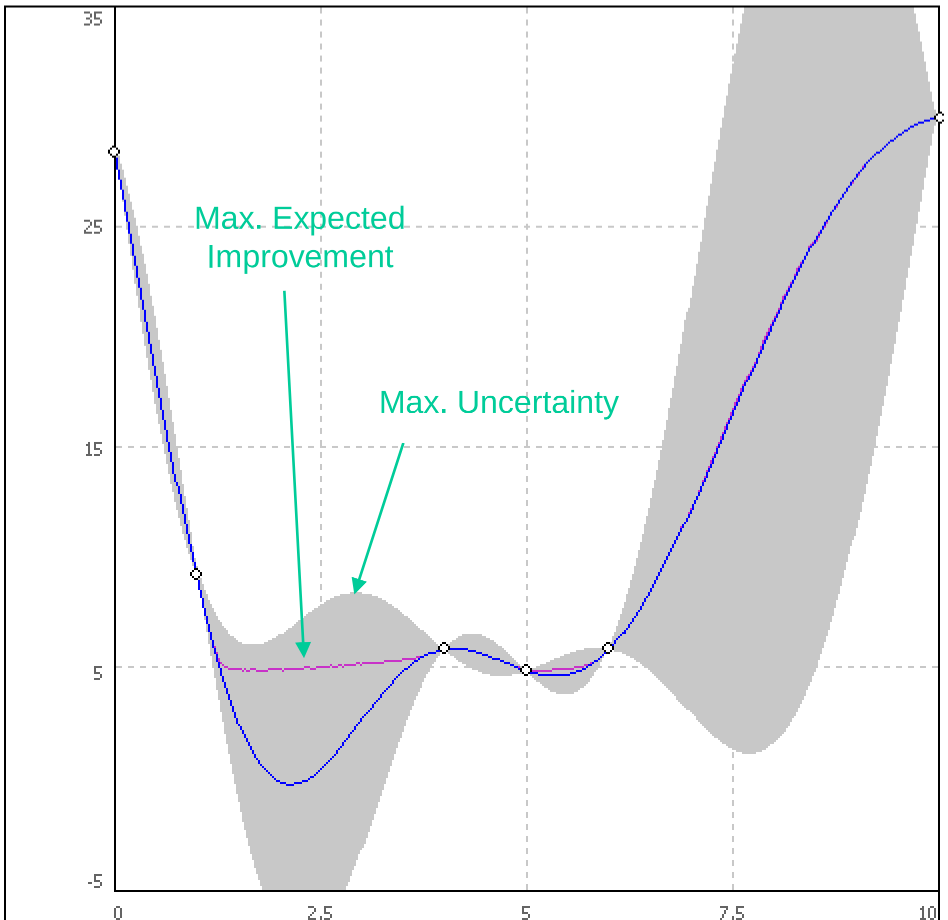
Approximation Loops

Response Surface

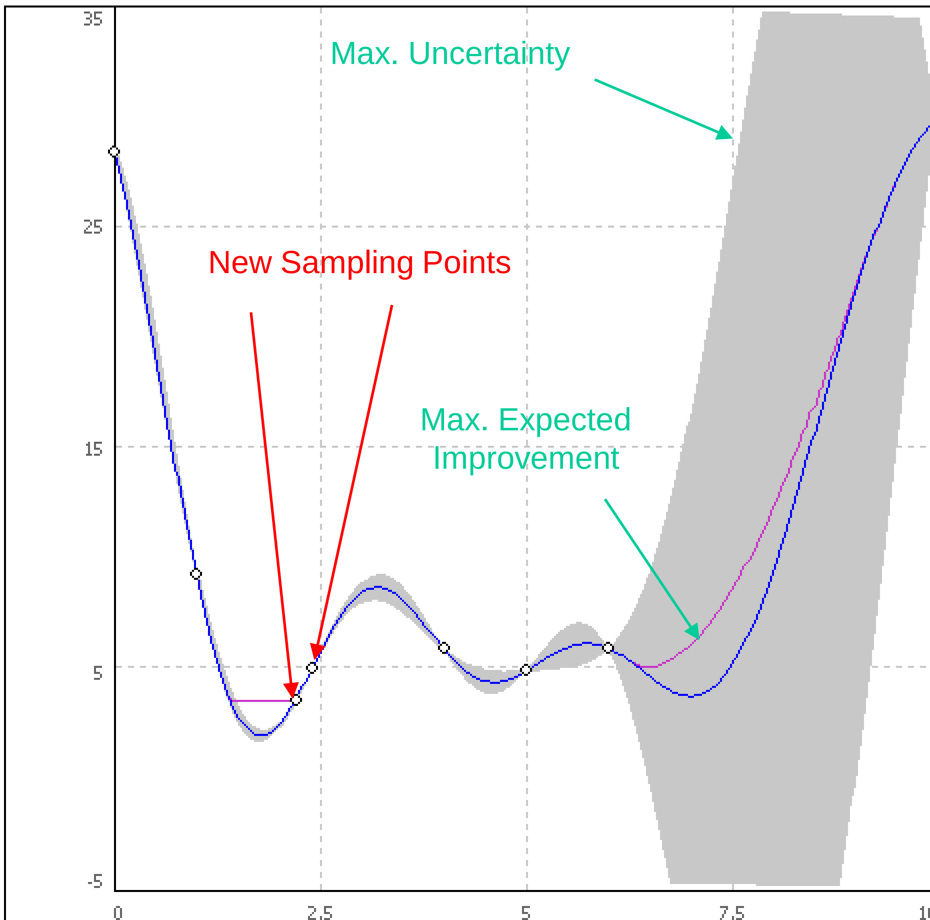
Expected Improvement EI

95% Confidence Interval

Start: 6 Sampling Points



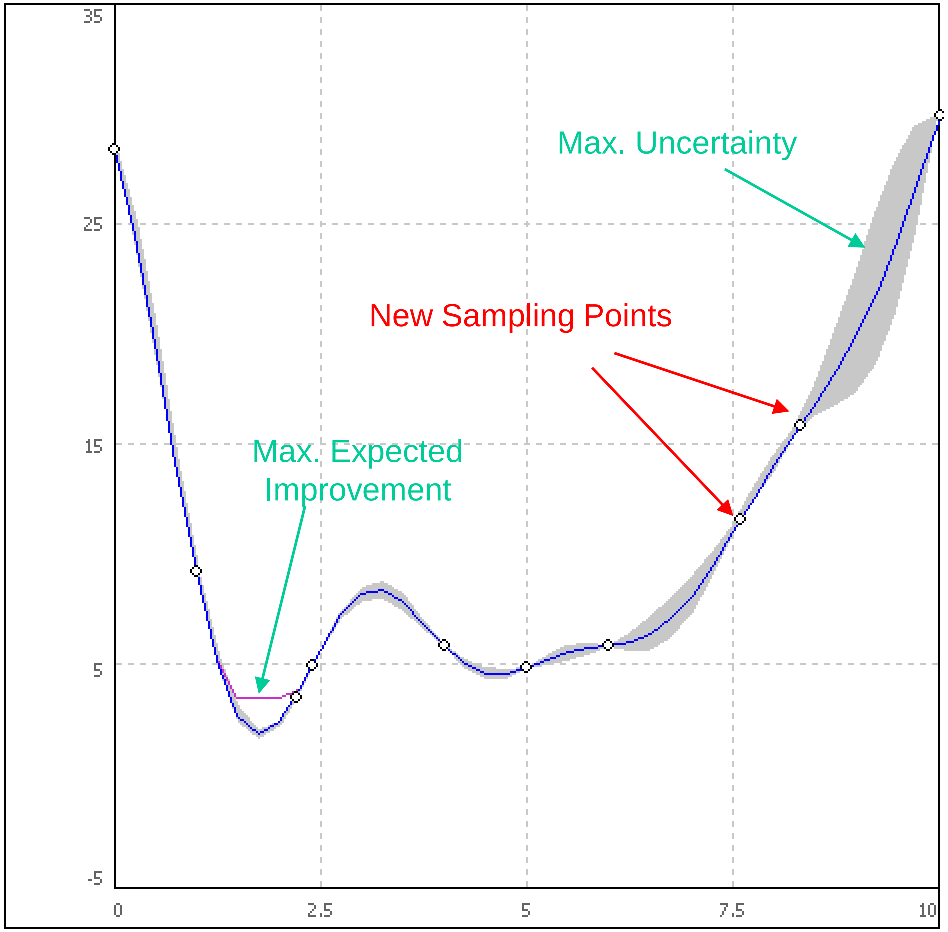
Loop 1



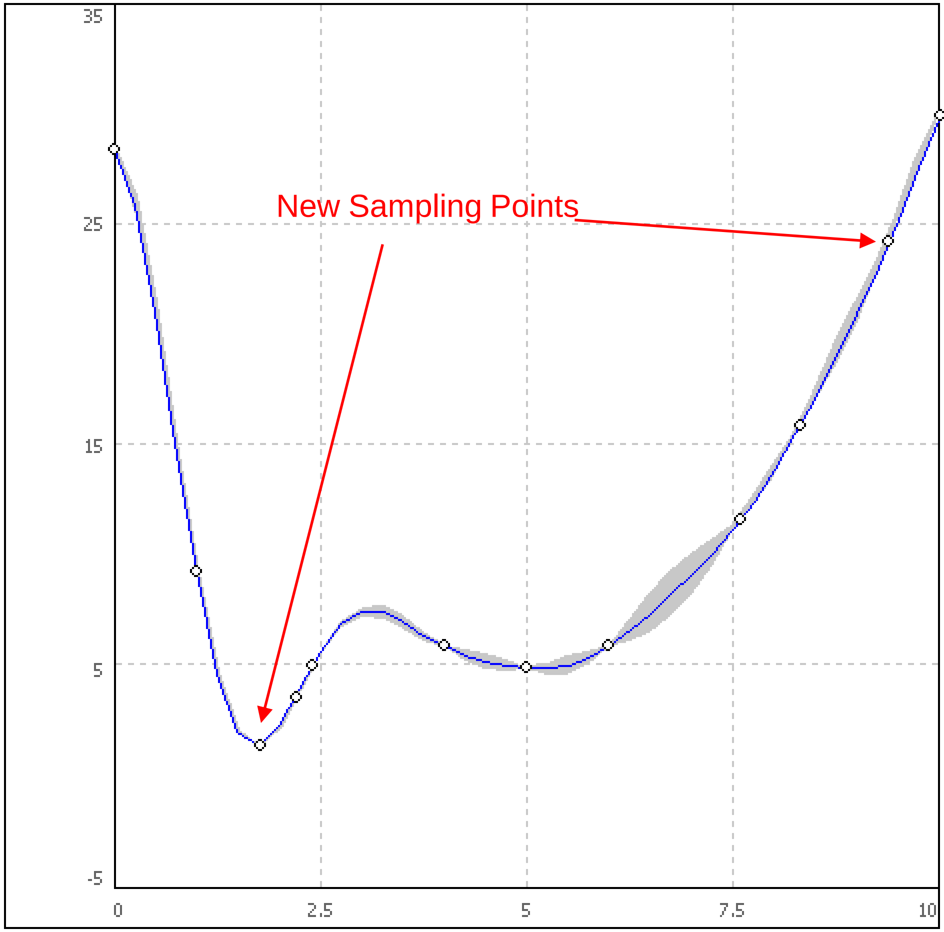
Approximation Loops

Stop-Criterion:
Expected Improvement < (Y_{max}-Y_{min})/100

Loop 2

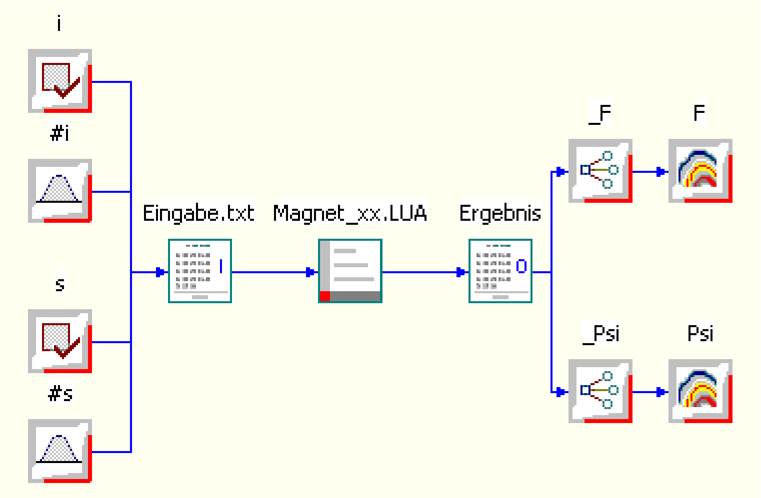


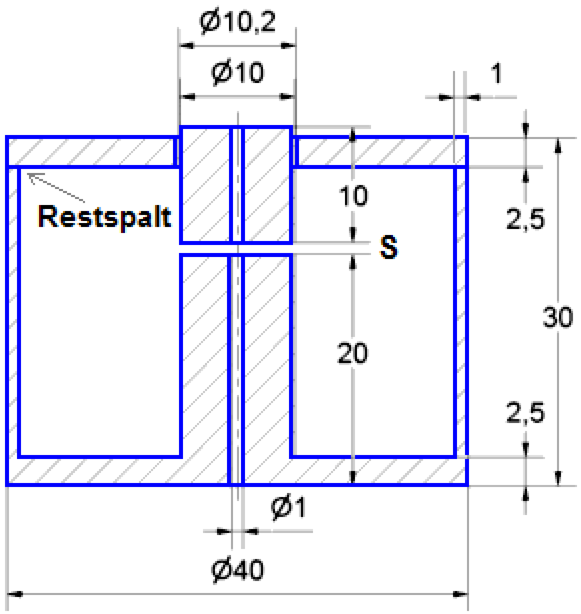
Loop 3: Automatic Stop

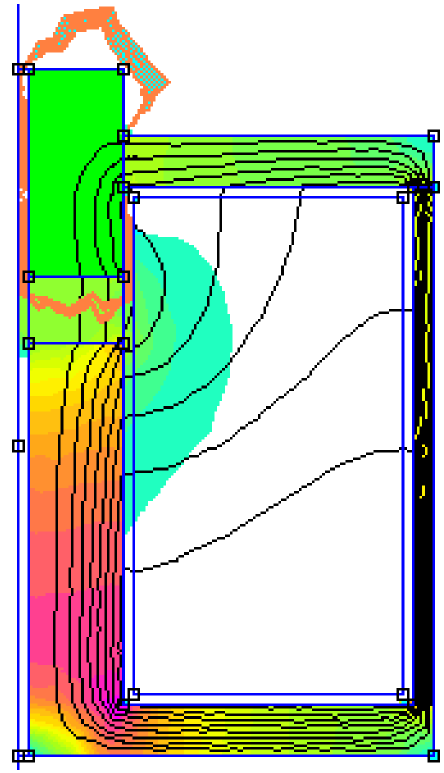


Example: Electromagnetic Actuator

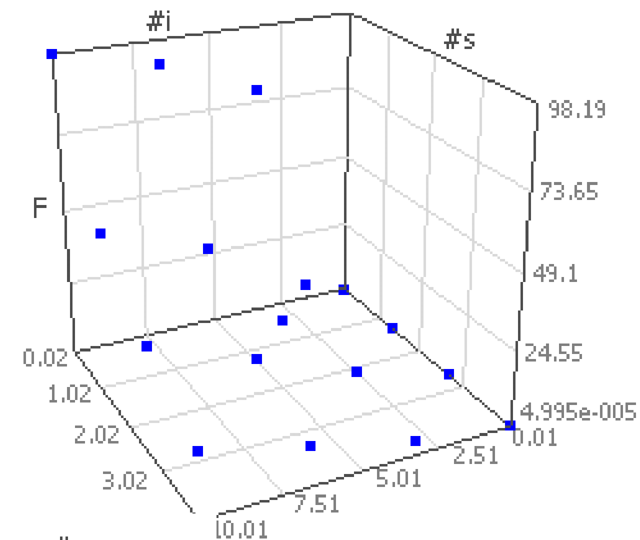
- Using the program **FEMM** and LUA script the parameterized model of a static pot magnet has been created (2D-axisymmetric).
- By means of OptiY the characteristic diagrams ***f(i,s)*** and ***Psi(i,s)*** can be identified for ***F*** (force) and ***Psi*** (coupling flux).
- It is shown how exported C code can be implemented in a SimulationX model as an electro-mechanical converter.





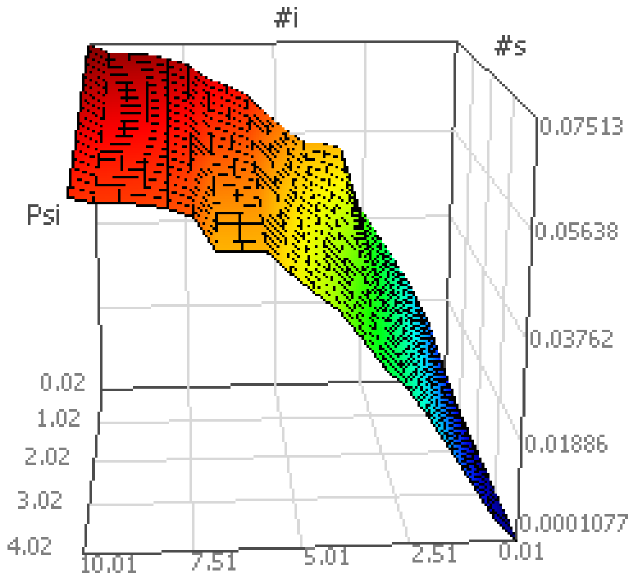


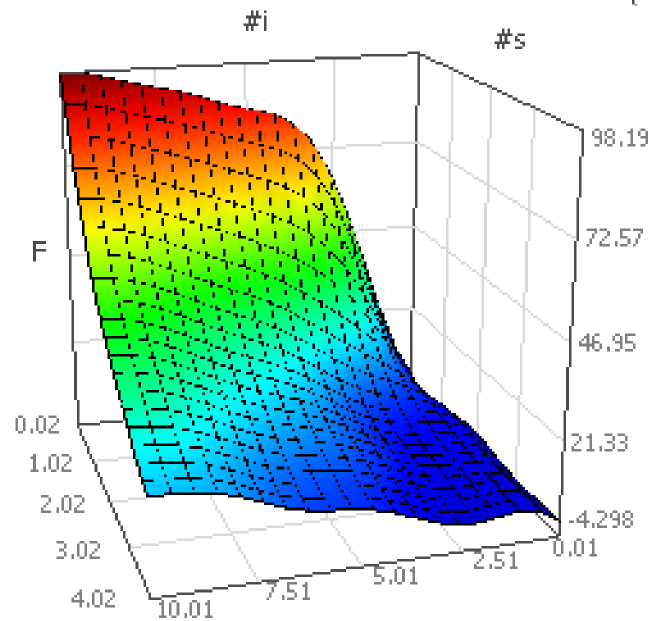
Identification of Characteristics



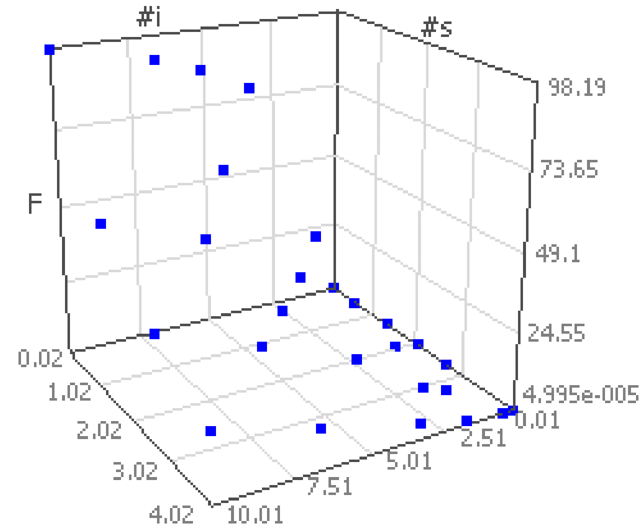
1. Optimal Setup of the Gaussian Process:

- Full Factory Design = Basic Grid → **(4x4)** +1
- Covariance Function → **Square Exponential**
- Approximation Order → **2**



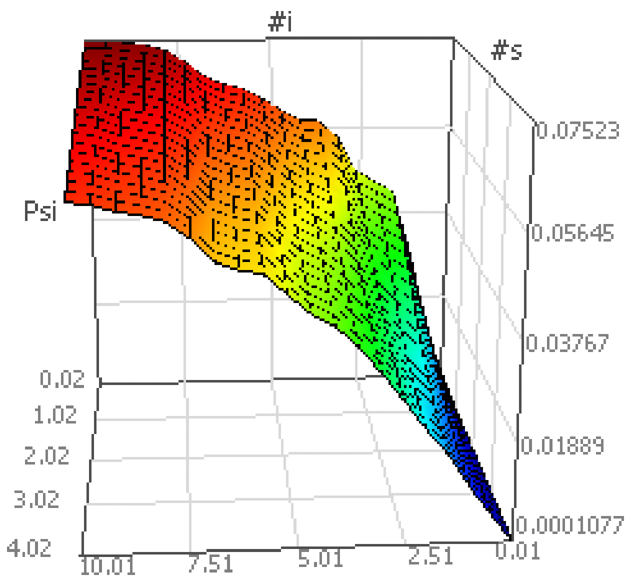


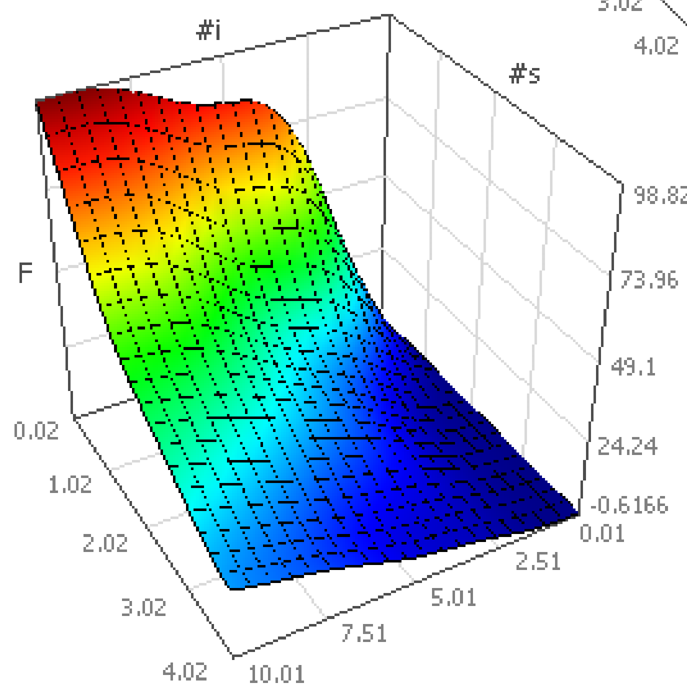
Identification of Characteristics



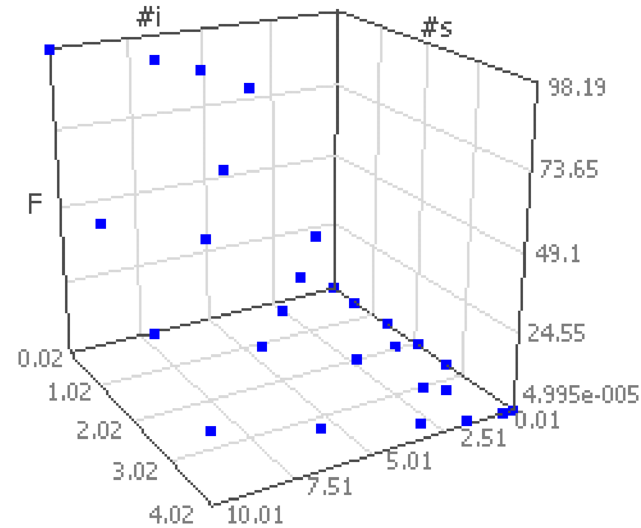
2. Adaptive Gaussian Process

- In addition to the basic grid further scan points are calculated within larger confidence intervals.
- The previous optimal setup of the Gaussian process ensures a stable convergence of the adaptive process.



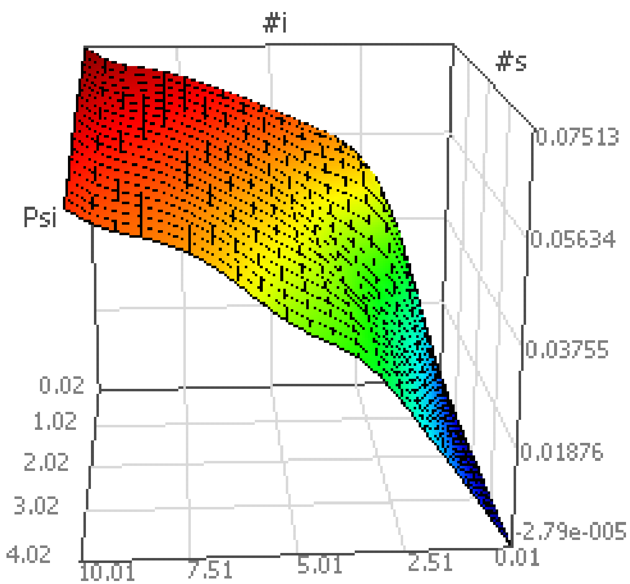


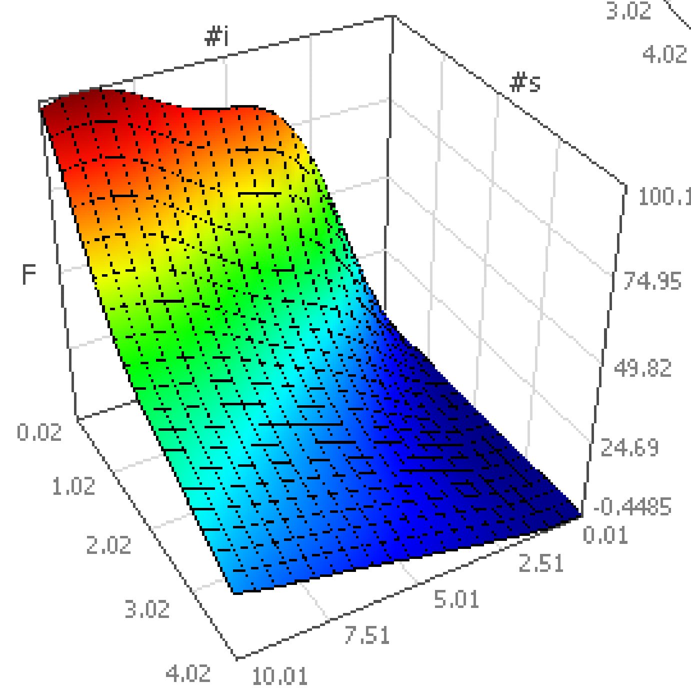
Identification of Characteristics



3. Fine Tuning of the Approximation Order (AO):

- AO = 2 ensures a stable convergence of the adaptive Gaussian process.
- Caused ripples in the identified response surfaces.
- The reduction to AO = 1 proved to be advantageous.





System Simulation based on the Characteristics

```
double Covariance(double x1[],double x2[],double p[])
{
    double Co, W;
    W = 0;
    for(int i = 0; i<2; i++) {
        W = W + (x1[i]-x2[i])*(x1[i]-x2[i])*p[i]*p[i];
    }
    Co = exp(-W);
    return Co;
}
```

```
double F(double i, double s)
{
    double p[2];
    double x1[2];
    double x2[2];
    double y = -46.7372056;
    y = y+10.5264863*pow(i,1);
    y = y+4.62081477*pow(s,1);
    p[0] = 0.161298213;
    p[1] = 0.928373134;
    x1[0] = i;
    x1[1] = s;
    x2[0] = 5.01;
    x2[1] = 2.02;
    y = y-183.986679*Covariance(x1,x2,p);
    x2[0] = 0.01;
    x2[1] = 0.02;
    y = y-8624.5598*Covariance(x1,x2,p);
    x2[0] = 2.01;
    x2[1] = 0.02;
    y = y+27677.7263*Covariance(x1,x2,p);
    :
    :
    x2[0] = 10.01;
    x2[1] = 4.02;
    y = y-1042.30105*Covariance(x1,x2,p);
    return y;
}
```

1. Code-Export (C-Code) and Creation of a DLL-File:

- GNU C compiler **gcc** in **cygwin**
- Only marginal changes of the C source code needed (Currently still **float** → **double**)
- Process can be automated using DOS batch commands:

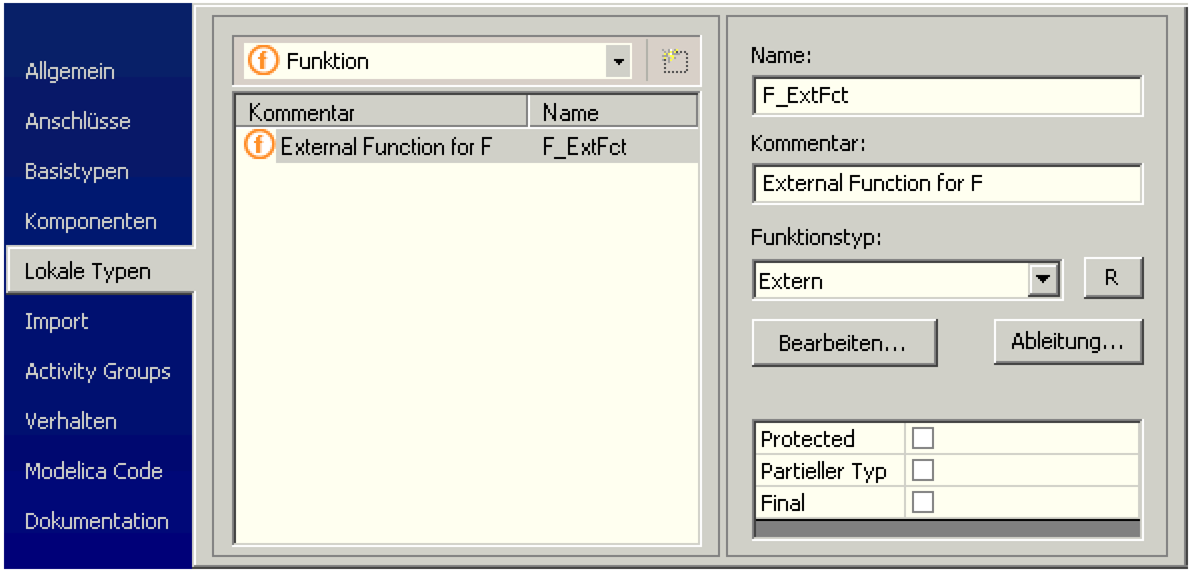
```
gcc-3 -mno-cygwin -shared -o Magnet_RSM.dll Magnet_RSM.c
```

- The DLL file has to be saved in a folder for SimulationX External functions: *Extras->Options->Directories->External Functions*

System Simulation based on the Characteristics

2.1. External Function in User-Defined Element Type:

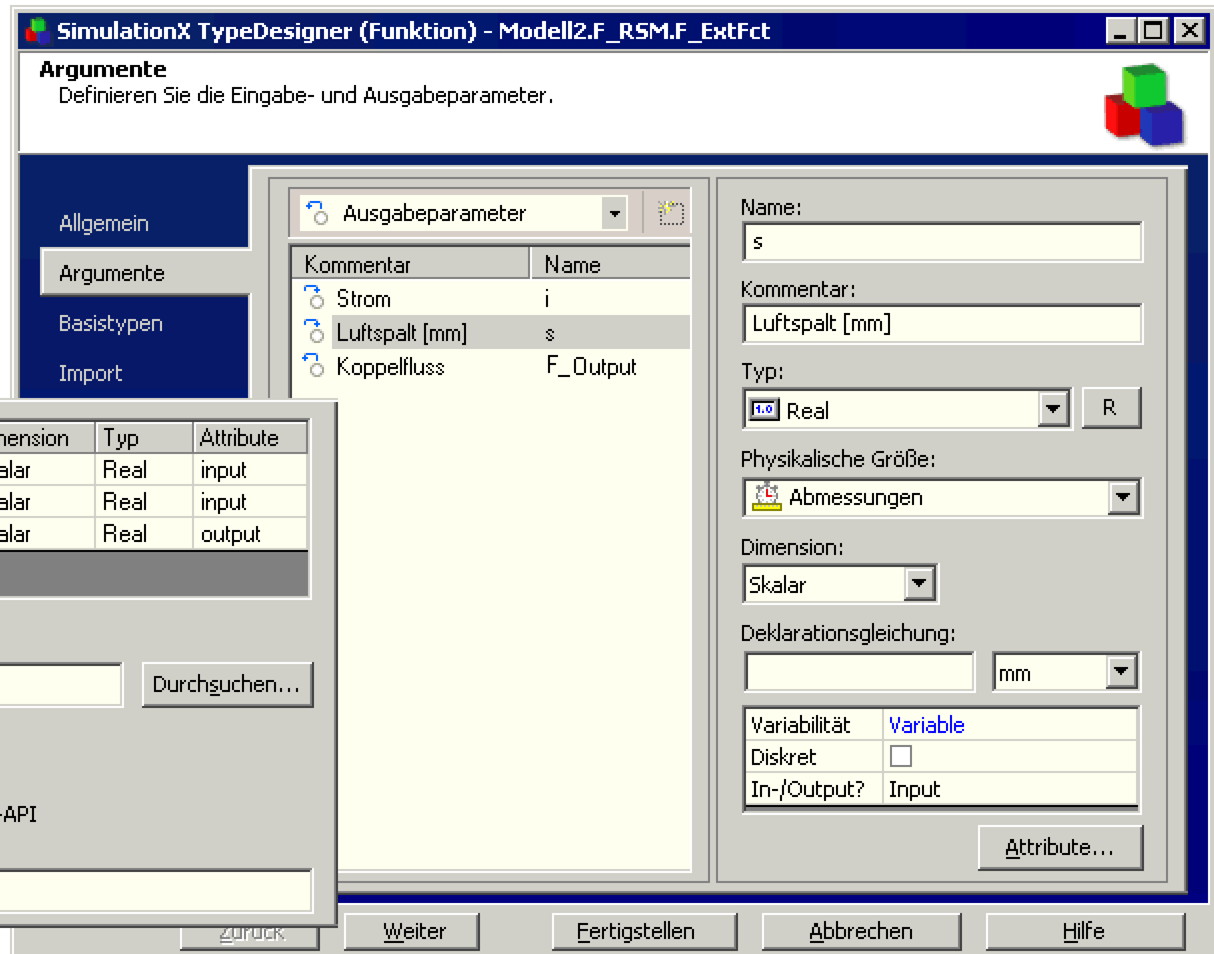
- Use of SimulationX *TypeDesigner* to define a custom converter type.
- Integration of external functions as local types in the user-defined element type.
- Definition of a function of type ‘External’ with name and comment.

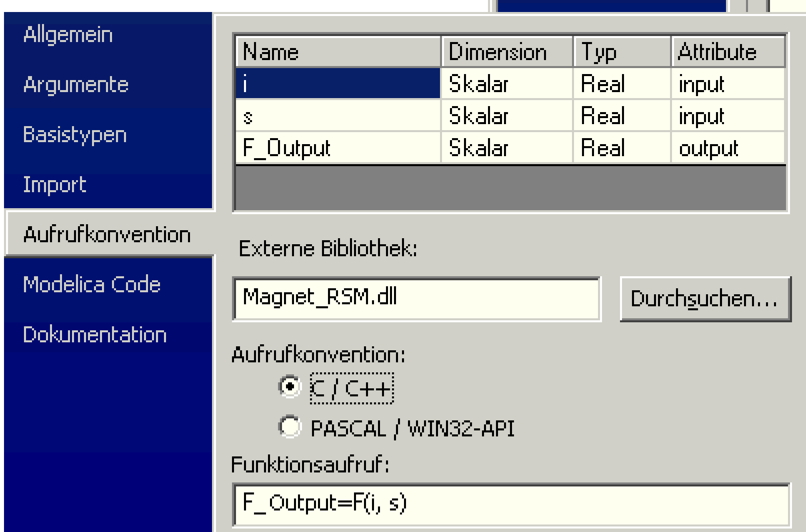


- "Edit" opens a special SimulationX *TypeDesigner* for functions.

System Simulation based on the Characteristics

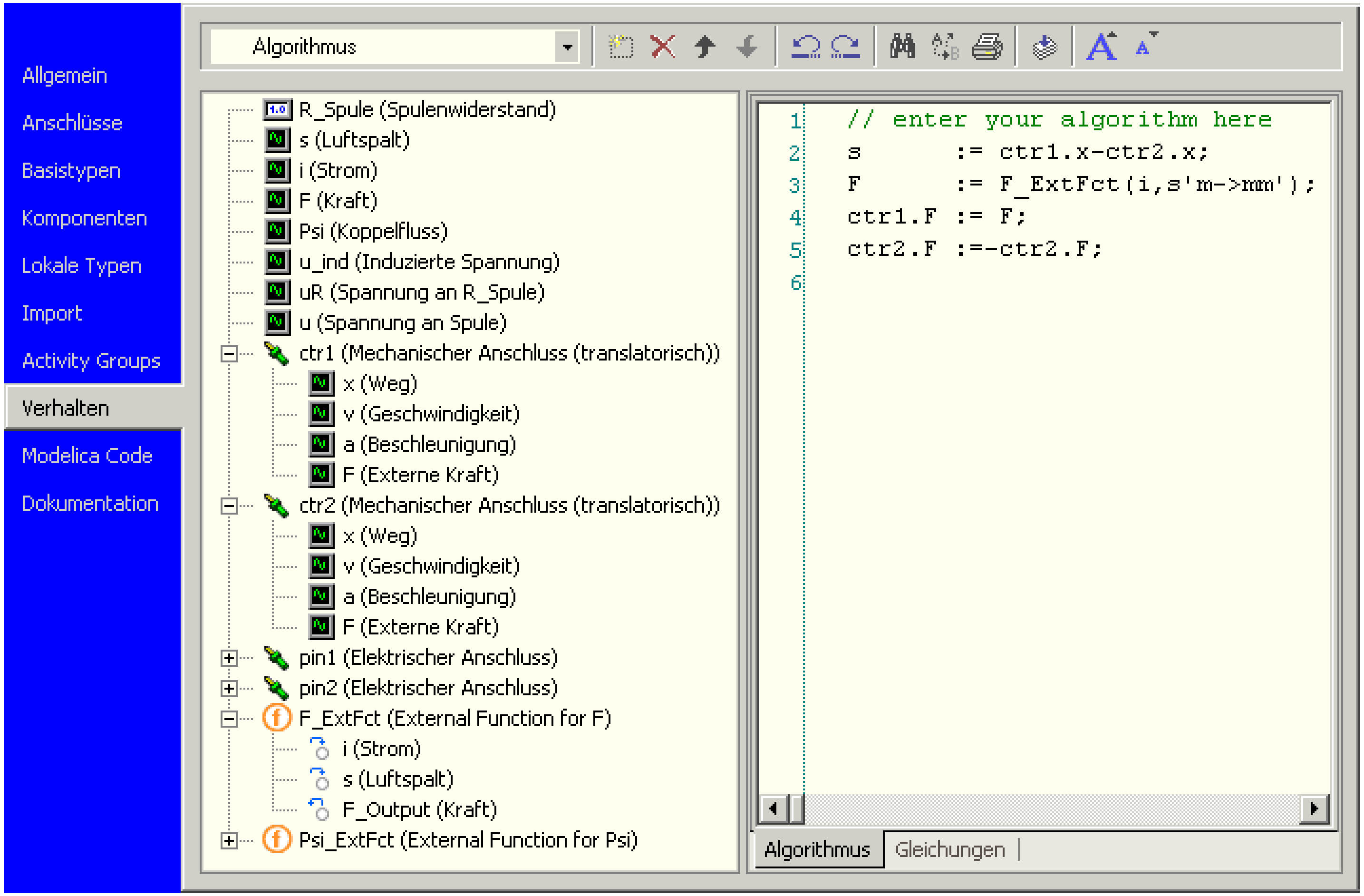
2.2. Definition of an interface to the external function:





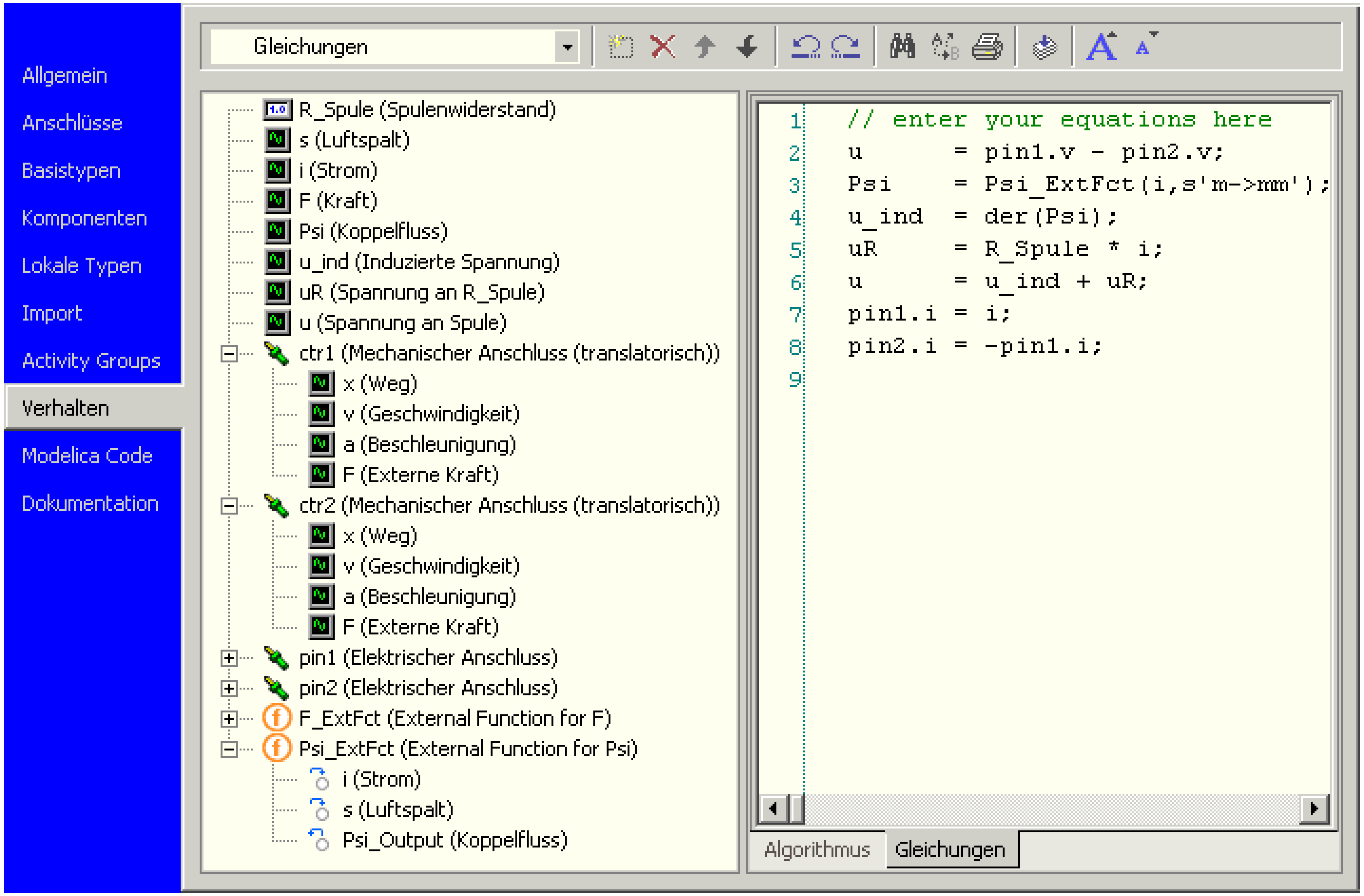
System Simulation based on the Characteristics

3.1. Electromechanical Converter (mechanical side):



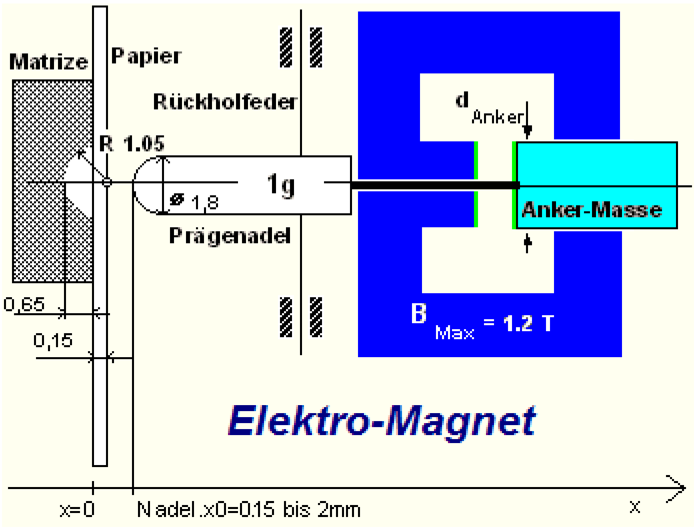
System Simulation based on the Characteristics

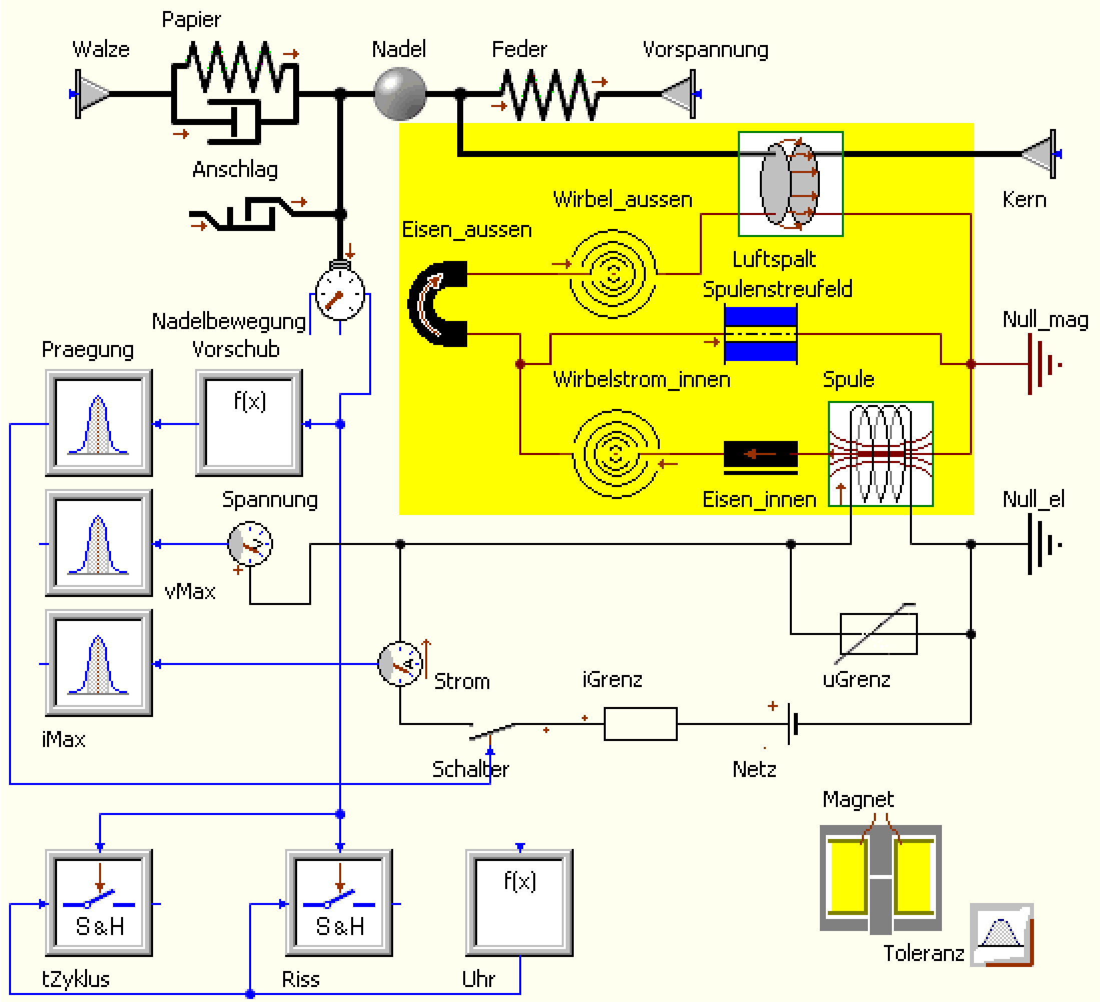
3.1. Electromechanical Converter (electrical side):



System Simulation based on the Characteristics

4.1. Network model of an electromagnetic actuator for the Braille blind embossing

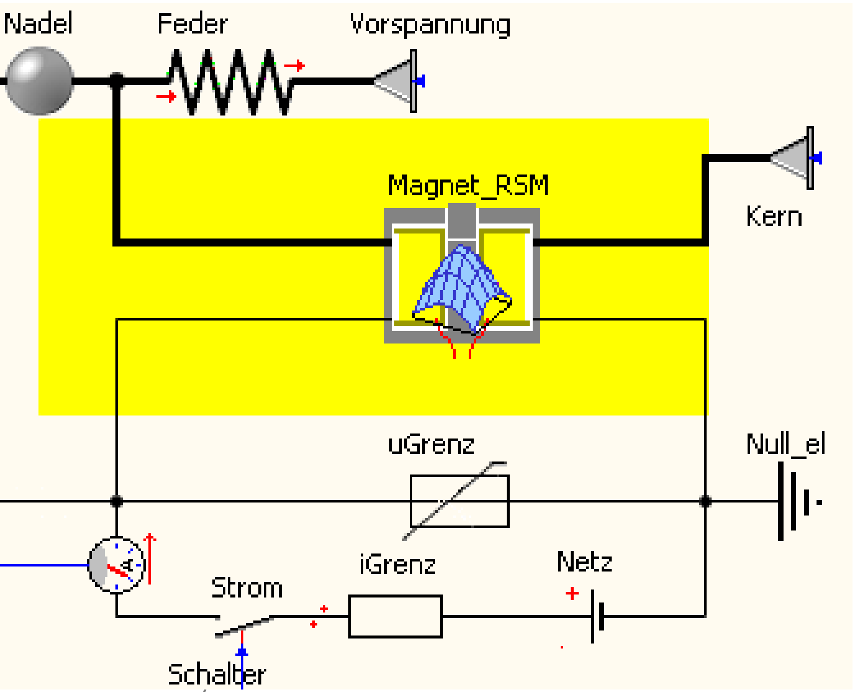


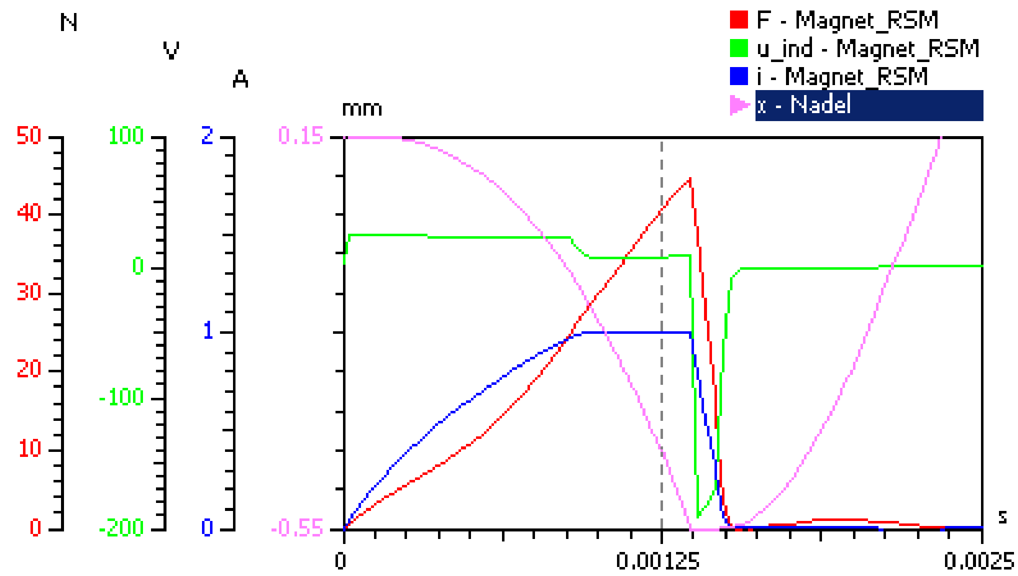


System Simulation based on the Characteristics

4.2. Network model of an electromagnetic actuator based on the characteristic diagrams:

- The characteristic diagrams using response surfaces of a FE calculation vary accurately reflect the transmission behavior even for a complicated converter geometry.
- All model parameters except the converter geometry can be varied in simulations.





Conclusion

- Modeling and simulation of a real product or process is infeasible because of unknown relationships or time-consuming computations. Current solutions for solving this problem apply model reduction to network elements, which is very time- and cost-intensive
- The new approach in OptiY® allows a fast and simple extraction of a mathematical surrogate model from measurement data or complex FEA. The adaptive process can suggest new sampling points for the measurement or model calculation to build the surrogate model more accurately.
- The exported C code can be included as an external function in appropriately designed element types of SimulationX models.
- The surrogate model of complex components can be used as part of a complex system model.
- The advantages of network-based system simulation can be combined with the advantages of the FEA and the measurement of real objects throughout the design process.