Meta-Modeling With OptiY® - Design Space Visualization for Electromagnetic Applications in CST Studio Suite®

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CST European User Group Meeting

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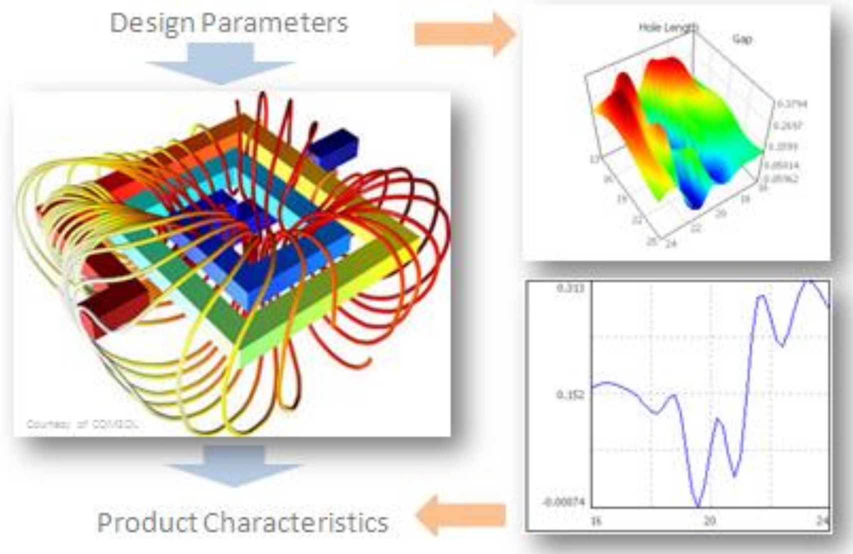
Outline

1. Objective
2. Theoretical Basics
   - Gaussian Process
   - Visualization of the Adaptive Gaussian Process
3. Practical EM Example
   - Waveguide Hybrid Junction
   - Design Space of Reflection and Transmission

Objective

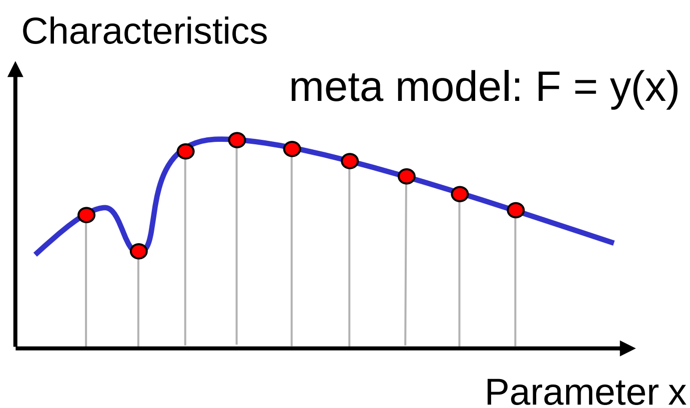
Design Space Visualization

- Knowledge about the relationship:
  Design Parameters – Product Characteristics
- Reliability, Safety and Quality Engineering
- Reduce development, manufacturing cost and failure
- Increasing lifetime
- Reduce service after sale



Current Solutions

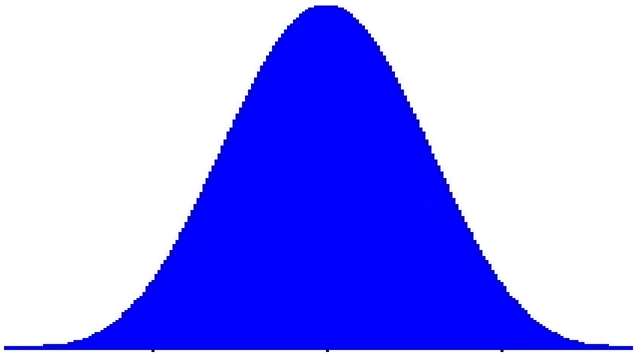
- Full Factorial Design (Parameter Sweep)
  - **n** design parameters with **k** tunable values
  - $\mathbf{n}^{k}$ number of model calculations required
  - High computing effort
  - Infeasible for large model (one run takes some hours)
- Other Methods for Design of Experiment (DOE)
  - Less number of model calculations
  - Inaccurate



Gaussian Process

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

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



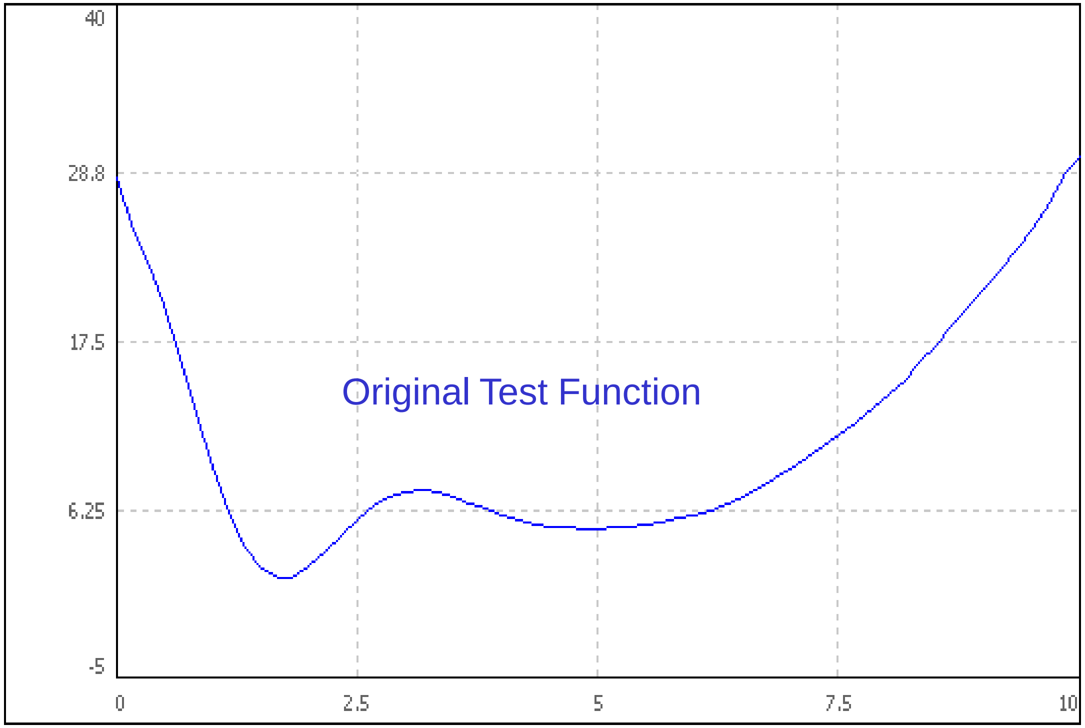
Correlation Function R(**x**)

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

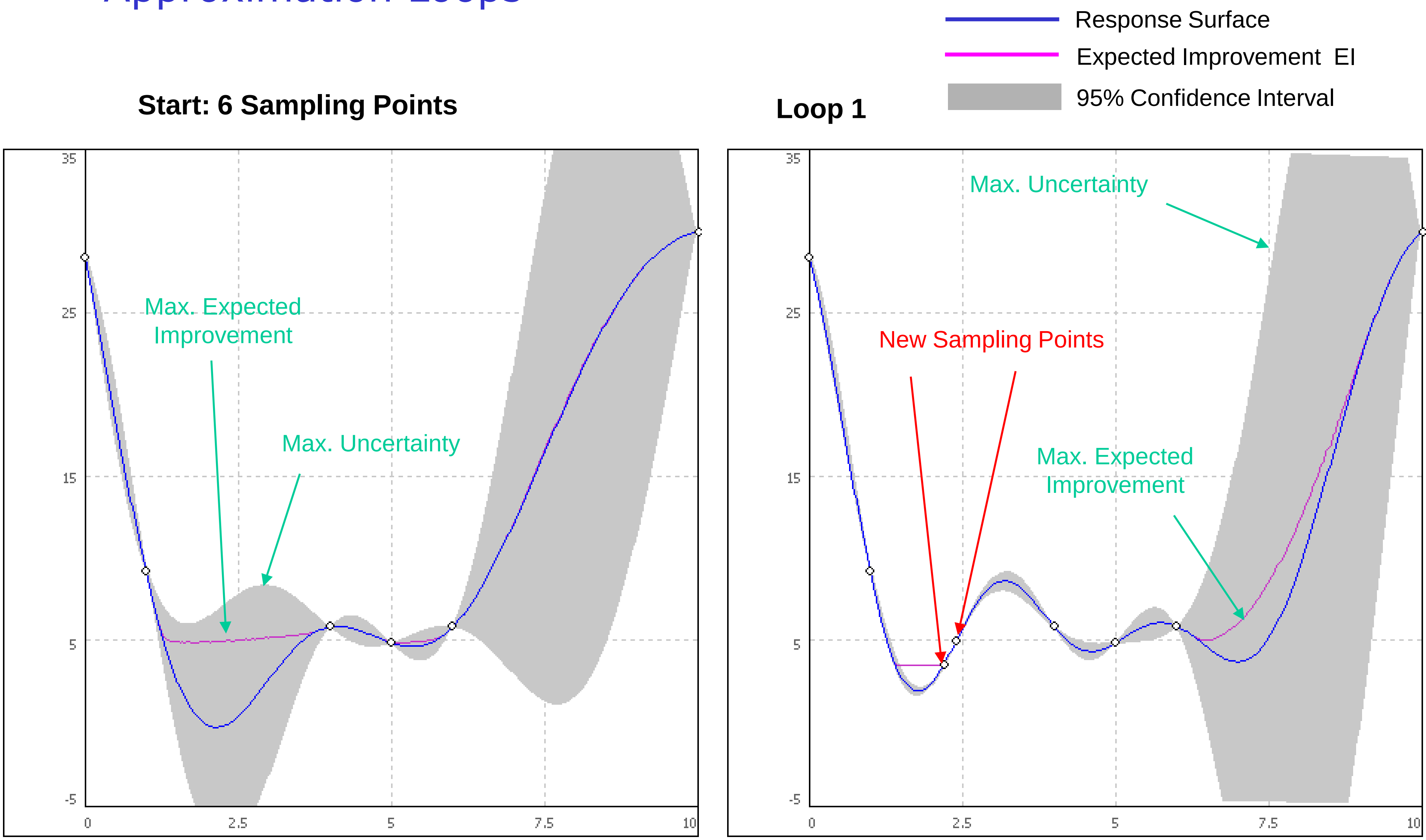
$$R(x_i, x_j) = \sum_{k=1}^{n} w_k^2 (x_i - x_j)^2$$

Visualization of the Adaptive Gaussian Process

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



Approximation Loops

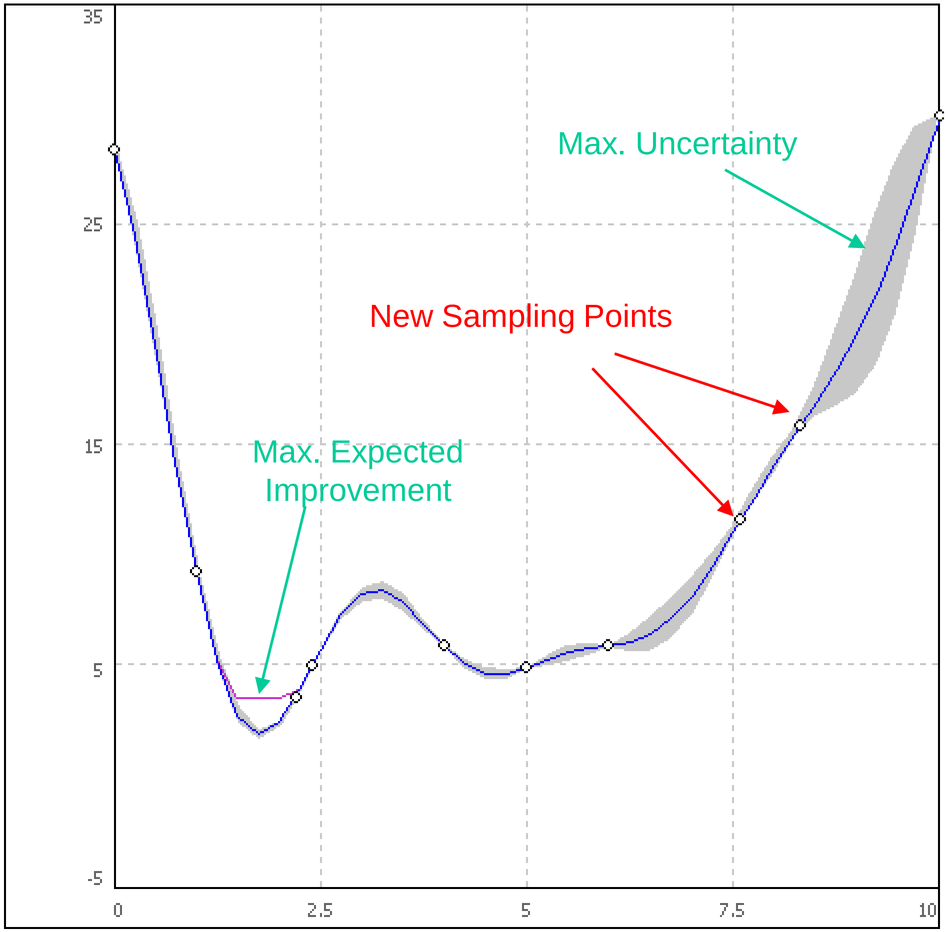


Approximation Loops

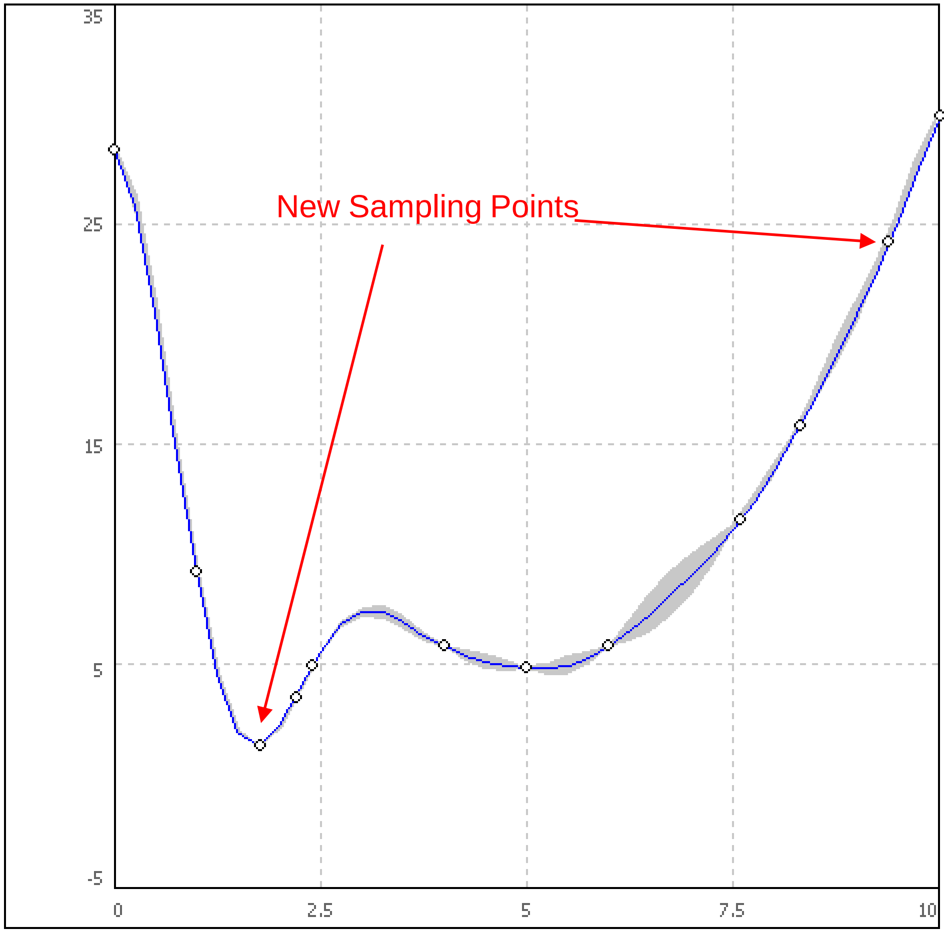
Required number of model calculations depends on:

- Number of design parameters
- Degree of response nonlinearity
- Correlation between design parameters

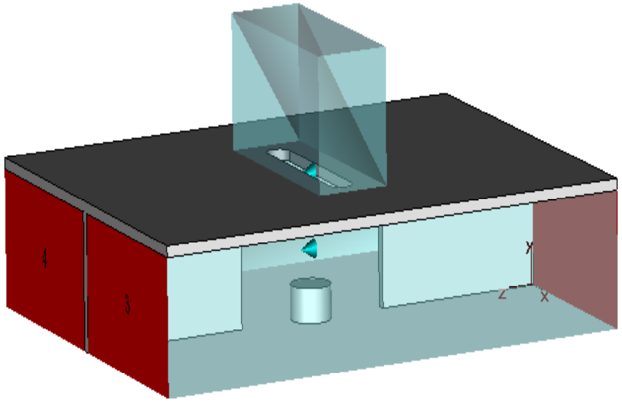
Loop 2

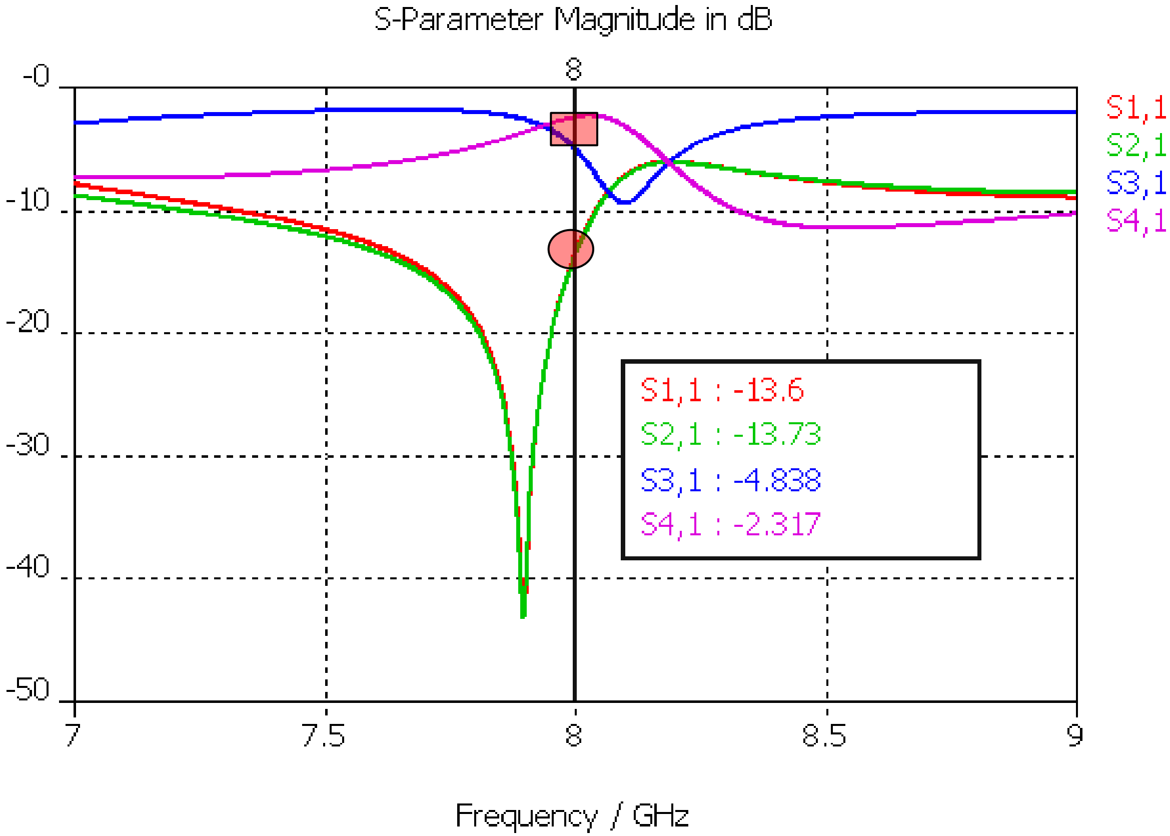


Loop 3: Automatic Stop



Waveguide Hybrid Junction





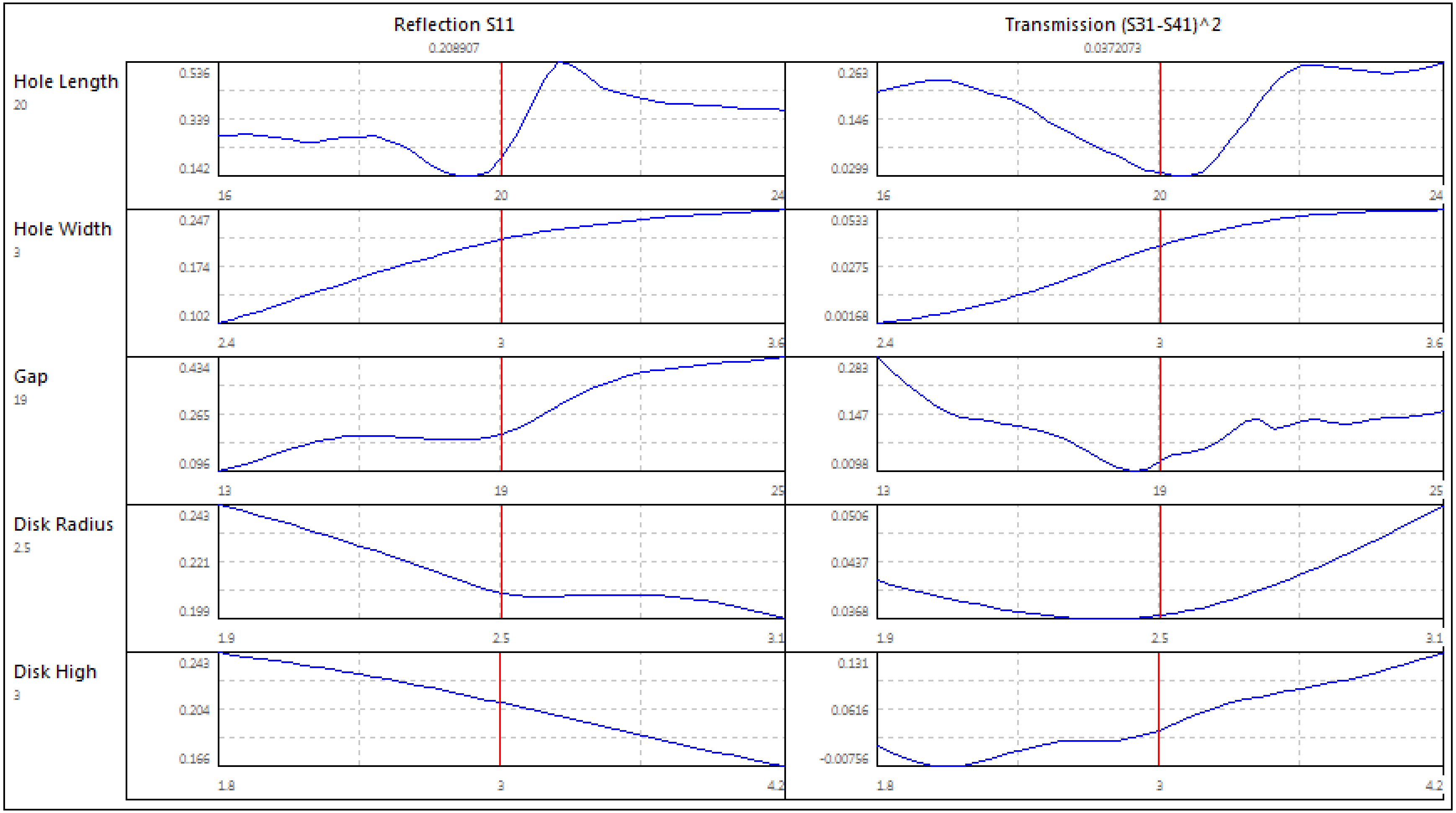
Design Space

Hole Length 16 – 24 mm
Hole Width 2.4 – 3.6 mm
Gap 13 – 25 mm
Disk High 1.8 – 4.2 mm
Disk Radius 1.9 – 3.1 mm

Product Characteristics:

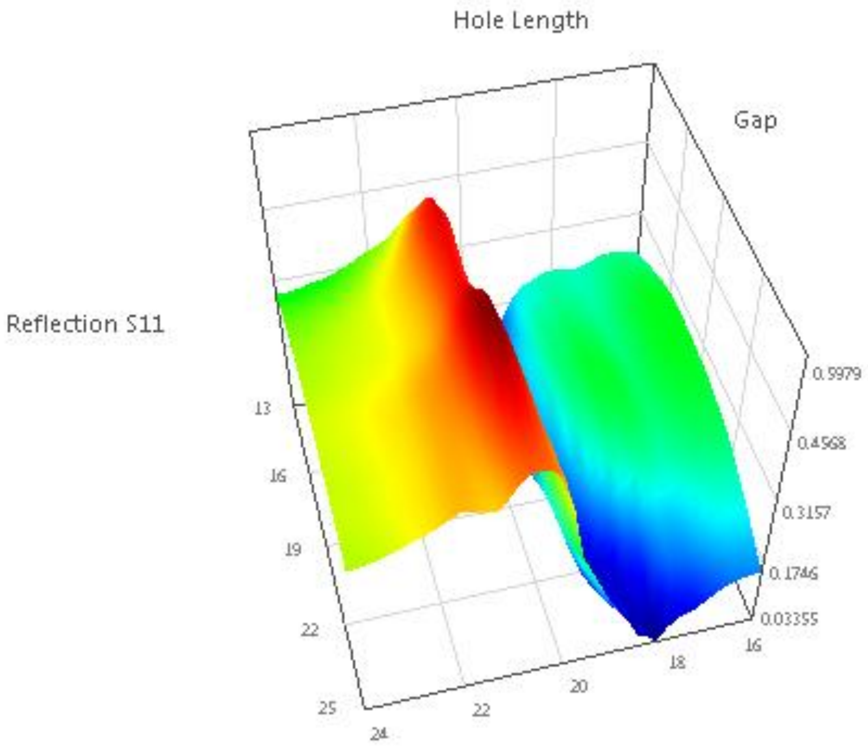
Transmission and Reflection at the operating point 8 GHz based on transient simulation in CST Studio Suite

Design Space Visualization: 2D Section Diagrams

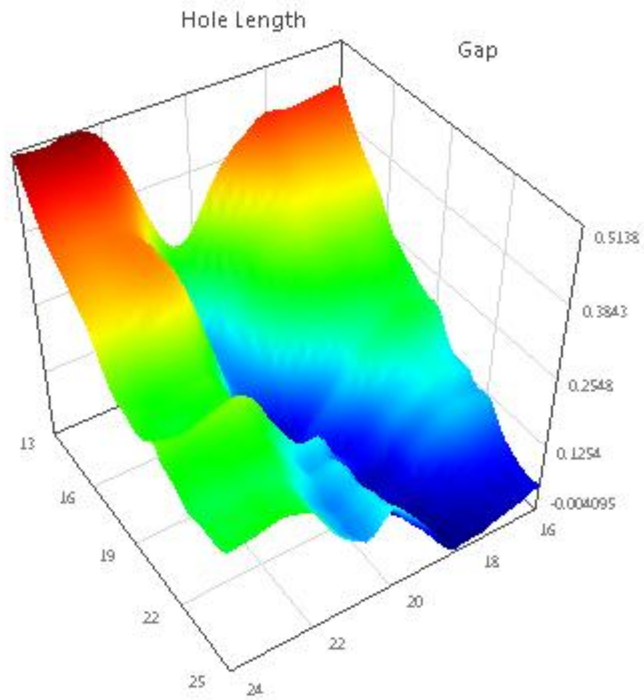


Design Space Visualization: 3D Graphics

Reflection

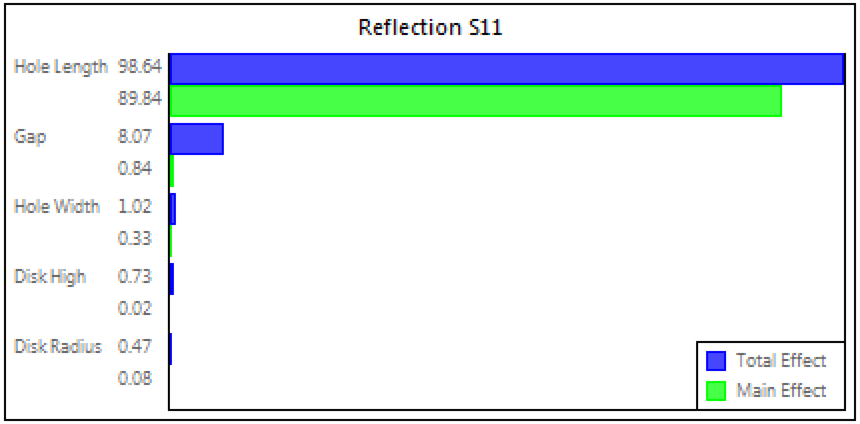


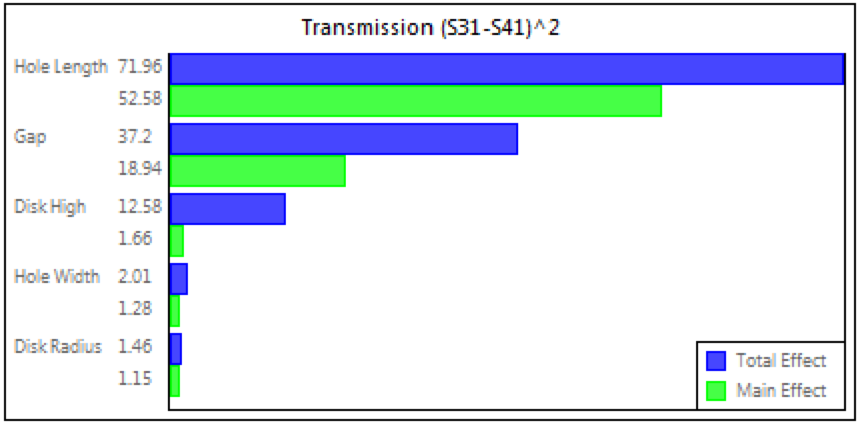
Transmission Difference



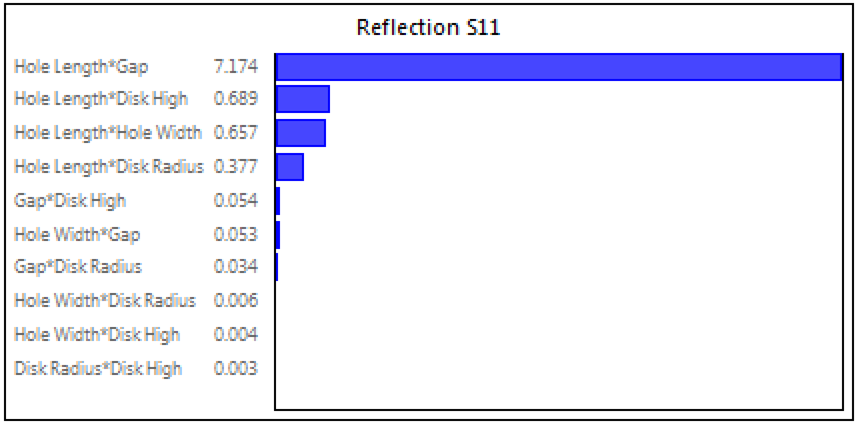
Global Nonlinear and Quantitative Sensitivity Analysis

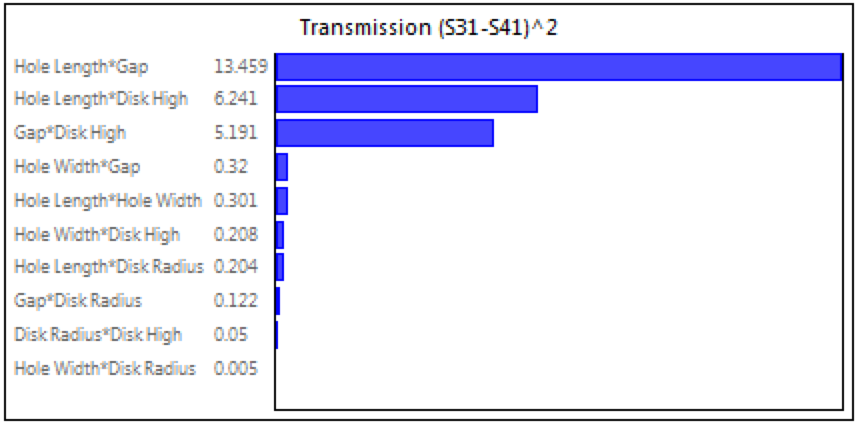
Design Parameter Importance





Design Parameter Interactions





Probabilistic Simulation (Yield Analysis)

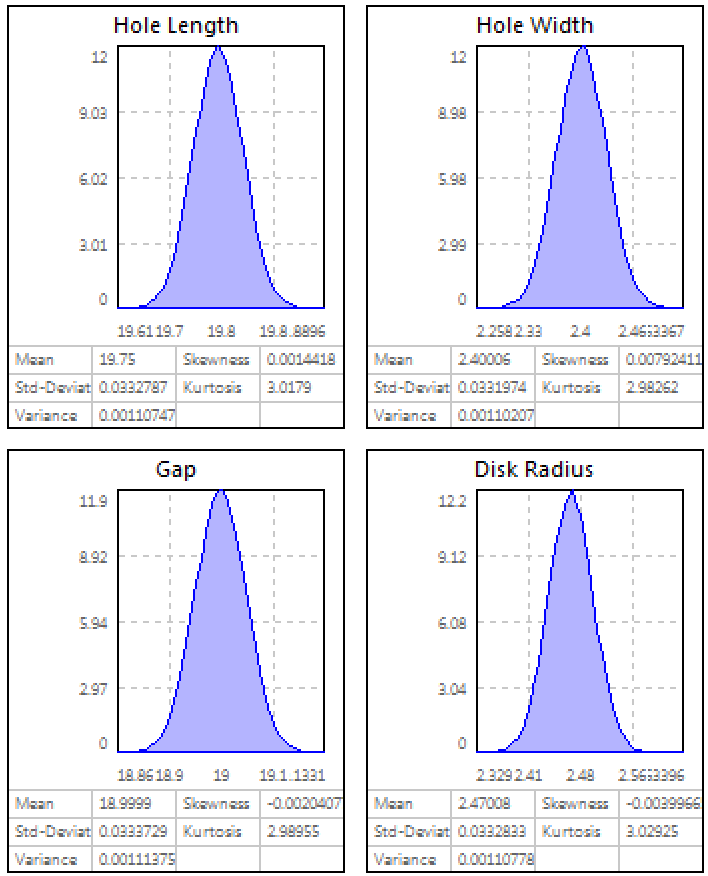
Design Optimization
Design goal: minimize the reflection S11 to get the optimal design point in the design space (Table: optimal design parameters with manufacturing tolerances)

Design Robustness
Tolerances of design parameters cause variability of the reflection and transmission: quality and reliability in series manufacturing

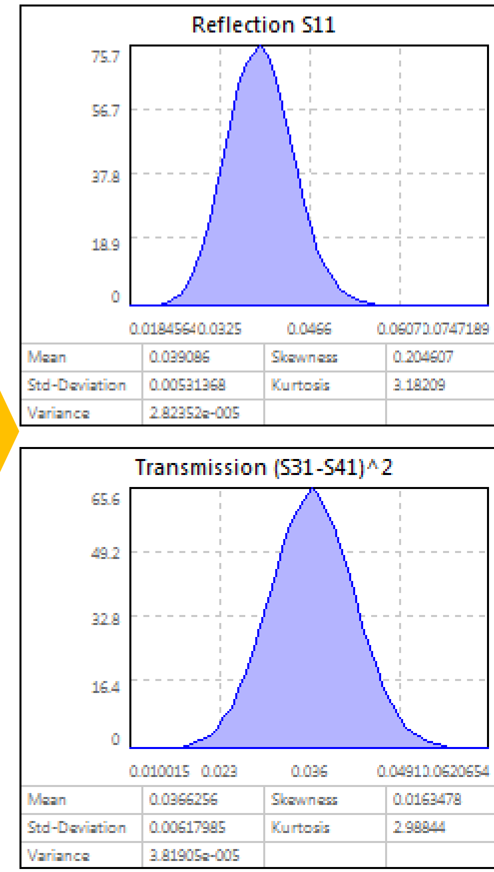
Actual Parameters

Name	Values	Local Tolerance	I	(
Hole Length	19.75	0.2		H
Hole Width	2.4	0.2		H
Gap	19	0.2		G
Disk Radius	2.47	0.2		D
Disk High	4.2	0.2		D

Input Distributions



Output Distributions

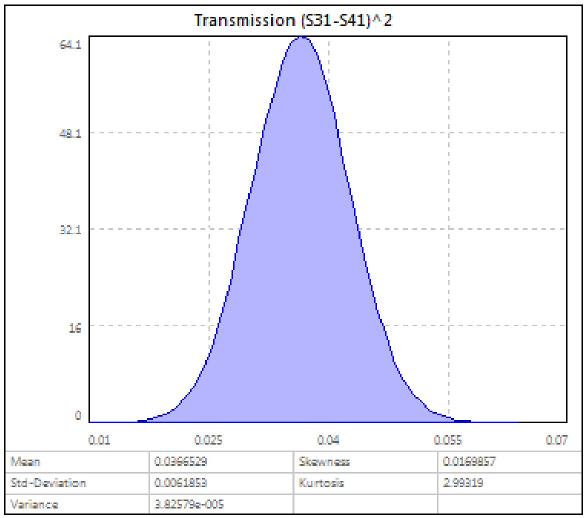


Multidisciplinary Analysis and Optimization

Robust Design Optimization

- Taguchi Quality Loss Function:
  L = Cost*(Variance + (Mean – Target Value)^2)
- Quality loss of Transmission S31,S41
  Target Value = 0 (e.g. S31 = S41), Cost = 1

Nominal Design



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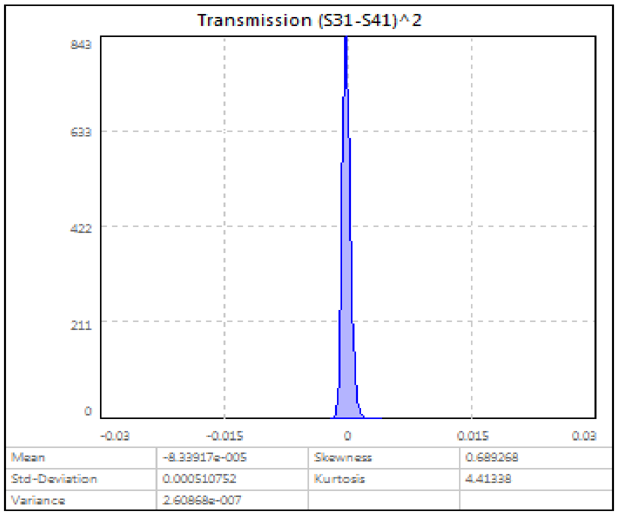
Robust Design



Actual Parameters

Name	Values	Local Tolerance	U	C
Hole Length	18.6992372	0.2		H
Hole Width	2.60716168	0.2		H
Gap	24.1586773	0.2		G
Disk Radius	2.25980617	0.2		D
Disk High	2.05806809	0.2		D

Minimizing the quality loss function for the transmission

- Nominal Design
  L = 1.3E-3
- Robust Design
  L = 2.6 E-7

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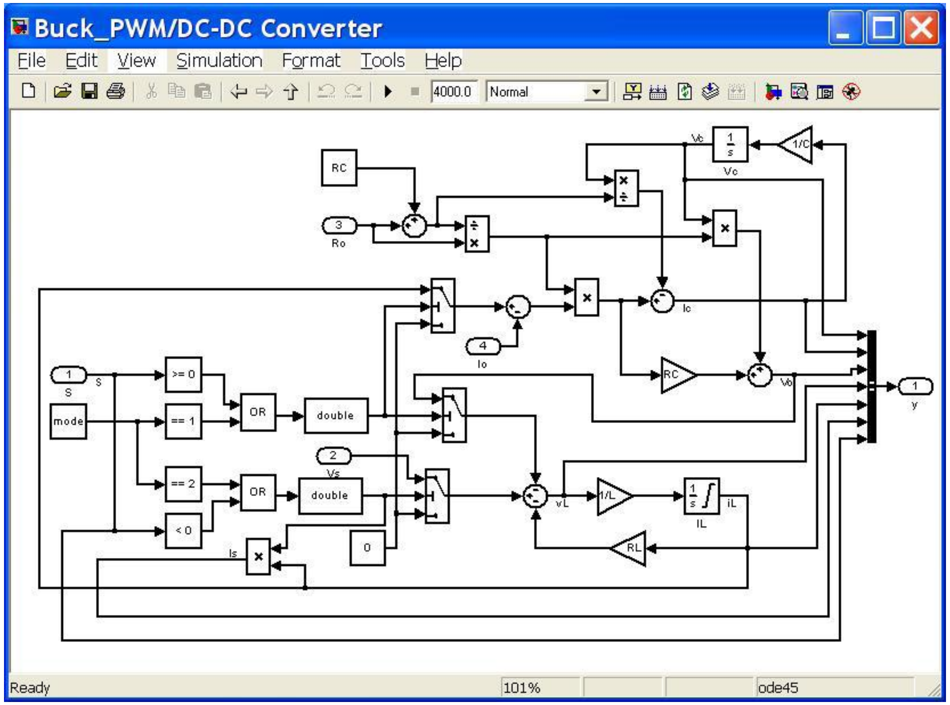
Code-Export of Surrogate Model for System Simulation

- Automatic Code-Export in C, Modelica or Matlab
- Fast surrogate model for total system simulation (e.g. Matlab/Simulink, Circuit-Simulator)
- Development of controller or circuit in case of co-simulation with electromagnetic applications

```
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;
}
```



Conclusion

- Meta-Modeling is a process to win the mathematical relationship between design parameters and product characteristics based on the adaptive response surface methodology.
- The number of required model calculations is less. Therefore, it is applicable for large product models with running time of hours.
- The meta-model can be used for improvement of the design under real conditions related to quality and reliability. It can be also exported to surrogate model in the case of system simulation
- We apply on the waveguide hybrid junction in CST Studio Suite. The robust design process has been demonstrated

Thank you for your attention

Thank CST AG for the cooperation

- Dr. Peter Thoma, Managing Director
- Dr. Ullrich Becker, Support Director
- Frank Mosler, Software Engineer