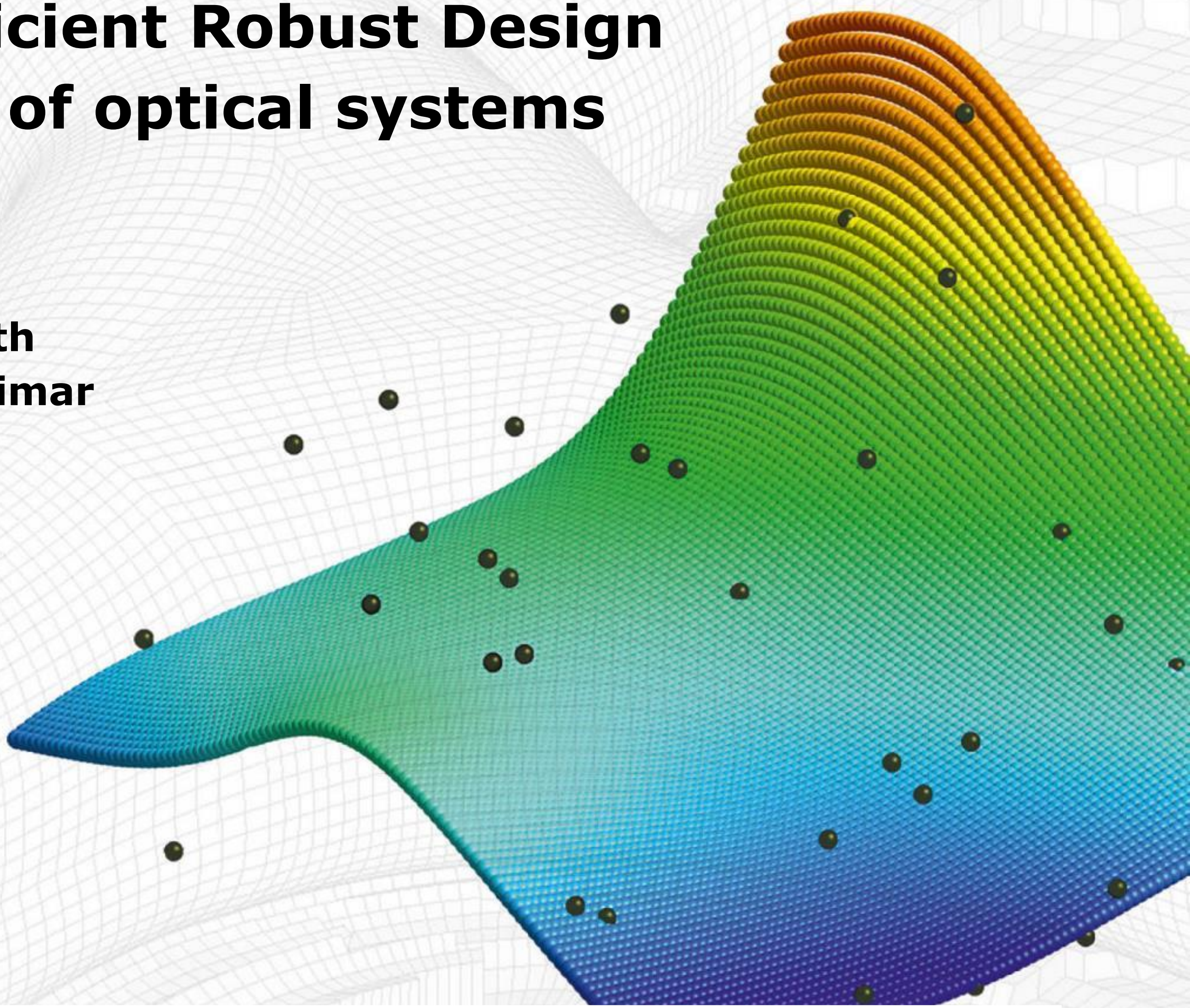
Exploring efficient Robust Design Optimization of optical systems

Dr. Stephanie Kunath
Dynardo GmbH, Weimar



Dynardo

- Founded in 2001
- More than 60 employees, offices at Weimar, Vienna and San Francisco
- Support of leading technology companies like Daimler, Bosch, Siemens, BMW

Software Development

Dynardo is engineering specialist for CAE-based

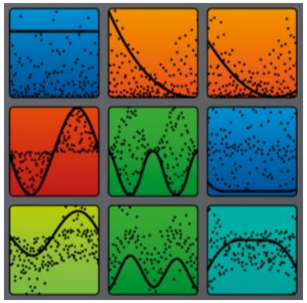
- sensitivity analysis,
- optimization,
- robustness evaluation and
- robust design optimization

CAE-Consulting

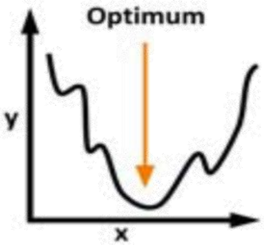
- Mechanical engineering
- Civil engineering & Geomechanics
- Automotive industry
- Consumer goods industry
- Power generation

Motivation

- The **optimization of advanced optical designs** is very challenging due to their
  - complexity,
  - nonlinearity,
  - a huge number of input parameters and
  - interactions between them.

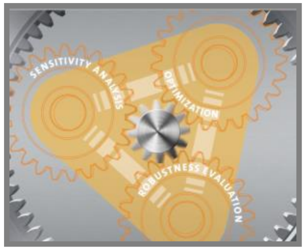


- The demands for the system's **performance** are
  - versatile and
  - very high and even get higher concerning optimization and robustness criteria.



- Furthermore, **totally new developments**, like
  - new materials,
  - manufacturing possibilities and
  - very short product development times,

  simultaneously, require advanced methodologies to develop competitive optical products.

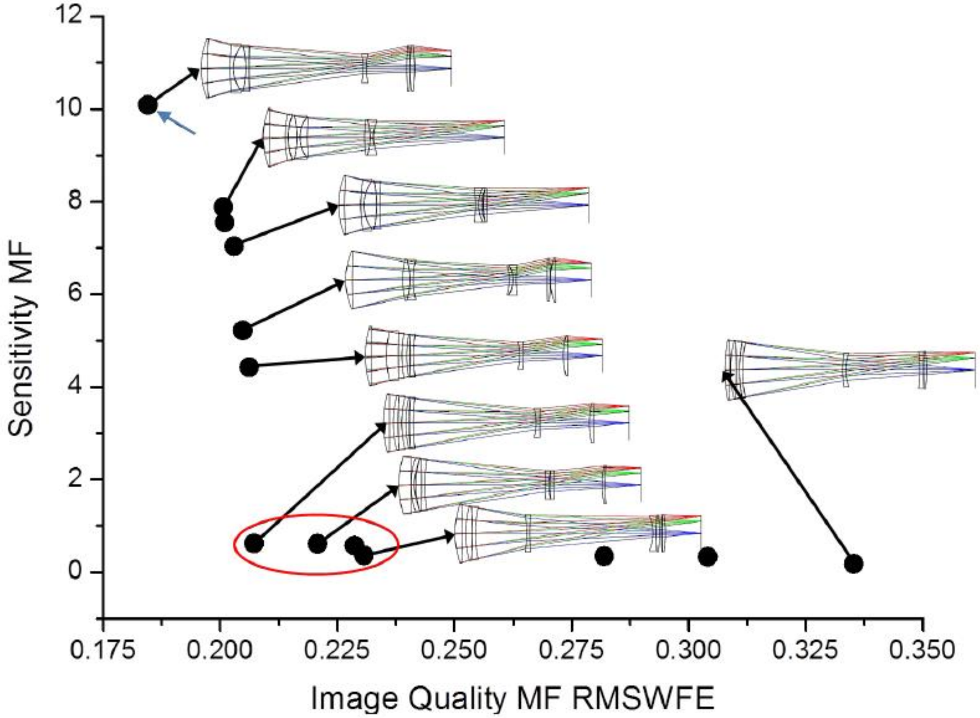


Solution

- Dynardo supports the whole virtual product development process with software solutions including
  - Process integration
  - Building workflows
  - Automation
  - Robust Design Optimization

Robust Design Optimization of optical systems

- Pareto optimization for the Cooke triplet problem
  -> optimization criteria vs. robustness



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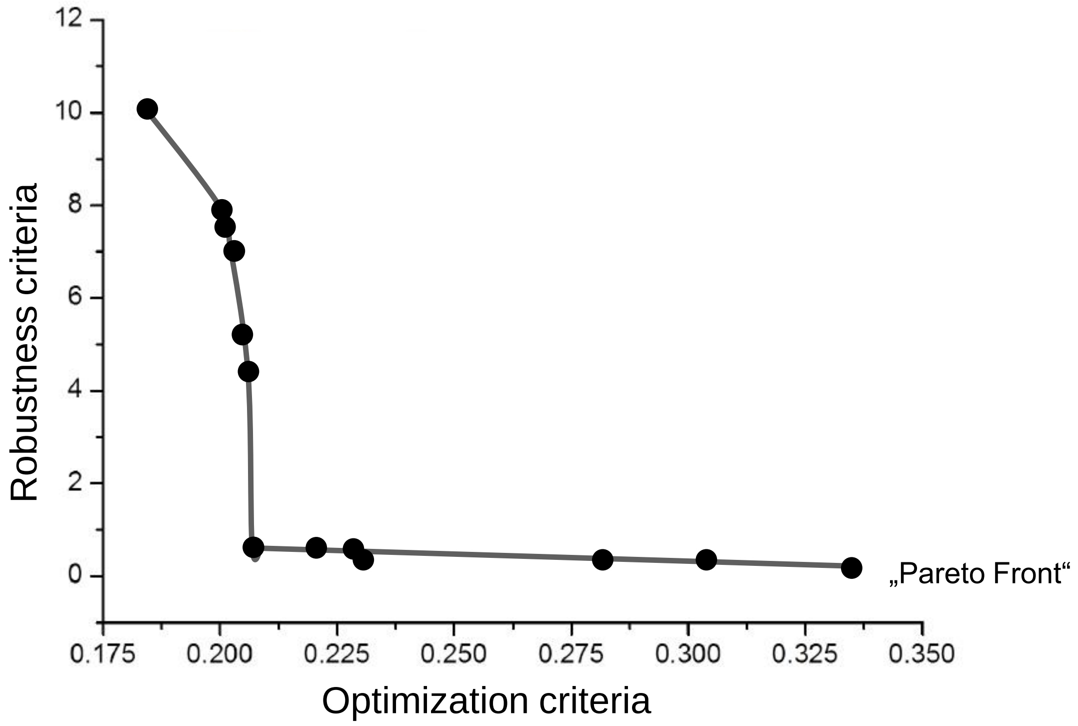

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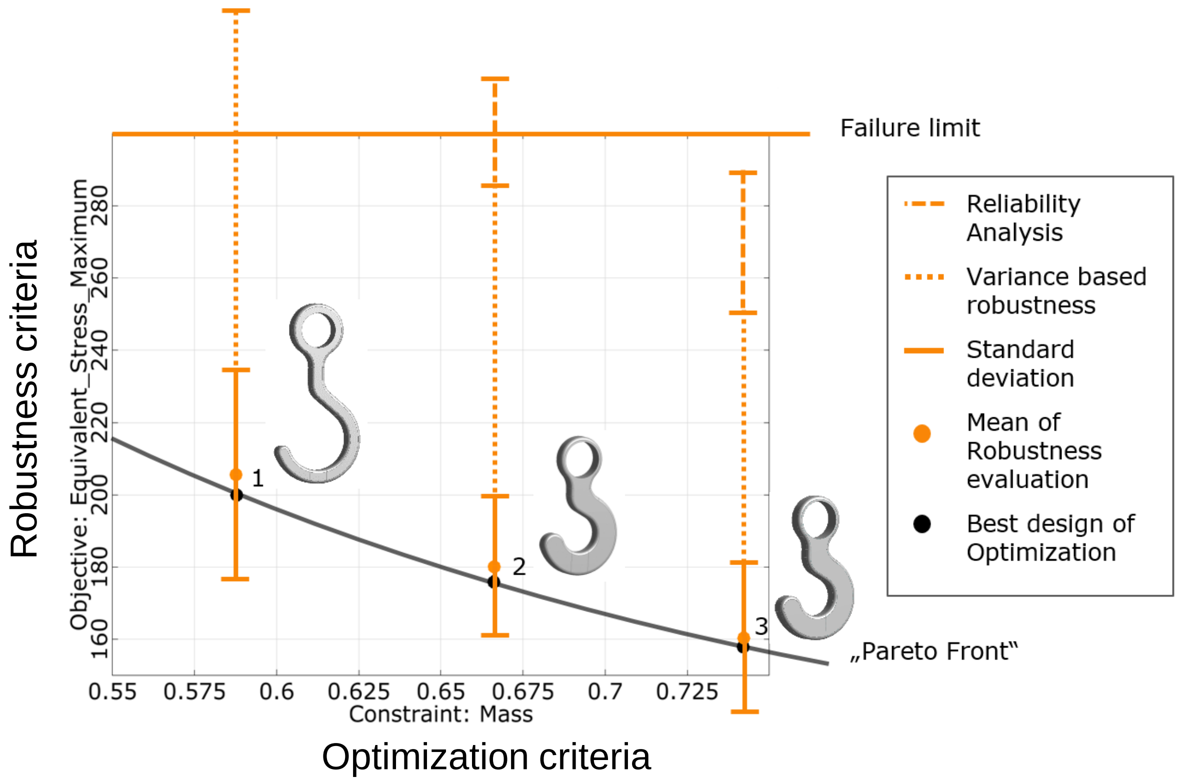
Robust Design Optimization of mechanical systems

- "Pareto optimization" for a mechanical hook
  -> optimization criteria vs. robustness



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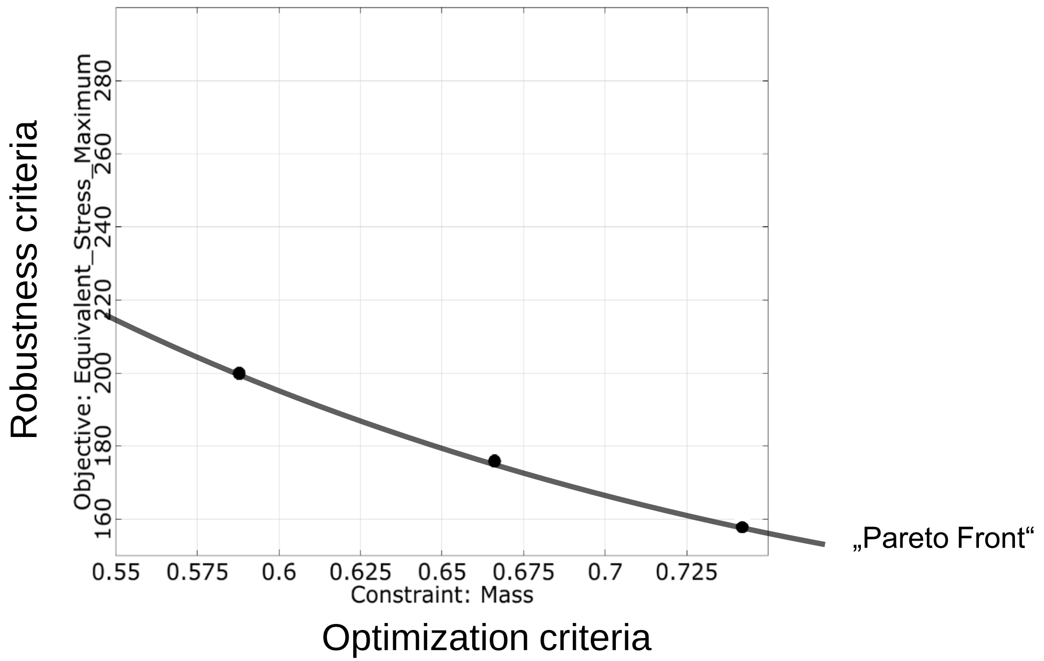

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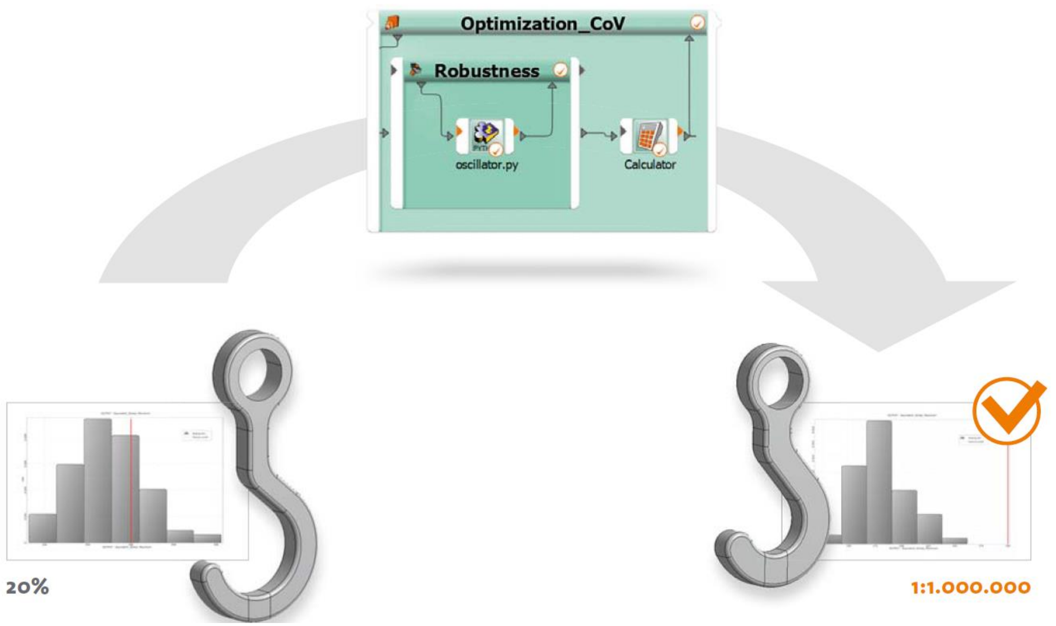
Robust Design Optimization of mechanical systems

- "Pareto optimization" for a mechanical hook
  -> robustness criterium: *failure rate* was minimized from 22% to less than 1: 1.000.000
  -> optimization criterium: *mass* was minimized by 6%



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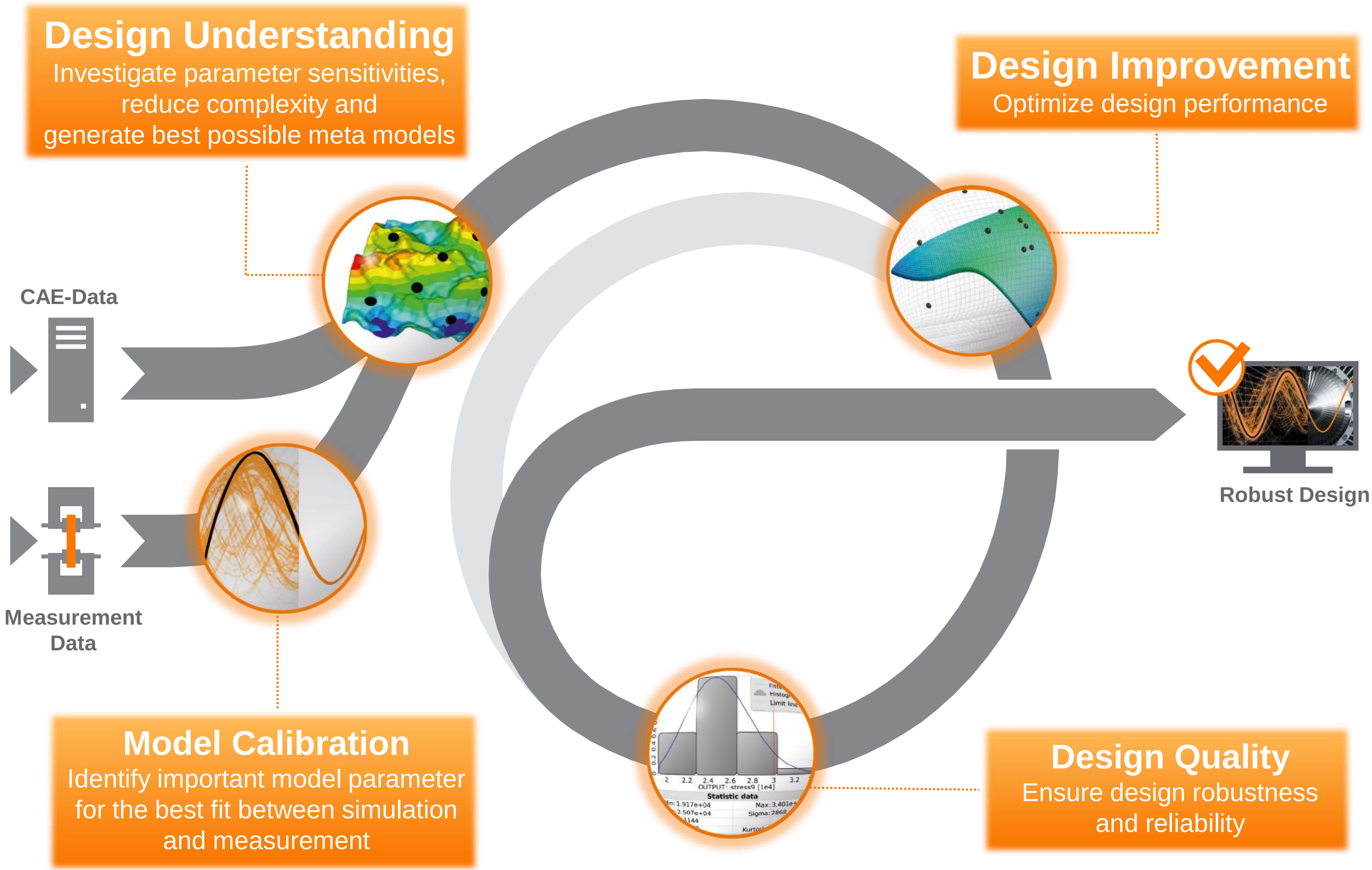
Robust Design Optimization for Product Development


Design Understanding
Investigate parameter sensitivities, reduce complexity and generate best possible meta models
Design Improvement
Optimize design performance
CAE-Data
Measurement Data
Robust Design
Model Calibration
Identify important model parameter for the best fit between simulation and measurement
Design Quality
Ensure design robustness and reliability

Tolerance Analysis vs. Robustness Analysis

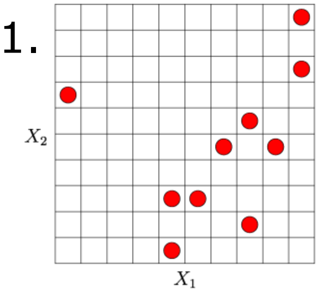
- **Zemax Tolerance Analysis**

1. MC analysis varies all factors at a time without sensitivity evaluation.
2. Local sensitivity analysis - „one factor at a time“
   - Assumption: all parameters are linear and independent

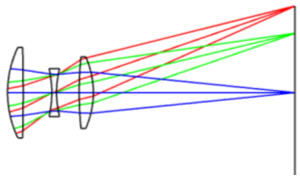
- **optiSLang Robustness Analysis** based on combination of MC analysis and sensitivity analysis

3. Improved MC-Sampling (Latin Hypercube Sampling based on 100 designs)
4. Calculates global sensitivities based on metamodels.

1.



Zemax



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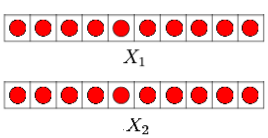

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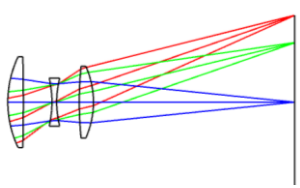

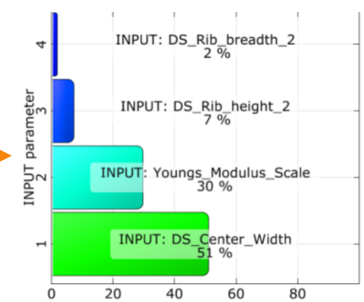

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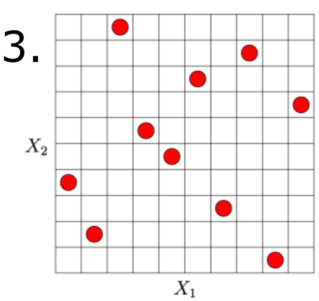

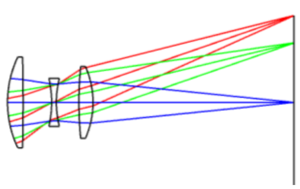

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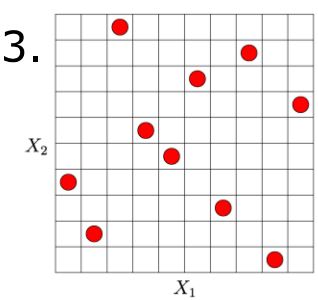

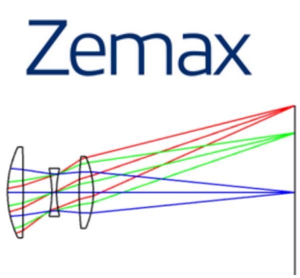

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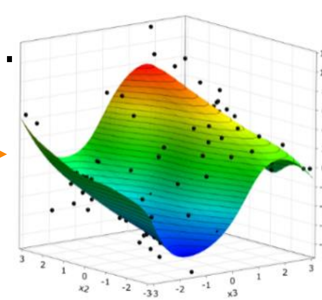
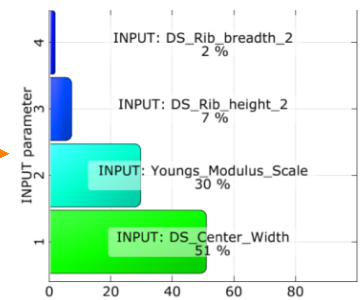
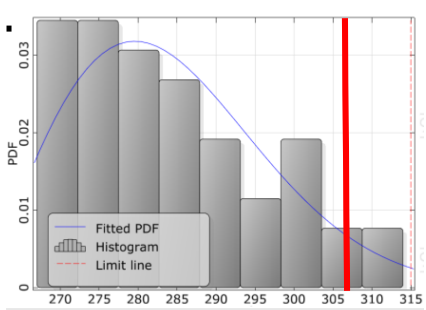




Robustness Analysis – optiSLang approach

- Investment of **100 designs** (only more designs necessary if number of inputs is higher than 50).
- More **realistic modelling** of the scattering behavior as all possible distributions and correlations between input parameters can be modelled
- Results for each output/ merit:
  1. Observed scattering
  2. Quantify the probability of failure by defining limits based on specs
  3. Global sensitivities of inputs
     -> Detection of causes
     -> Identify critical/ non-critical inputs

1.


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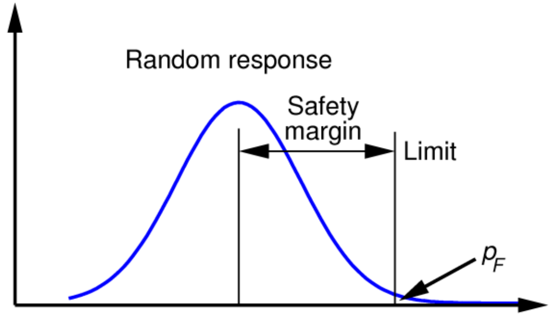

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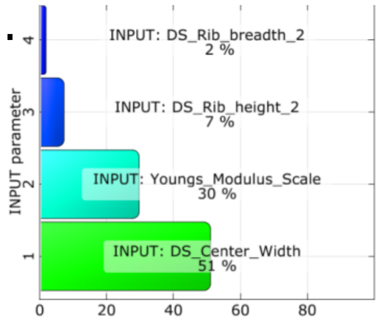
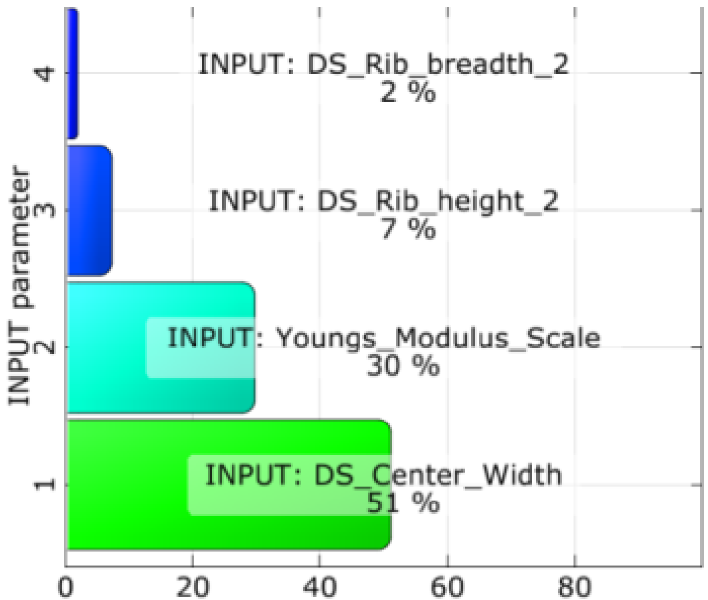


Robustness Analysis with Optimization

- Strategies:
  1. **Iterative RDO approach**: first Optimization, then Robustness analysis
     a. Reduction of critical input scattering
     b. Subsequent Optimization with changed constraints
  2. **Coupled RDO approach**: Optimizer contains optimization and robustness criteria as
     a. Constraint
     b. Second merit function



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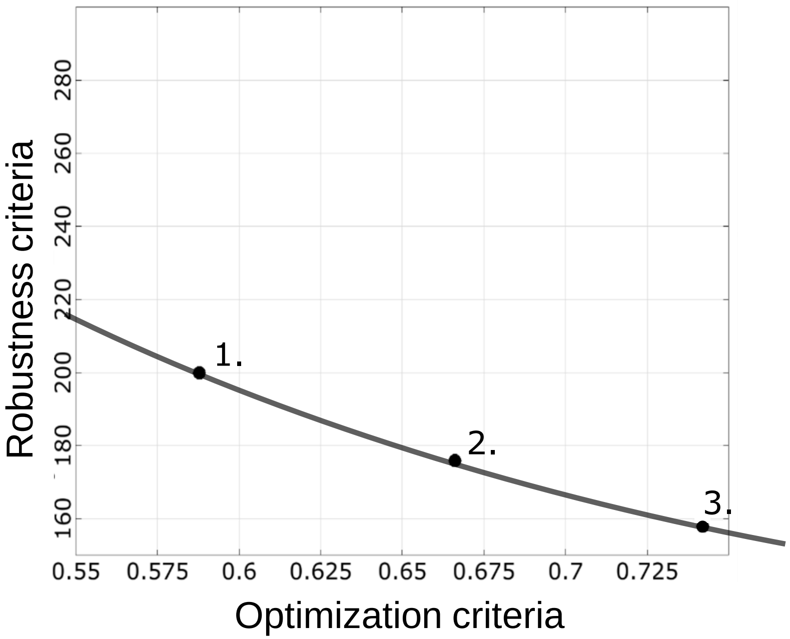

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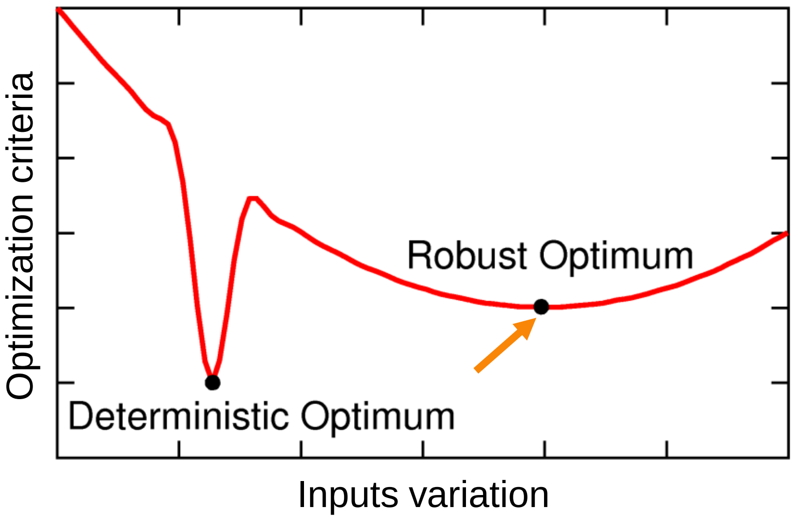

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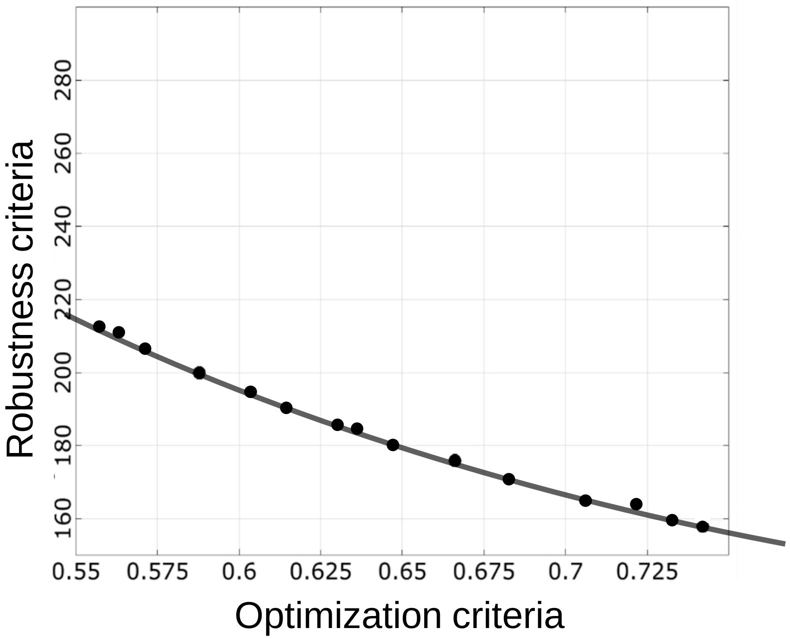


Process Integration and Workflow Generation

Integration of Optical Simulation Tools in optiSLang

SPEOS
LIGHT & HUMAN VISION SIMULATION

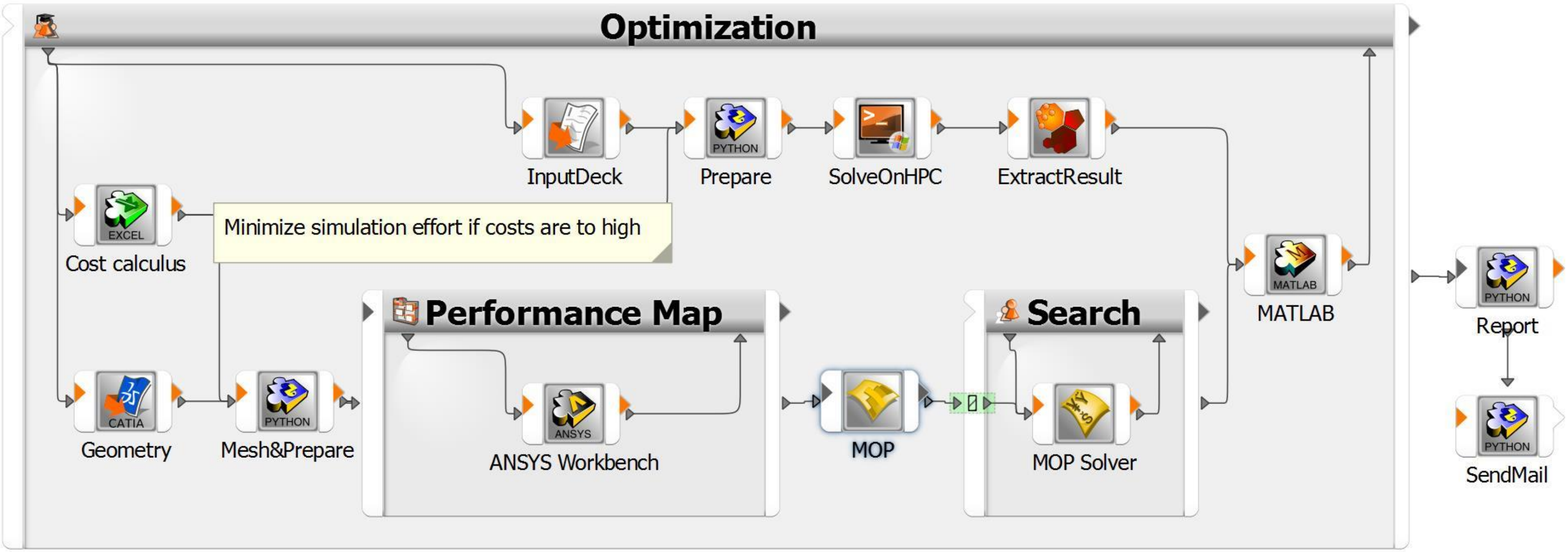
WYROWSKI
VirtualLab FUSION
UNIFIED OPTICAL DESIGN

MATLAB

Zemax

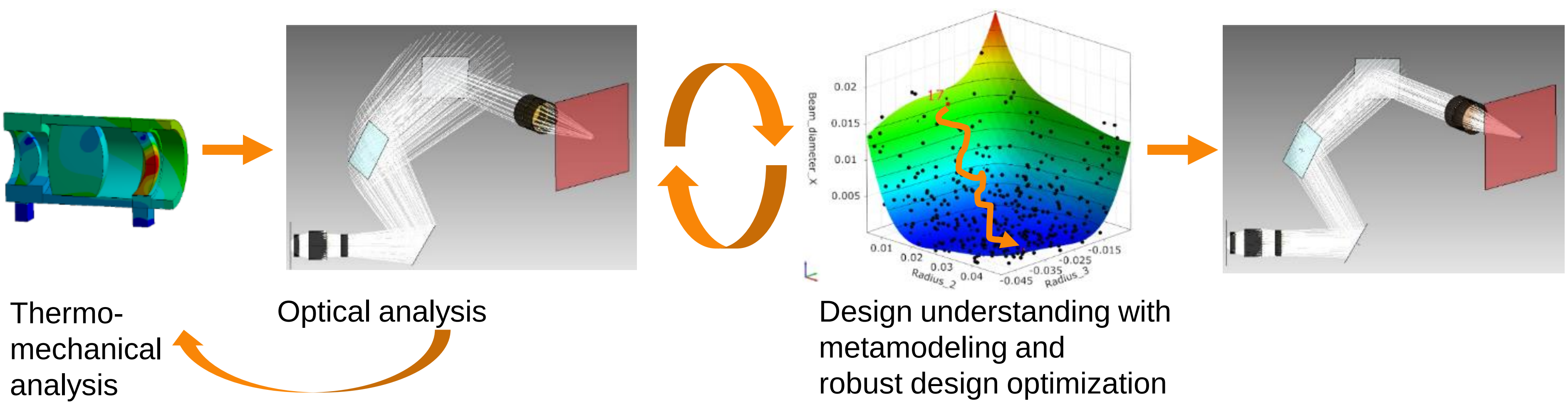
Workflow Generation

- Building of complex workflows based on several simulation tools possible
- ANSYS Workbench, Abaqus etc. can be coupled with different other solvers like Zemax, MATLAB or VirtualLab



Opto-Thermo-Mechanical Simulation

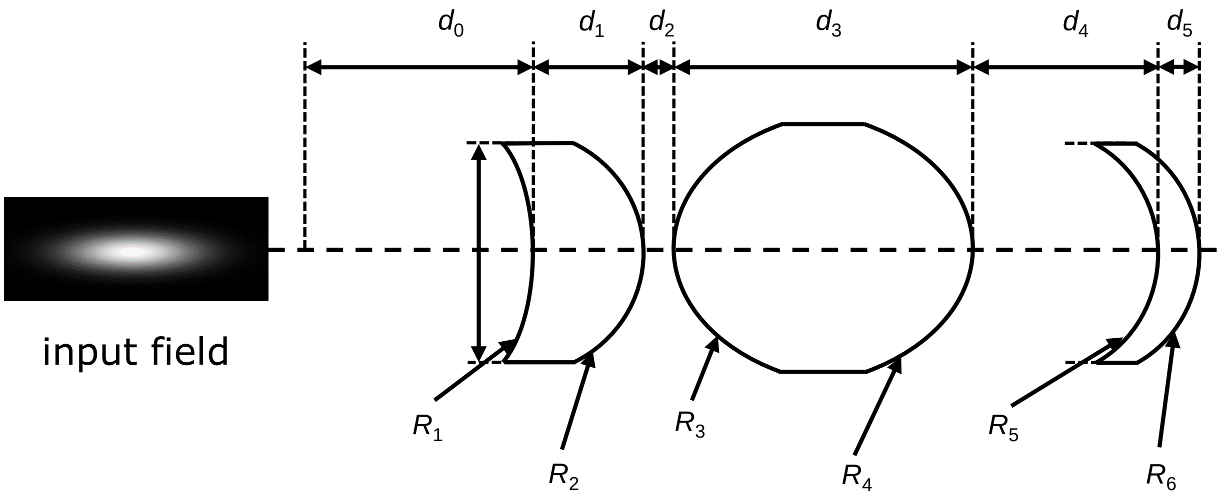
1. Integration optical and mechanical simulation tools in optiSLang
2. Built complex workflows
3. Automation of workflows
4. Robust Design Optimization
    - Sensitivity Analysis
    - Optimization
    - Robustness Analysis



Example:
Objective Lens

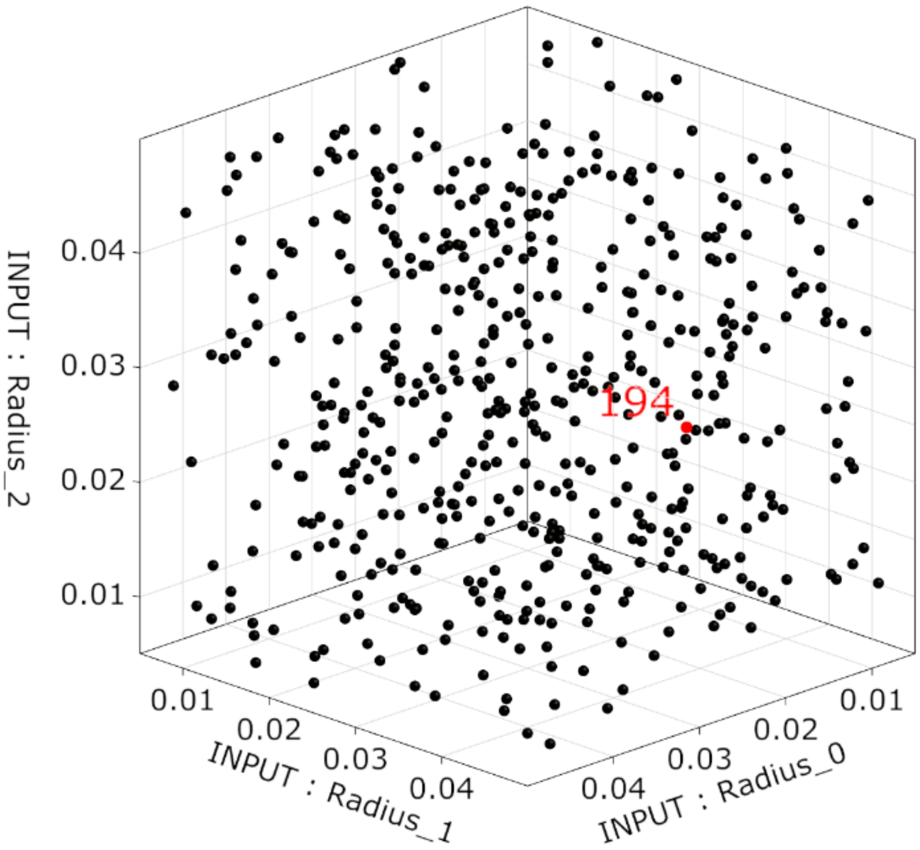
Problem Description

- Collimation of Diode Laser Beam by Objective Lens
- **Optimization objective**:
  - Minimize *divergence angle* in x and y direction
  - Minimize m^2 to be close to 1 in x and y direction
- **Robustness criteria**:
  - Coefficient of Variation (CoV) of *divergence angle* and m^2 in x and y direction should not exceed 20%



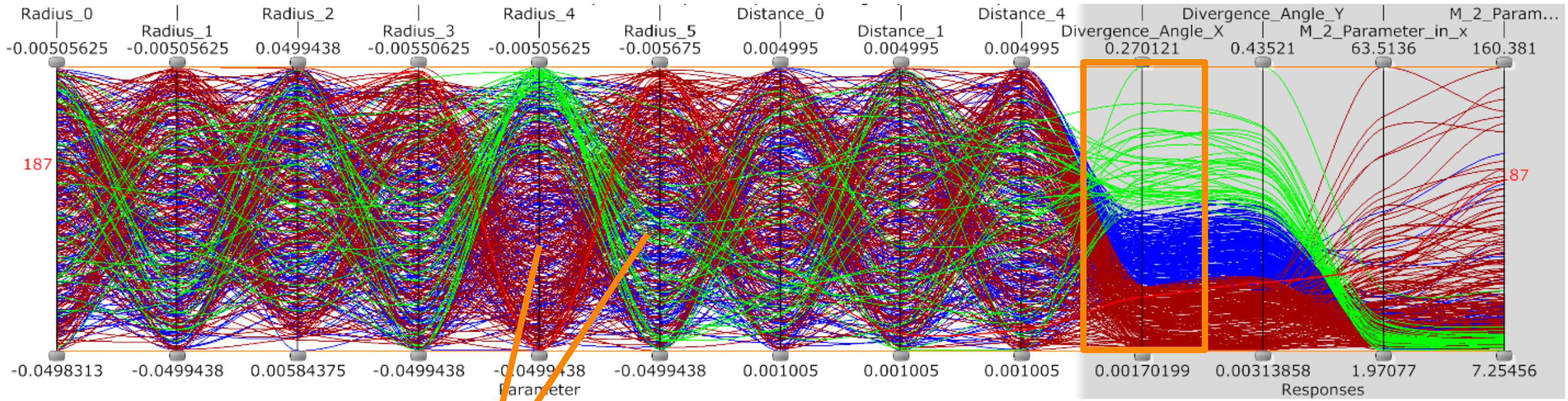
Inputs and Sampling

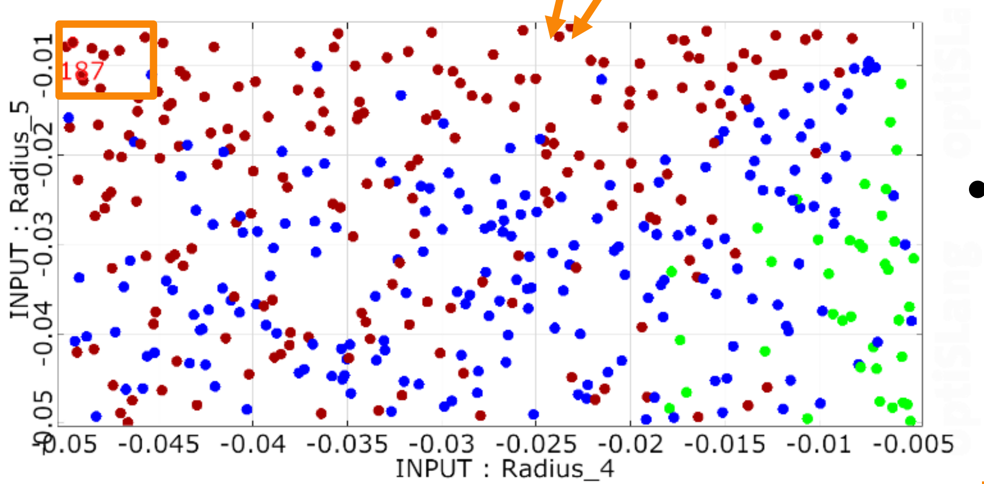
- 500 designs sampled with Advanced Latin Hypercube Sampling
- Inputs: 6 radii, 5 distances



Design Exploration

- Interactive Postprocessing: Cluster Analysis



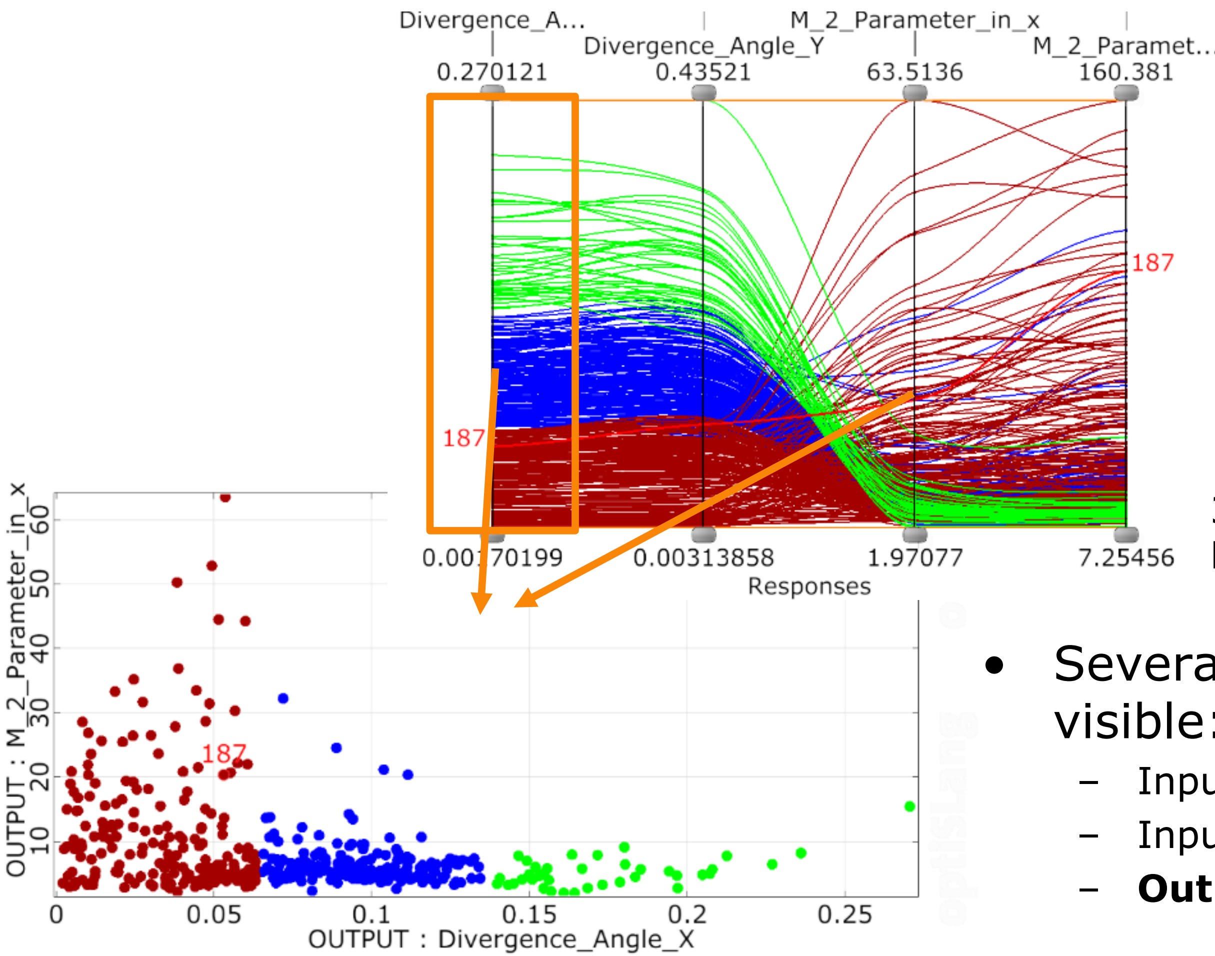


3 clusters for Divergence Angle X

- Several relations can get visible:
  - **Input-input**
  - **Input-output**
  - Output-output

Design Exploration

- Interactive Postprocessing: Cluster Analysis



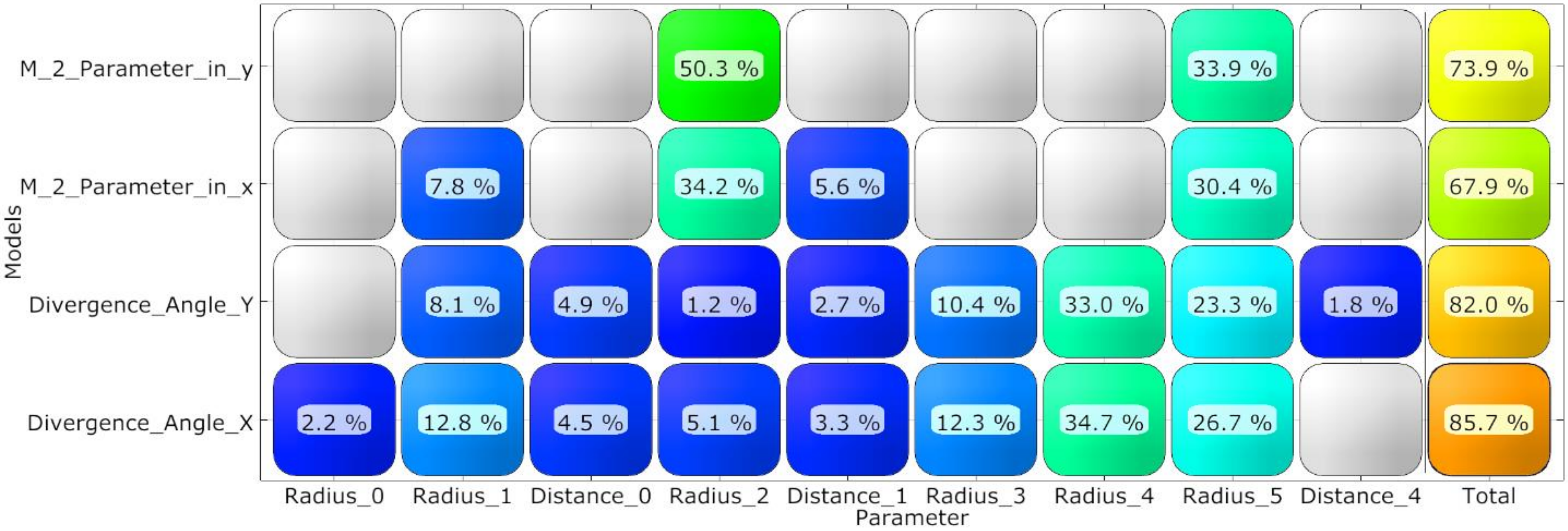
3 clusters for Divergence Angle X

- Several relations can get visible:
  - Input-input
  - Input-output
  - **Output-output**

Metamodelling

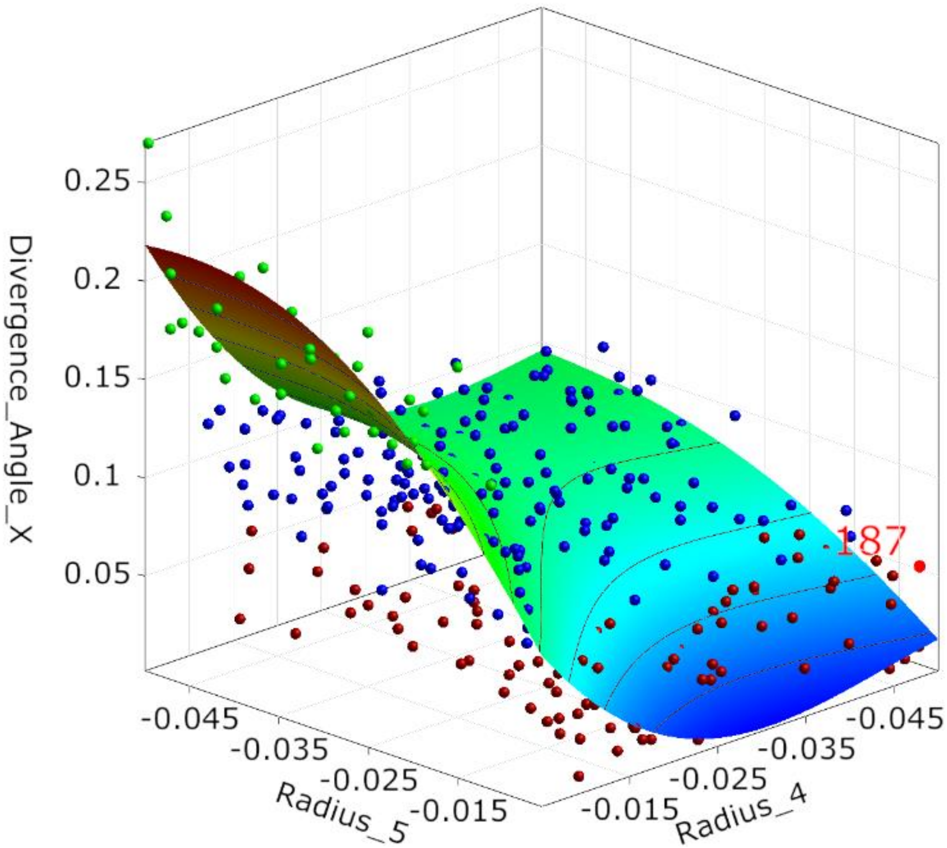
- Beam parameters obtained by field tracing can be described quite well (CoP > 70%), influence of radii is dominant

➢ **Fast pre-optimization on metamodel (MOP) is possible**



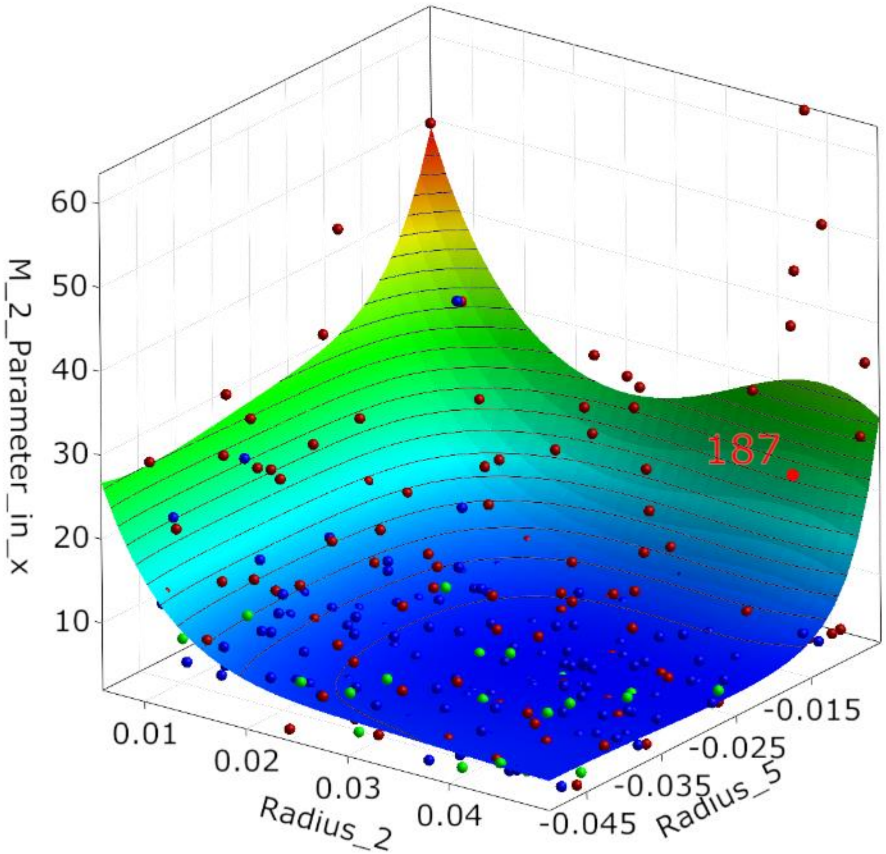
Metamodelling

- **Metamodel of Divergence Angle X**:
  The lower radius 5 the lower the divergence angle!
  An intermediate radius 4 leads to a low divergence angle!



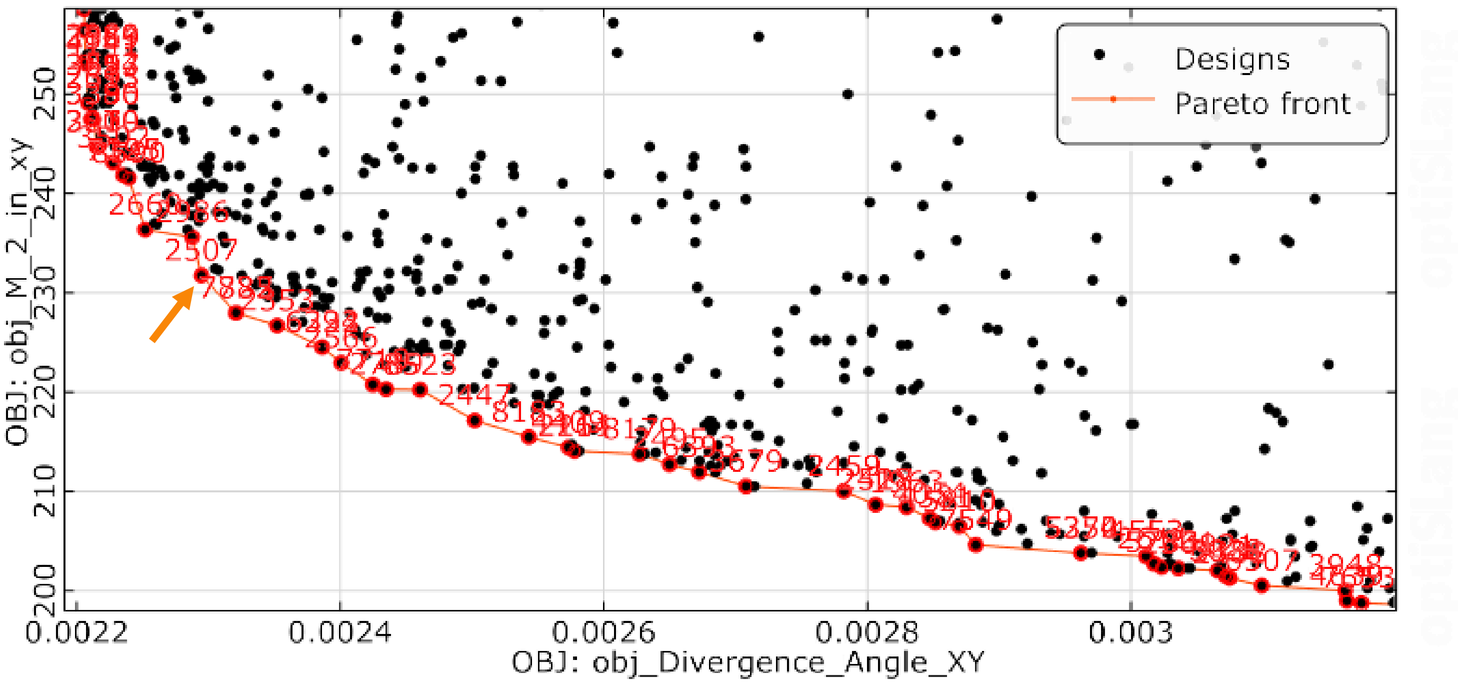
Metamodelling

- **Metamodel of m² in x direction**:
  The higher radius 2 and 5 the lower m² in x direction!



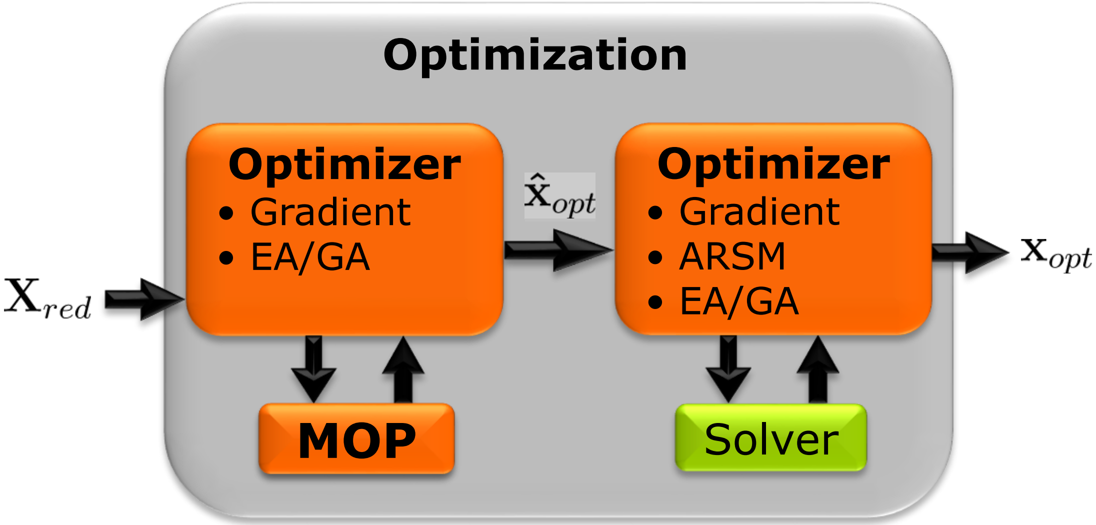
Pareto Optimization

- **Pareto optimization** on metamodel with the following objective functions:
  - Minimize *Divergence_Angle_Y+Divergence_Angle_X*
  - Minimize *(M_2_Parameter_in_x-1)^2+(M_2_Parameter_in_y-1)^2*
- Best design can be chosen from the Pareto front and used as start design for further direct optimization



Direct Optimization

- **Direct optimization** based on best design of Pareto optimization



Optimized inputs	Value & Unit
Radius 0	-0.00679898m
Radius 1	-0.00390681m
Radius 2	0.0210514m
Radius 3	-0.00873955m
Radius 4	-0.00504888m
Radius 5	-0.0070837m
Distance 0	0.00200701m
Distance 1	0.000967461m
Distance 2	0.00600046m
Distance 3	0.00448916m
Distance 4	0.00108139m

Optimized outputs	Value & Unit
wavefront error (RMS)	0.03λ
divergence Angle X x Y	0.02° × 0.01°
M^2 parameter in X x Y direction	1.0180 × 1.1802

Robustness Analysis: Inputs

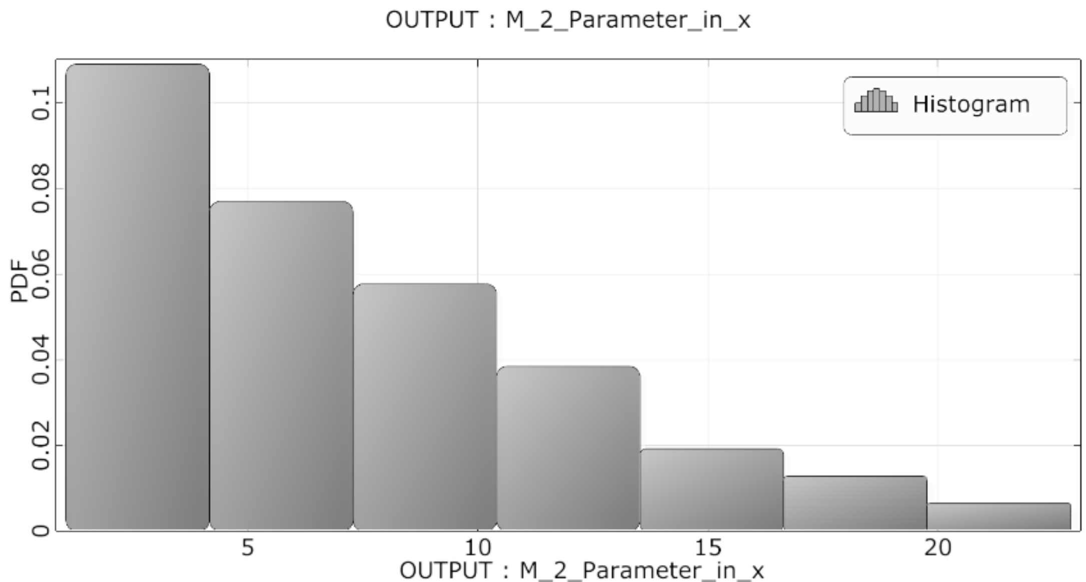
- **Robustness analysis**: Definition of scattering input parameters

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 %

Robustness Analysis: M² in x

- **Optical design is not robust** in terms of m² (CoV =71%!) due to the variation of the lateral shift



Statistical data			
Min:	1.02217	Max:	22.8507
Mean value:	7.24983	Standard deviation:	5.16479
CoV:	0.712401		

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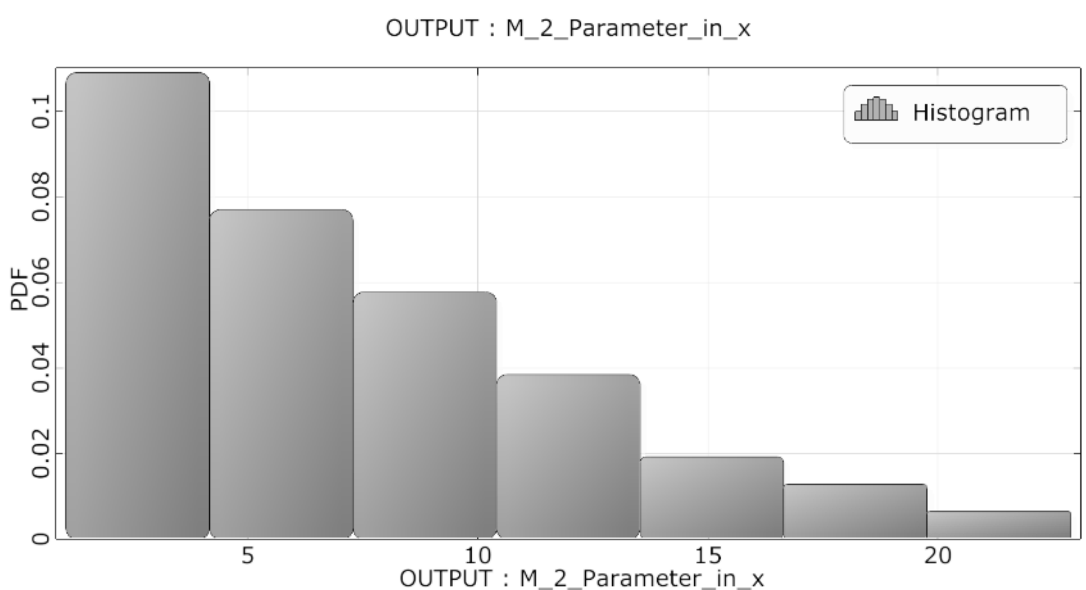

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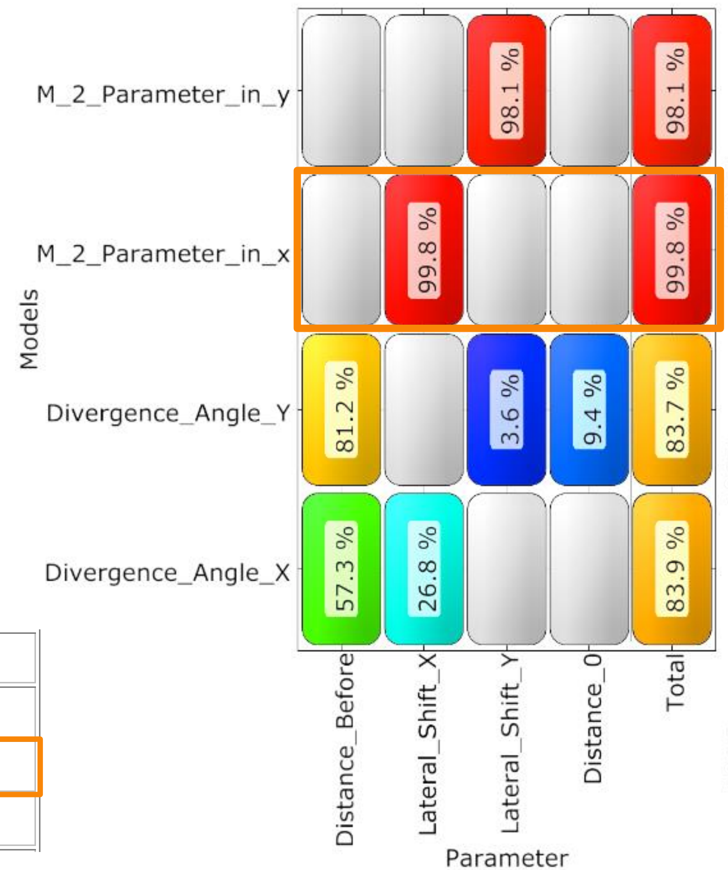
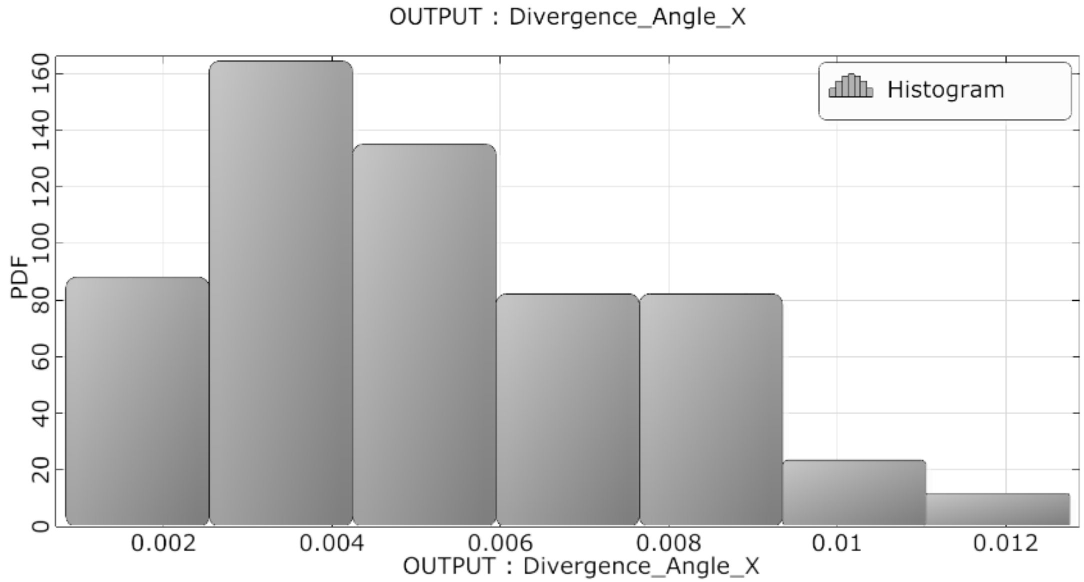
Min:	1.02217	Max:	22.8507
Mean value:	7.24983	Standard deviation:	5.16479
CoV:	0.712401		



Robustness Analysis: Divergence Angle in x

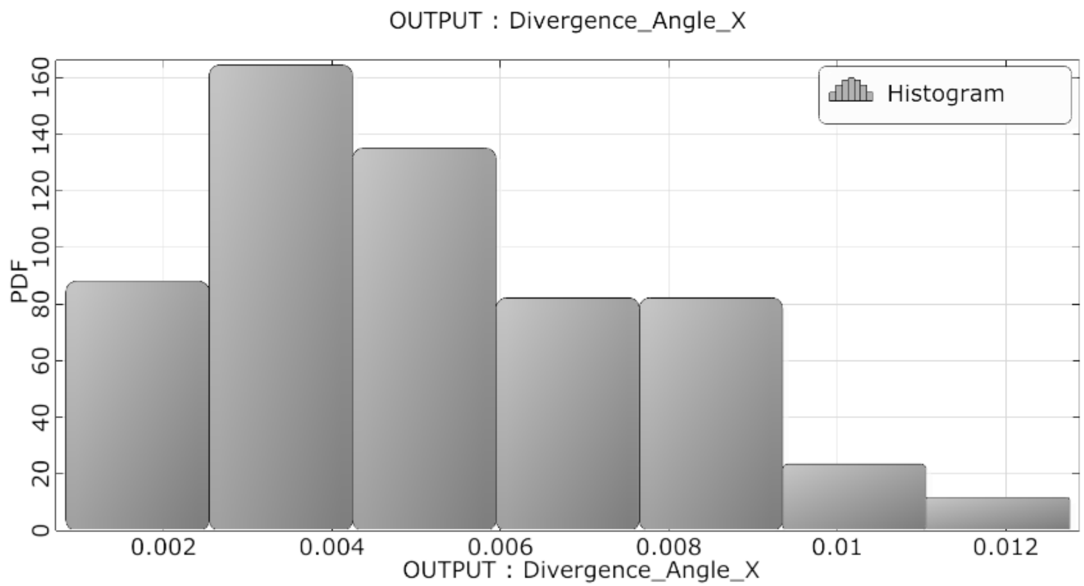
- **Optical design is not robust** in terms of divergence angle (CoV =51%!) due the variation of the lateral shift and distance before lens

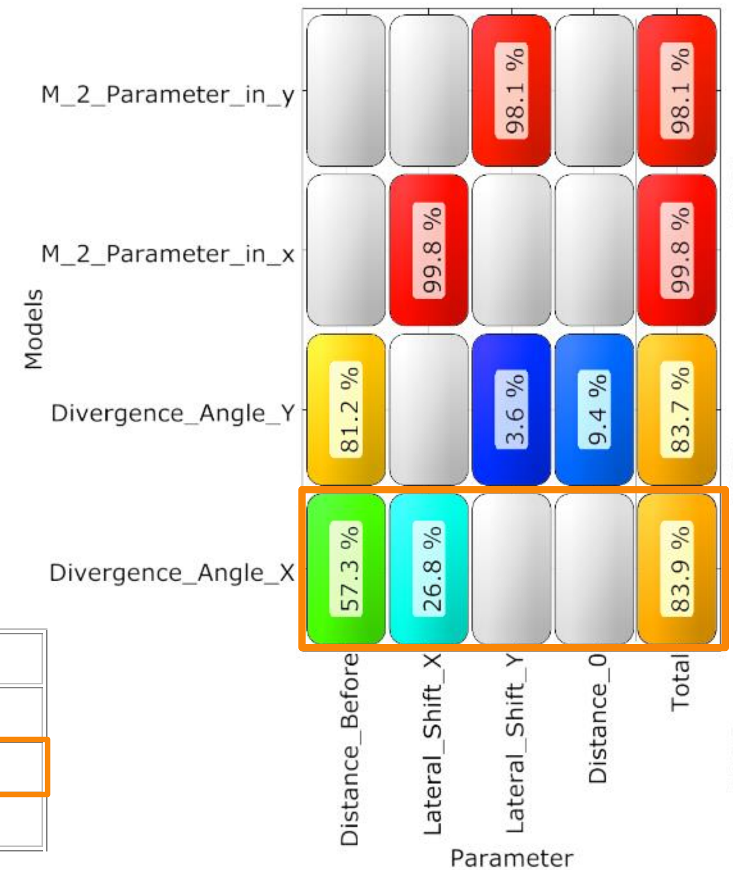


Statistical data			
Min:	0.00082438	Max:	0.0127391
Mean value:	0.00505156	Standard deviation:	0.0025927
CoV:	0.513247		

Robustness Analysis: Divergence Angle in x

- **Optical design is not robust** in terms of divergence angle (CoV =51%!) due the variation of the lateral shift and distance before lens

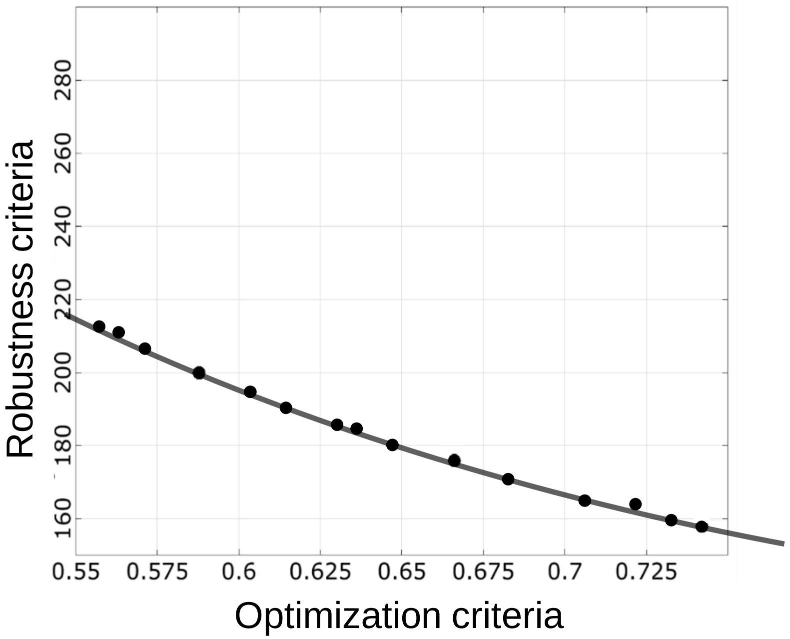




Statistical data			
Min:	0.00082438	Max:	0.0127391
Mean value:	0.00505156	Standard deviation:	0.0025927
CoV:	0.513247		

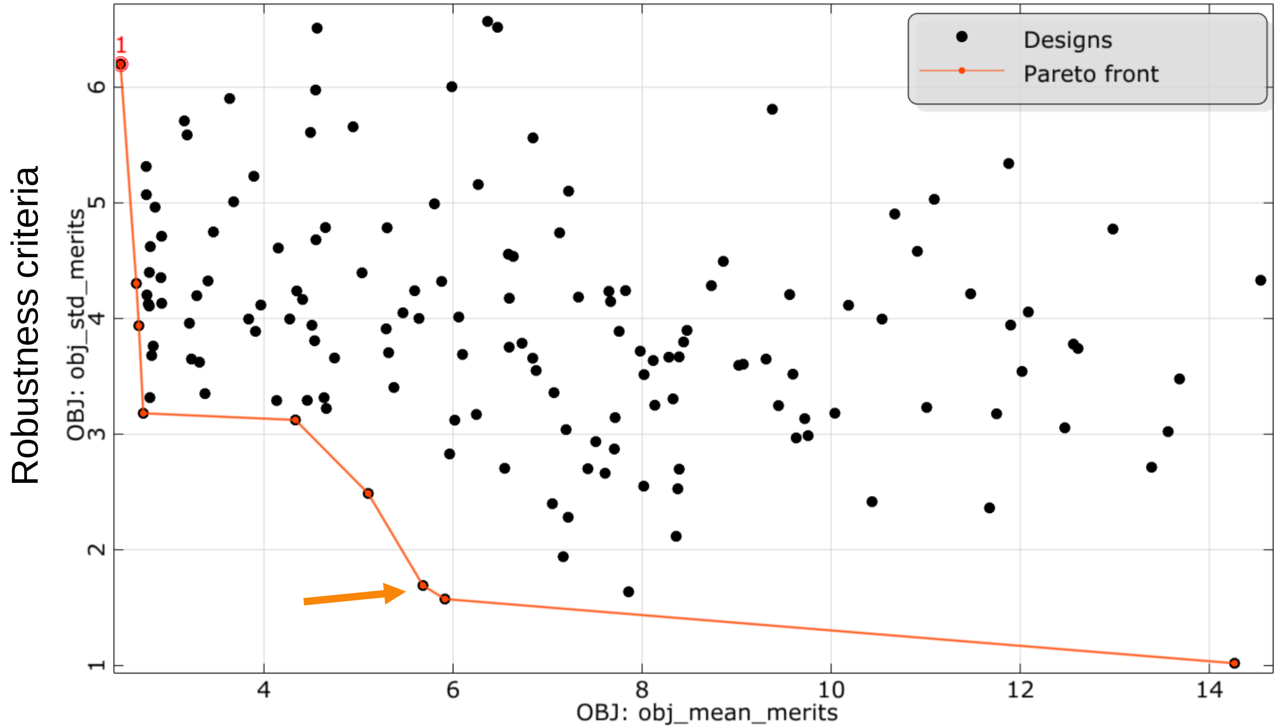
Robustness Analysis

- If design is not robust…
  1. **Iterative RDO approach**: first Optimization, then Robustness analysis
     a. Reduction of critical input scattering
     b. Second Optimization with changed constraints
  2. **Coupled RDO approach**: Optimizer contains optimization and robustness criteria as
     a. Constraint
     b. Second merit function



Coupled Robust Design Optimization

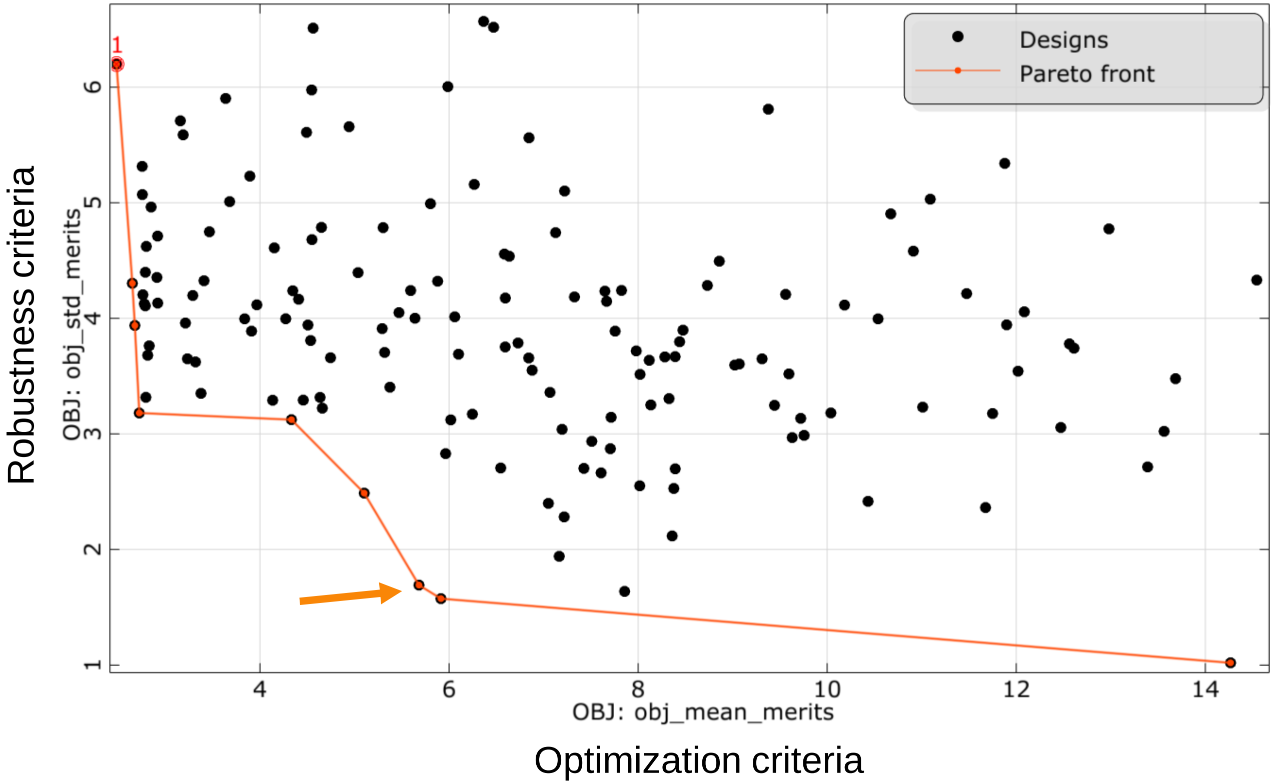
- **Optimization criteria**: weighted merits in one objective function
- **Robustness criteria:** weighted standard deviation of merits in second objective function



Optimization criteria

Coupled Robust Design Optimization

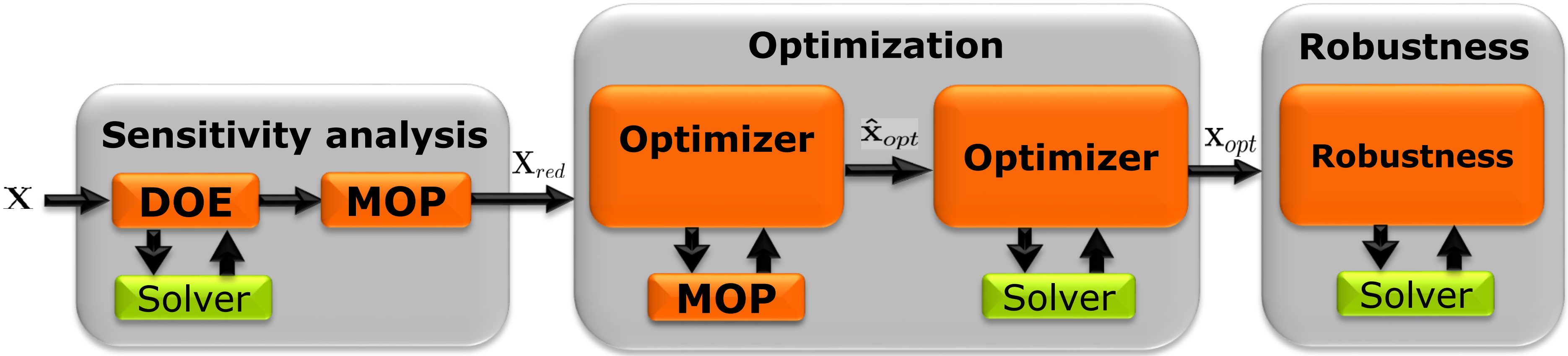
- **Further steps:**
  - Check value of inputs
  - Check performance of each output parameter



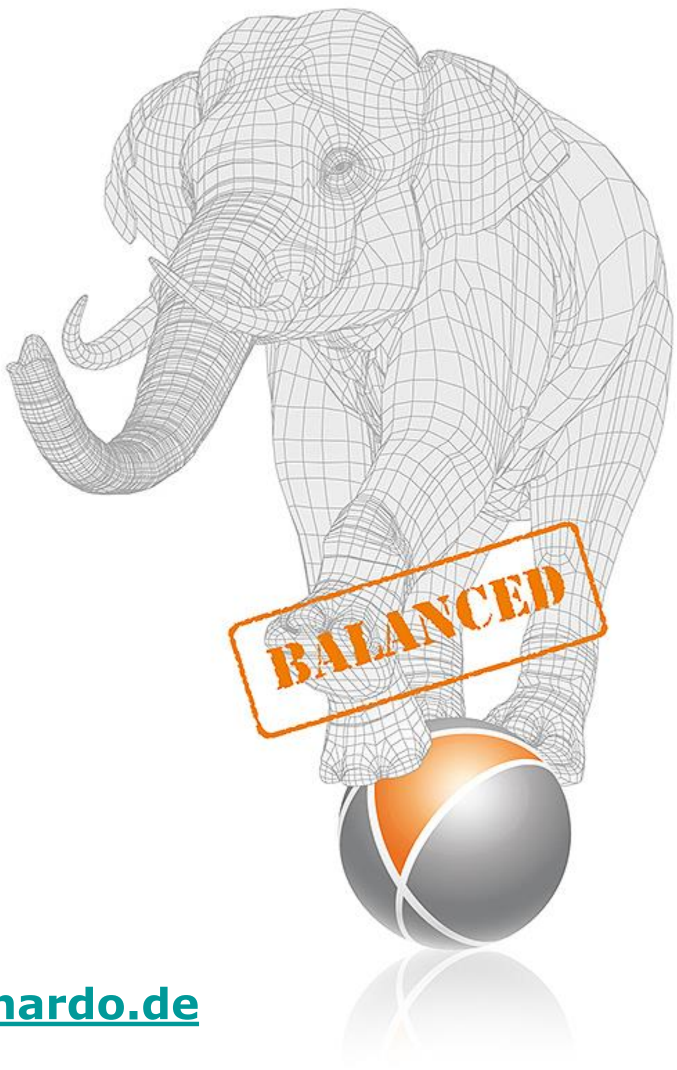
Summary: Robust Design Optimization

- **Workflow:**

1. Sensitivity analysis
   - Correlation and cluster analysis
   - MOP generation
2. Optimization on MOP using best design from sensitivity analysis
3. Optimization with direct solver calls using start design from previous optimization on MOP
4. Robustness analysis
5. Coupled or iterative Robust Design Optimization



Thank you for your attention!



Further information: www.dynardo.de

Contact information: stephanie.kunath@dynardo.de