# Computer-aided Calibration of IGBT SPICE Model with optiSLang™

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A. Biswas, M. Cotorogea, P. Türkes, F.J. Niedernostheide
Infineon Technologies AG

Special thanks: Rene Kallmeyer (Dynardo)

# Agenda

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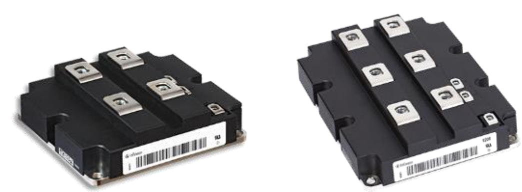
# Introduction

- IGBTs and power diodes are bipolar devices
  - Wide ranging applications from electric cars, solar/wind energy, traction, transmission line…

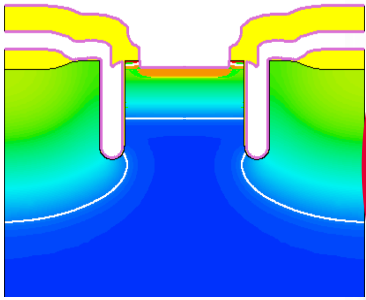
- Why virtual prototyping in IGBT-module development?
  - Reduce development costs and time by reducing learning cycles

- Target: accurately predict switching behavior through circuit simulations

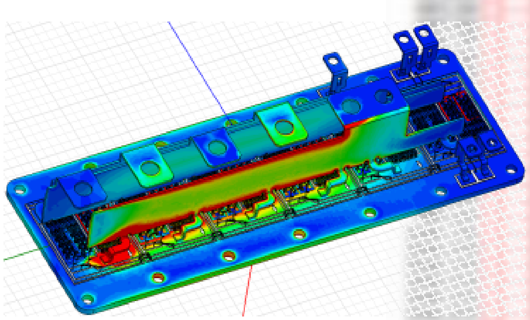
- Model requirements:
  - physics based models for IGBTs and diodes
  - knowledge of parasitic elements and couplings
  - Fast model implementation and simulation



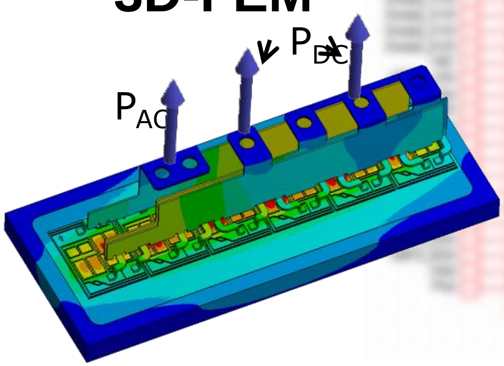
# Circuit simulation



2D-TCAD



3D-FEM




Manual model generation and calibration

Automated model generation

Minimum loss of precision!

Physics-based device compact model

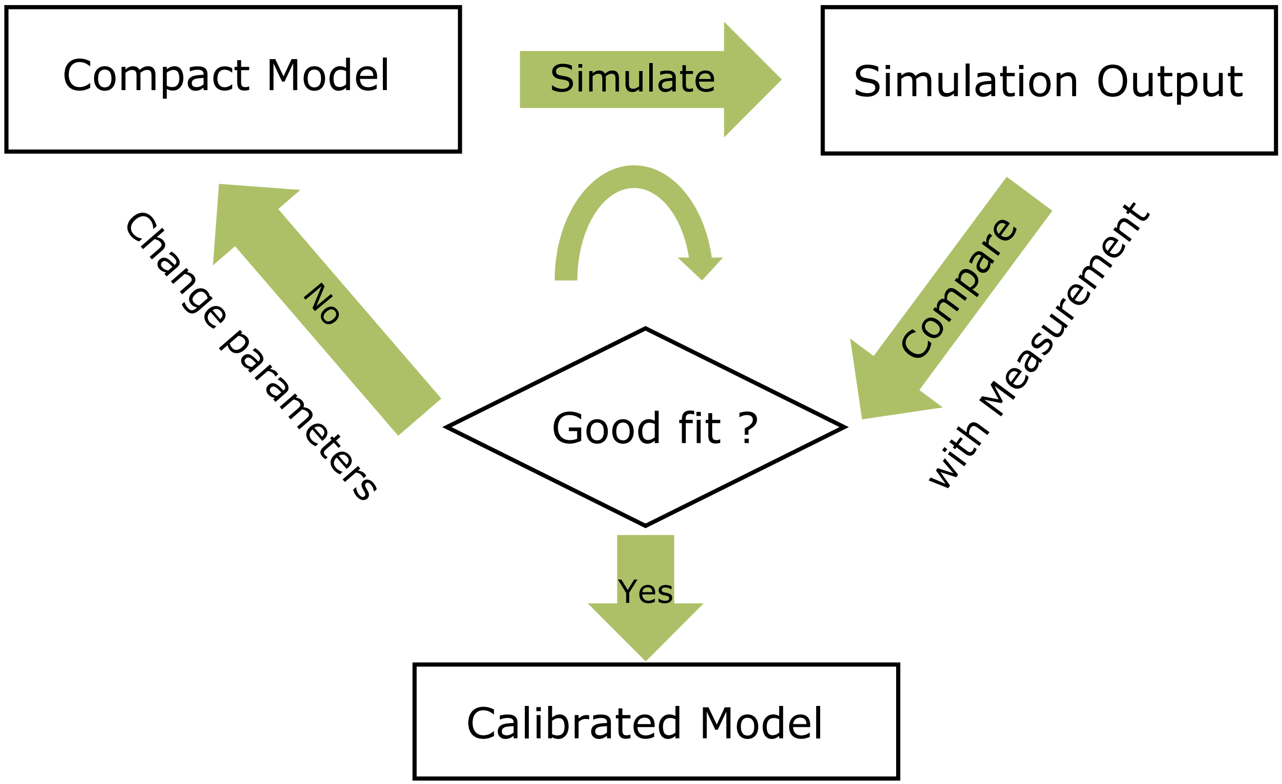
Electrical parasitics compact model

Thermal network as compact model

**Circuit simulation**

# Motivation

- Currently compact model calibration is a manual and time consuming process

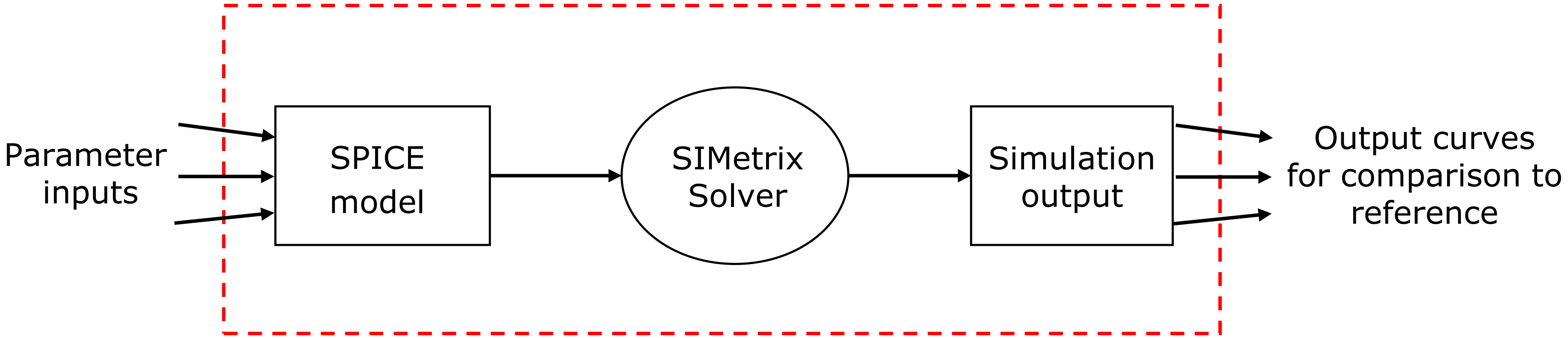



- To define a standardized calibration flow to be used for all diodes and IGBTs in the future

# Agenda

# SIMetrix Integration

- SIMetrix[1] : Mixed mode circuit simulator supporting SPICE/Verilog-A/VHDL

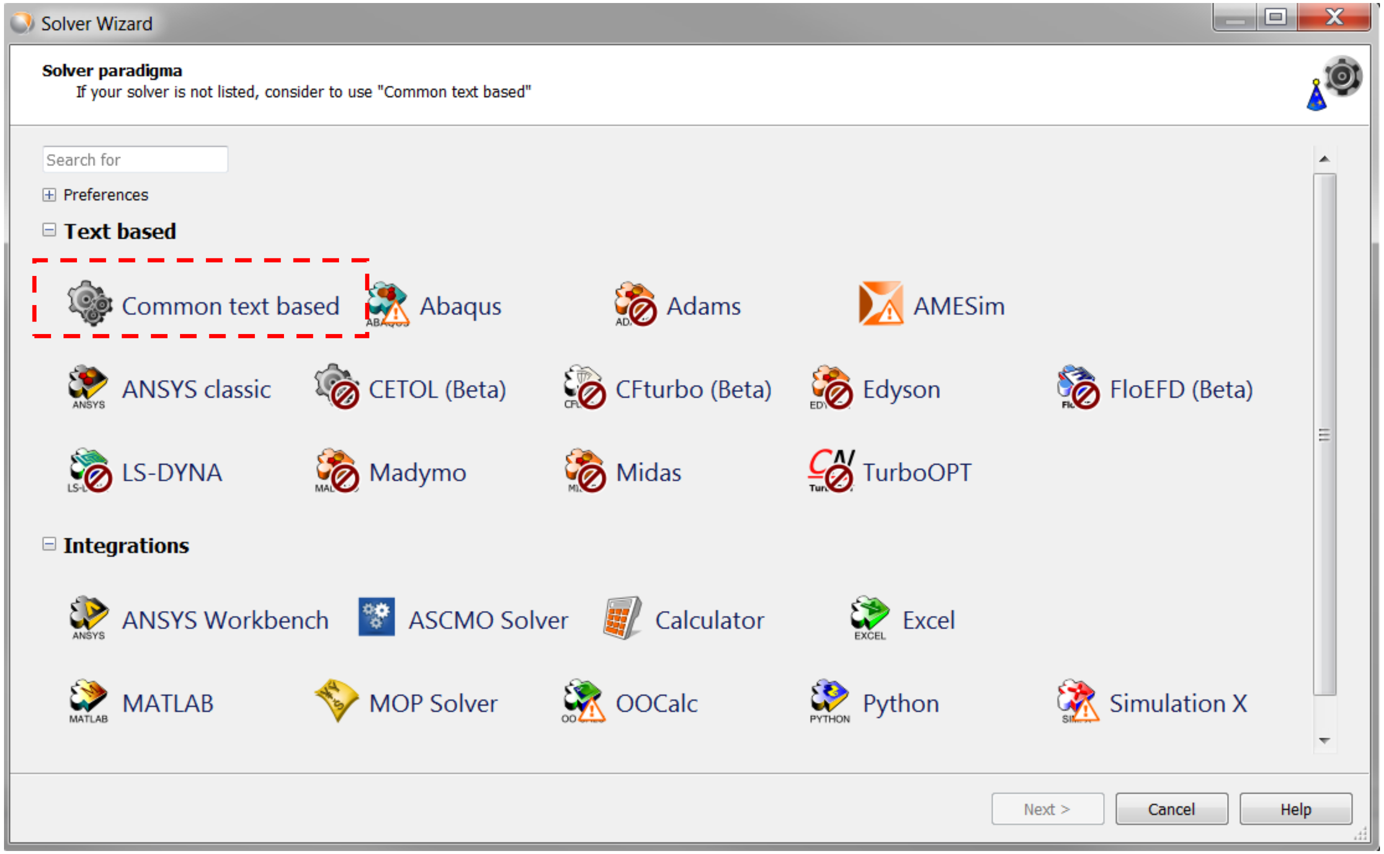



User inputs needed to set up the calibration flow:

- Definition of parameter variation range
- Objective and criterion definition for optiSLang
  - Which areas of the curve are more important than rest?
    - Weightage factors
  - For multiple curves : normalization if needed

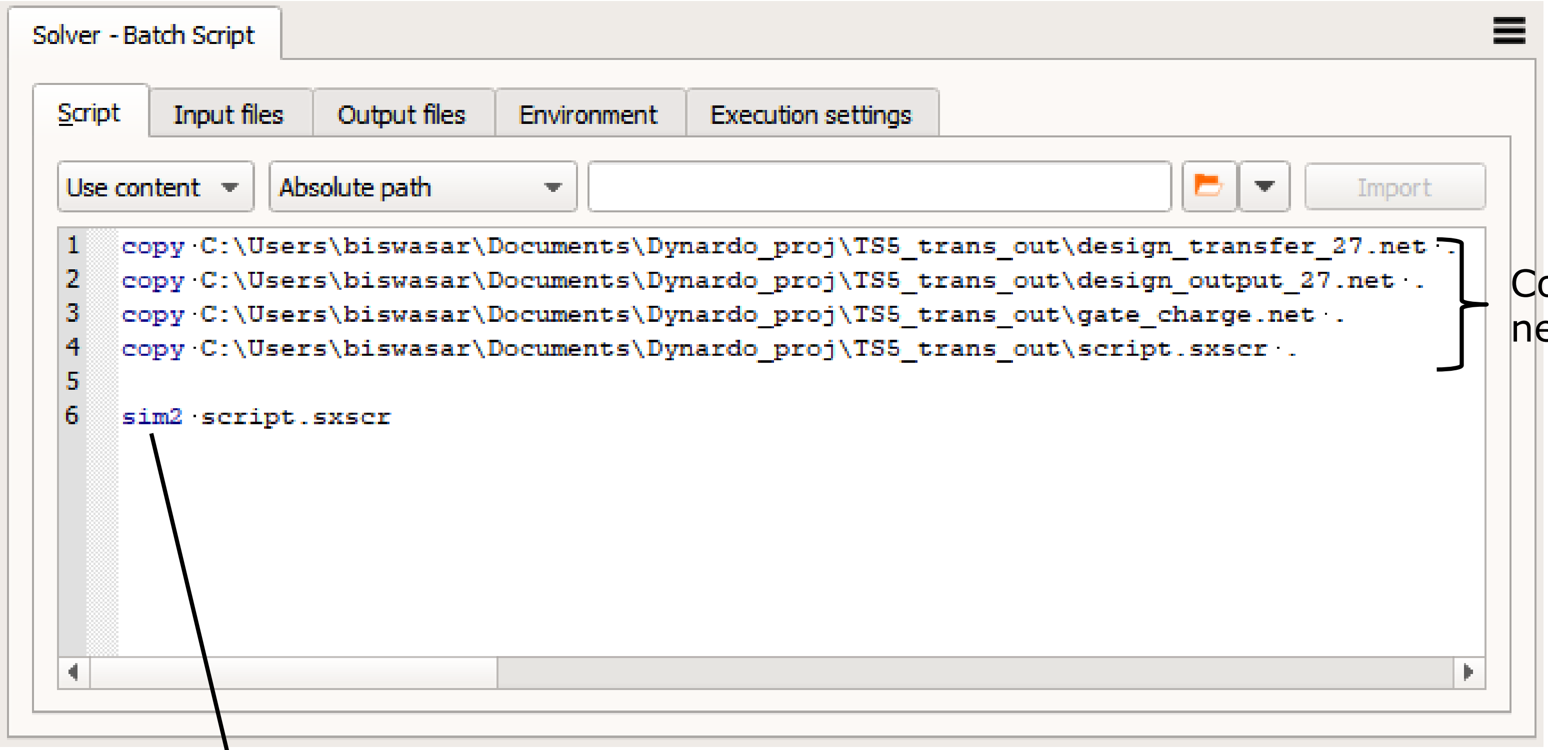
[1] www.simetrix.co.uk

# Choice of solver




- Support for many tool (solver) integration. Example: Matlab, Python, Ansys etc.
- Any solver with some scripting support can be used with "Common text based"
  - We use the SIMetrix scripting interface

# Solver definition

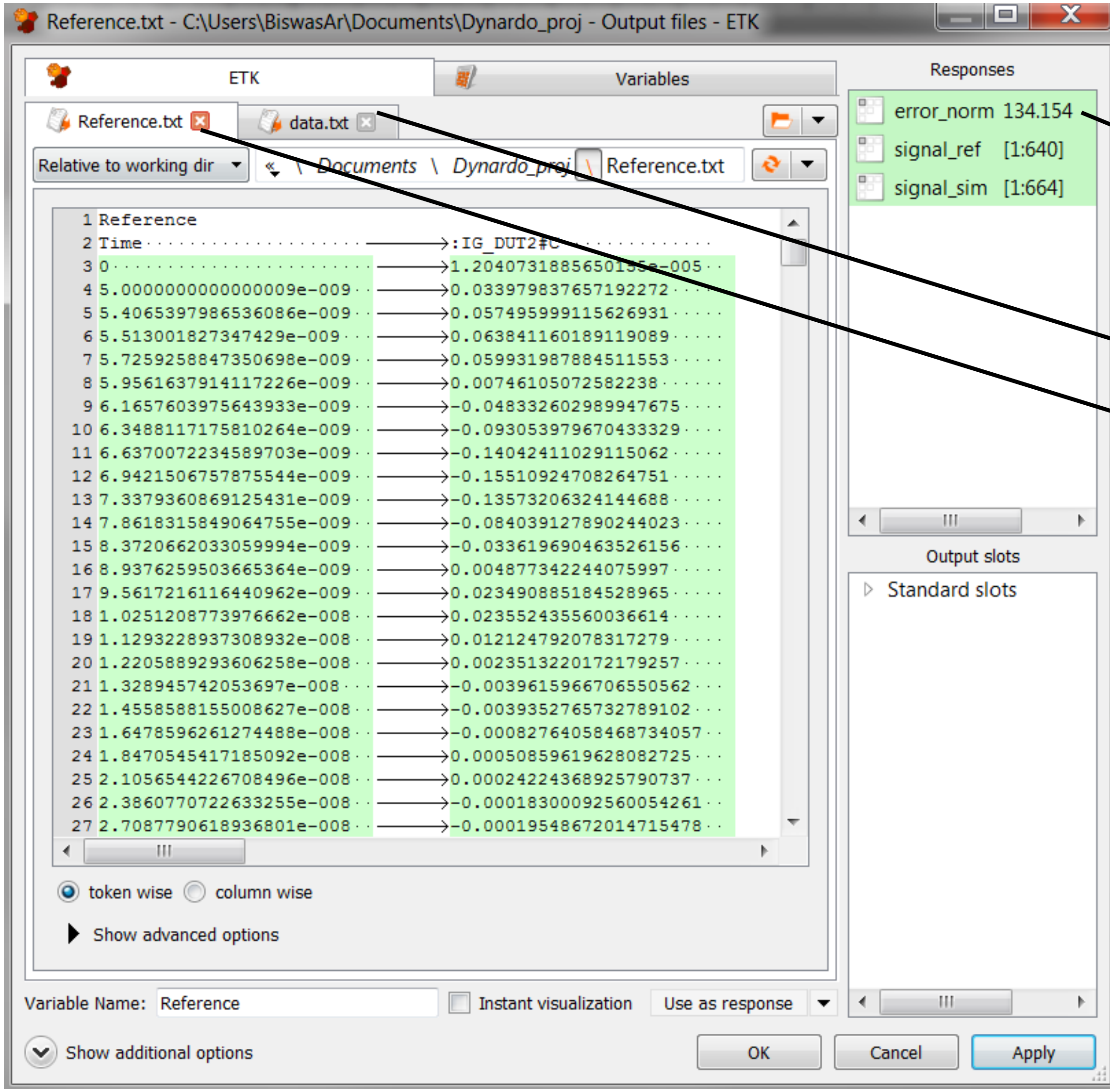



Copy of required netlist and scripts

Command line call for SIMetrix:

- Runs the required simulations
- Saves the results in a format recognized by optiSLang

# Definition of reference and simulation outputs



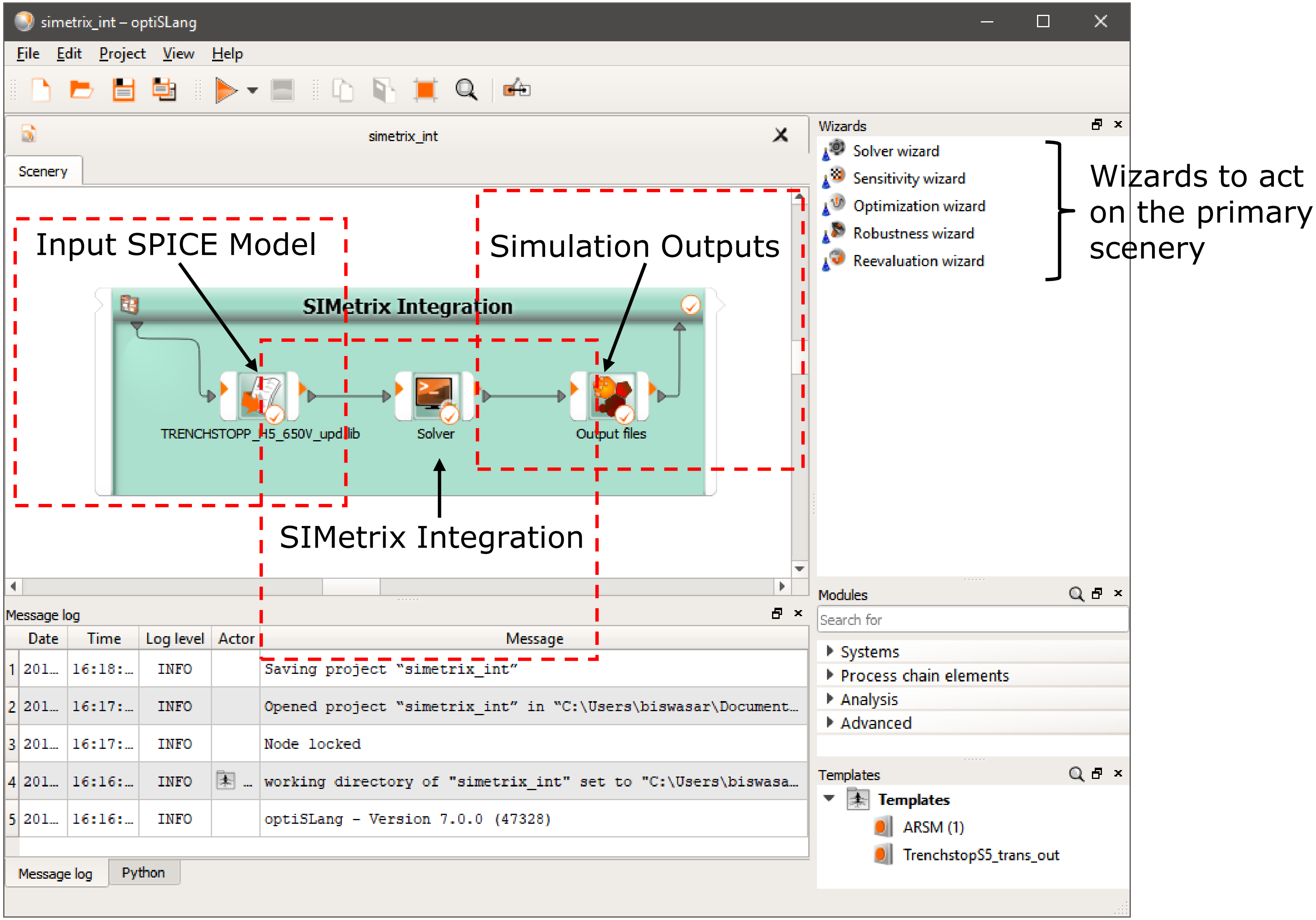

User defined response (error_norm)
$= \Sigma$ (signal_ref – signal_sim)$^2$

Solver output (signal_sim)

Reference data (signal_ref)

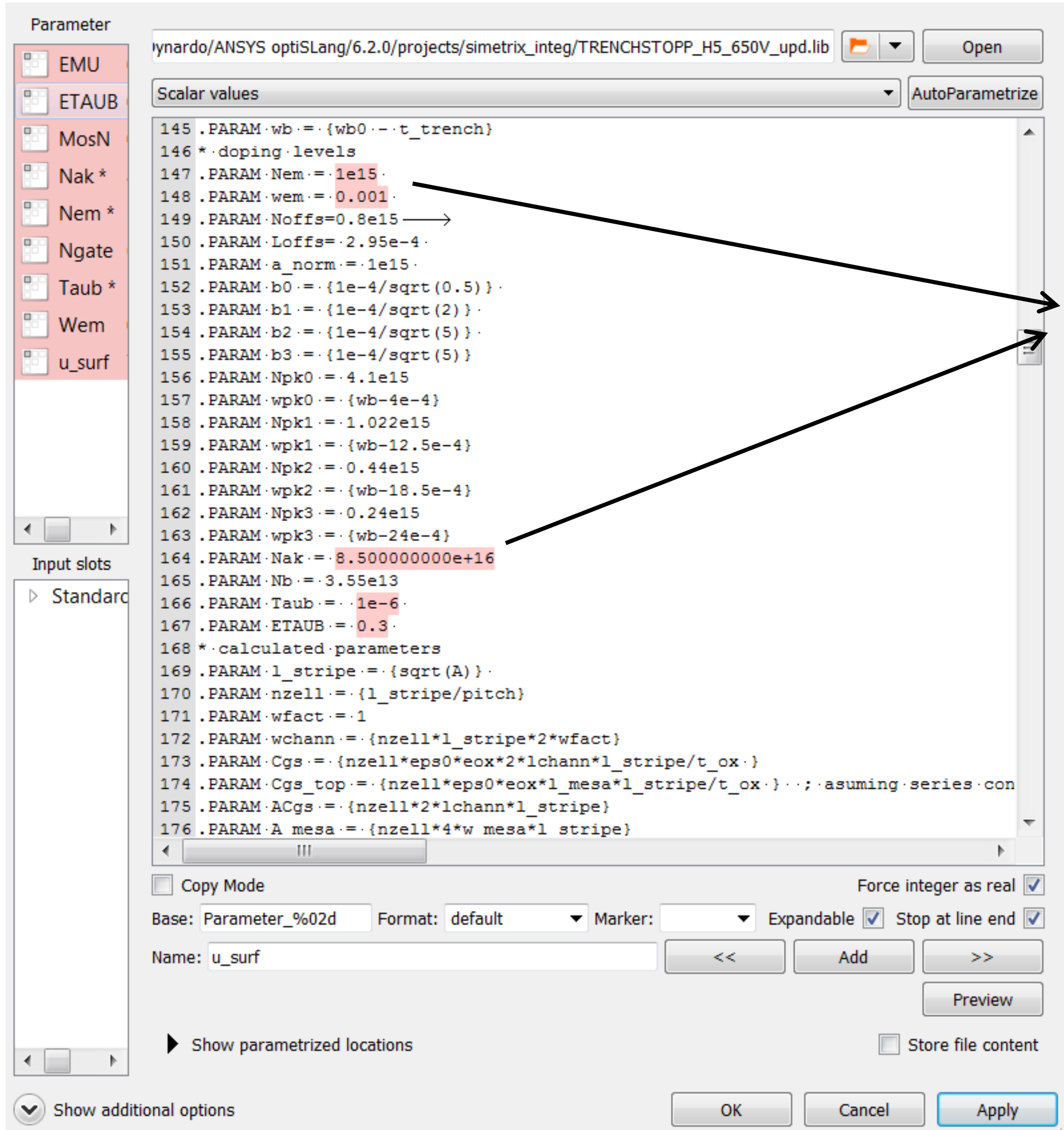
› Goal :
to minimize error_norm

# SIMetrix integration



# Input model (sub-circuit SPICE model)

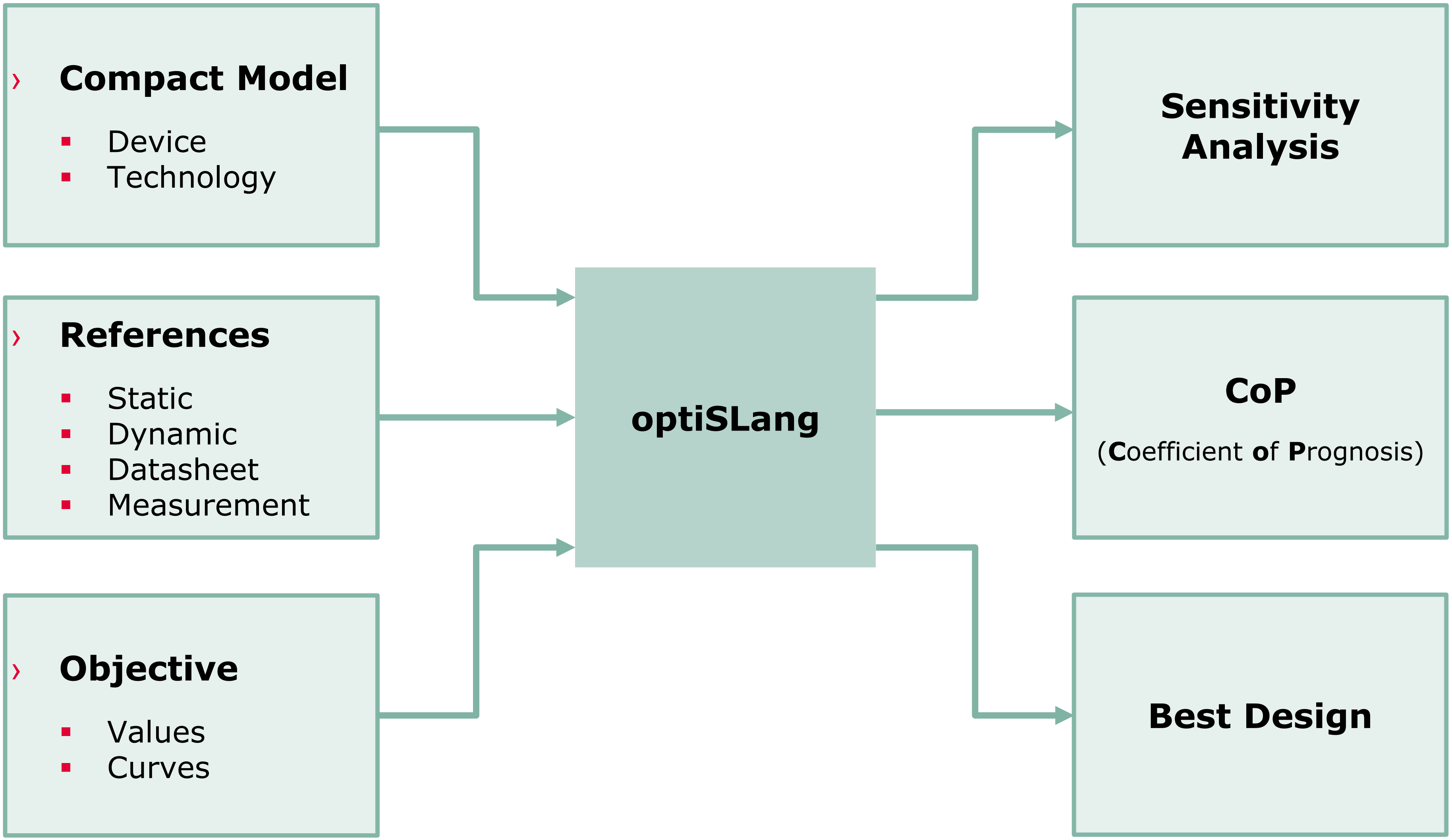
List of parameters to be optimized




Selection of parameters to be optimized

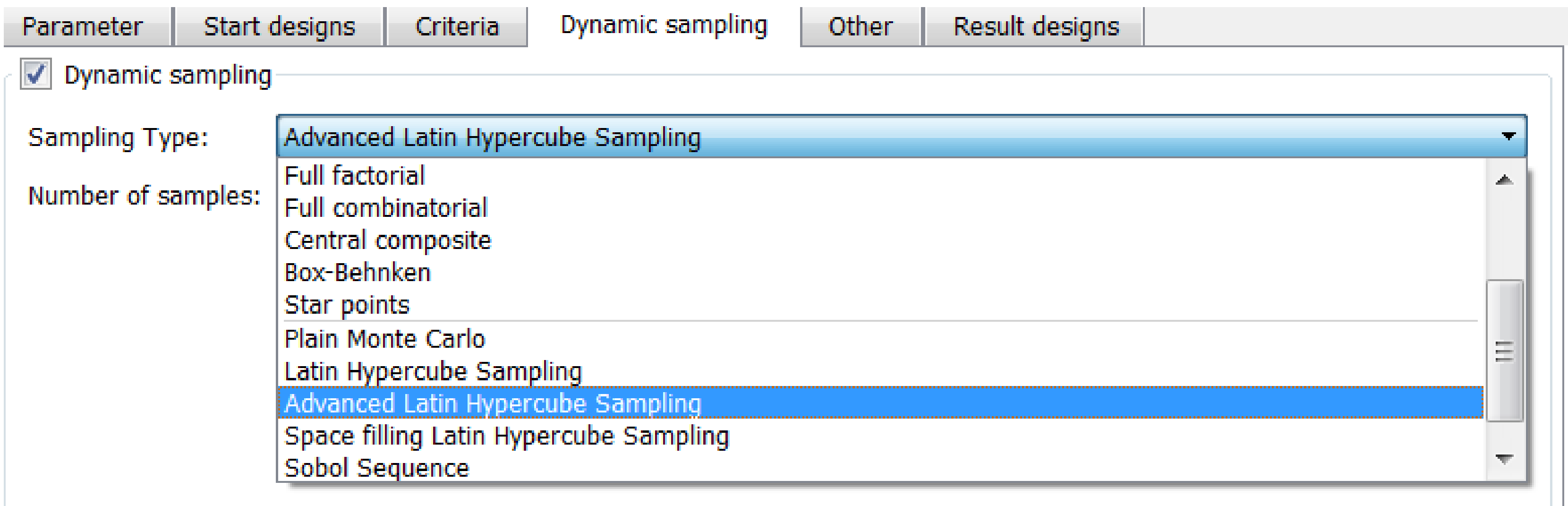
# Agenda

# Calibration Flow



# Calibration flow (detailed)

1) Identify parameters to be optimized for the calibration
2) Define input parameter range, which the optimizer must follow
3) Input reference data (measurement) to be calibrated
4) Definition of calibration objective using reference and simulation output (quadratic difference)
6) Perform a **Sensitivity Analysis** (DoE) using built in wizard

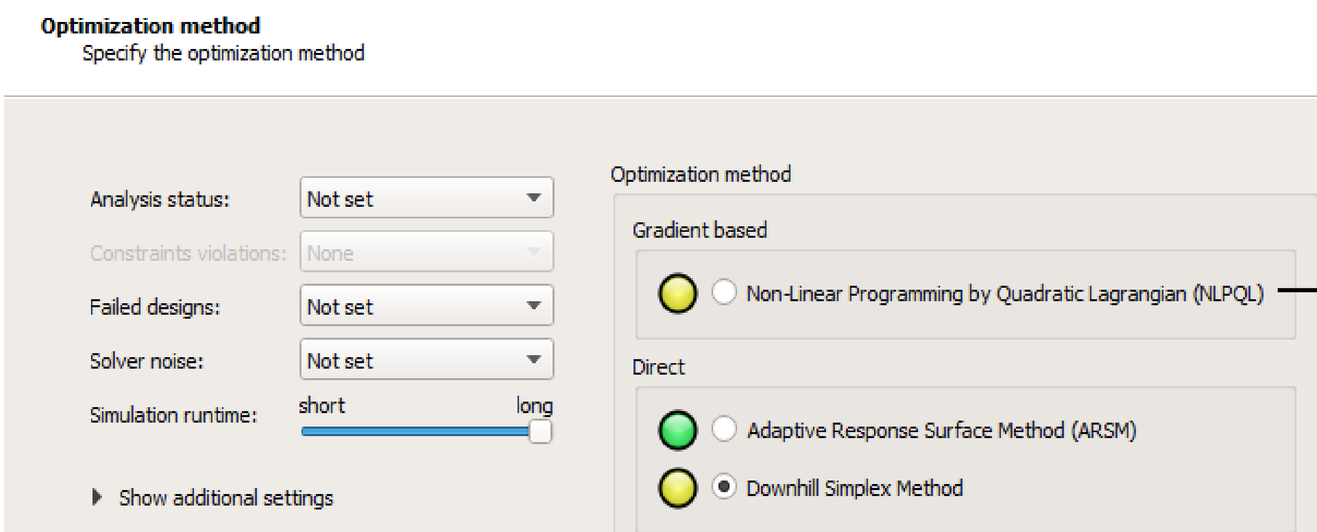



- ALHS : 100 simulations (default)
- Full factorial : $2^{\wedge\text{Number\_of\_Parameters}}$ simulations

# Calibration flow (contd.)

6) The MoP can be edited at this point to remove outliners (if any) to create a reduced design space for the final optimization step

7) An **Optimization** step is carried out either on the MOP output or directly
   - A set of best fit parameters are displayed
   - History of parameter variation are shown
   - Comparison of reference and optimized data



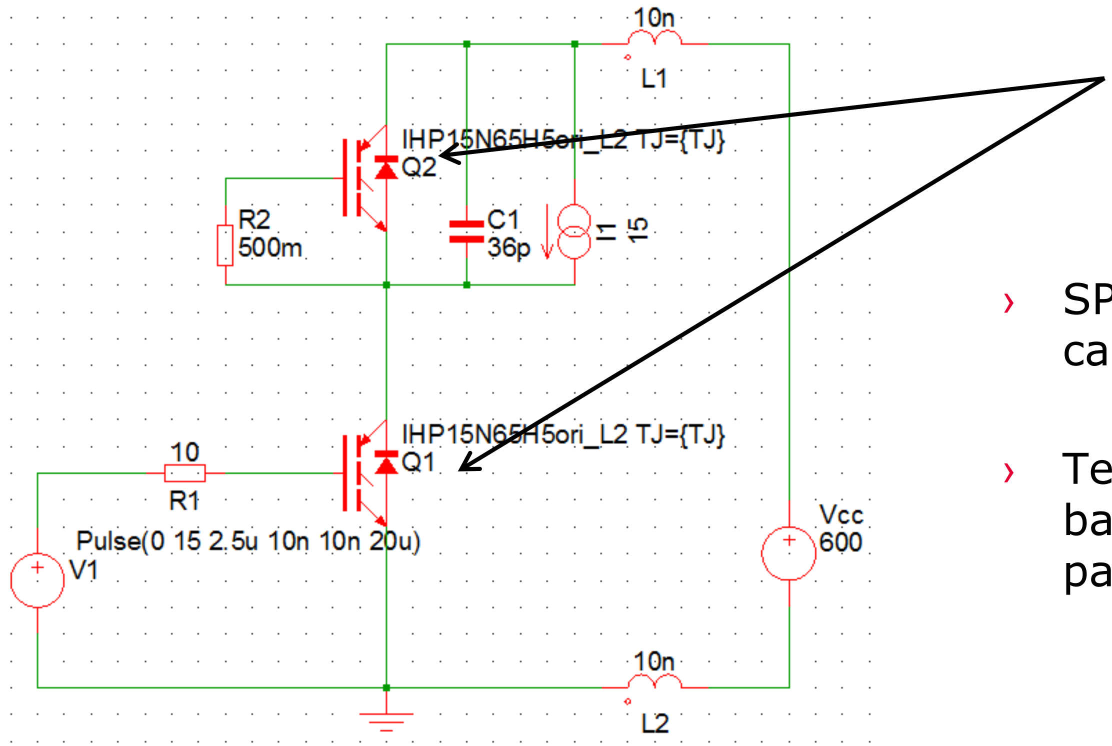

Acts on the MoP

Acts directly on sensitivity results

# Agenda

# Example 1 : Single transient curve

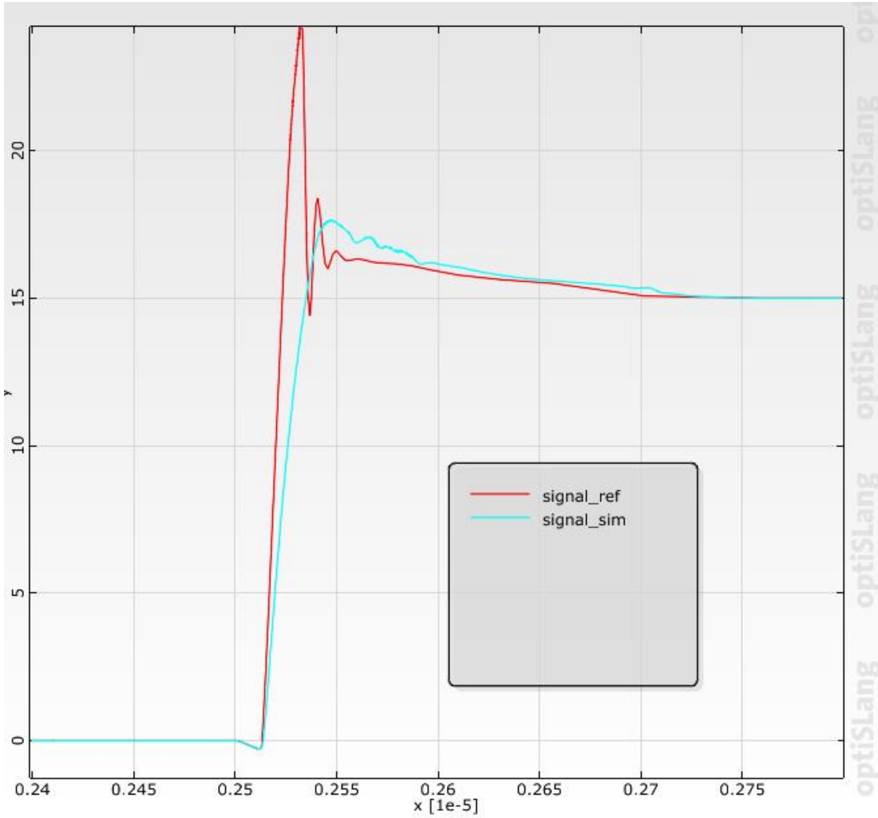
Calibration on a simulated curve

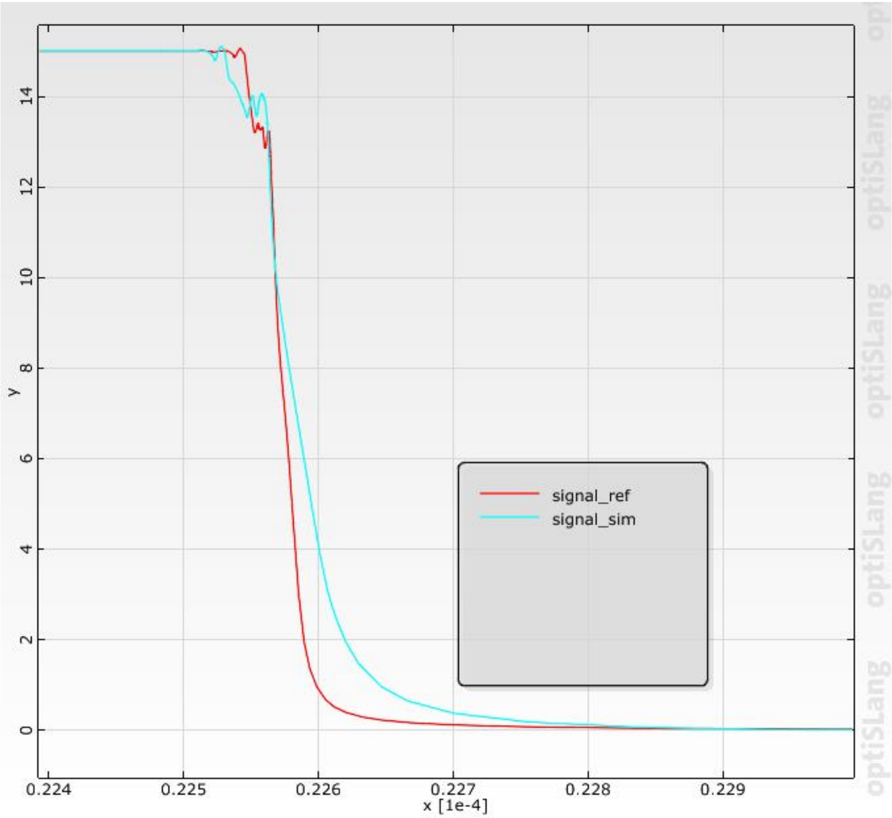



Test schematic used

- SPICE model manually de-calibrated
- Test: Can optiSLang give us back the original set of parameters ?

# Starting point of optimization




- Red: reference
- blue : uncalibrated initial solver output

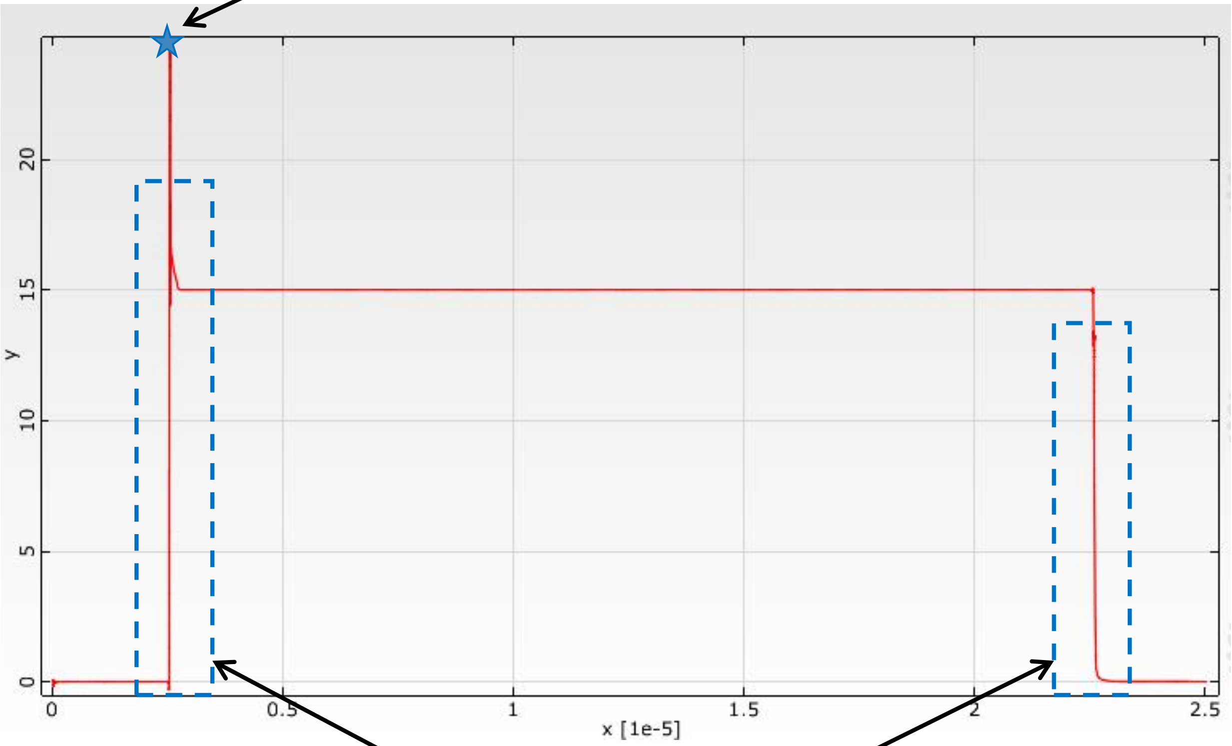
# Parameter range definition

| | Name | Parameter type | Reference value | Constant | Value type | Resolution | Range | | Range plot |
|---|---|---|---|---|---|---|---|---|---|
| 1 | EMU | Optimization | 0.1 | ☐ | REAL | Continuous | -2 | 1 | |
| 2 | Ngate | Optimization | 6e+09 | ☐ | REAL | Continuous | 5.4e+09 | 6.6e+10 | |
| 3 | Taub | Optimization | 5e-06 | ☐ | REAL | Continuous | 1e-06 | 3e-05 | |
| 4 | ETAUB | Optimization | 0.3 | ☐ | REAL | Continuous | 0.25 | 2 | |
| 5 | MosN | Optimization | 0.1 | ☑ | REAL | Continuous | 0.09 | 0.11 | |
| 6 | u_surf | Optimization | 75 | ☐ | REAL | Continuous | 50 | 500 | |
| 7 | Nak | Optimization | 8e+16 | ☐ | REAL | Continuous | 1e+15 | 1e+17 | |
| 8 | Nem | Optimization | 1e+16 | ☐ | REAL | Continuous | 1e+15 | 1e+17 | |
| 9 | Wem | Optimization | 0.001 | ☐ | REAL | Continuous | 9e-05 | 0.0011 | |

- Parameter range definition
- 8 Parameters for variation

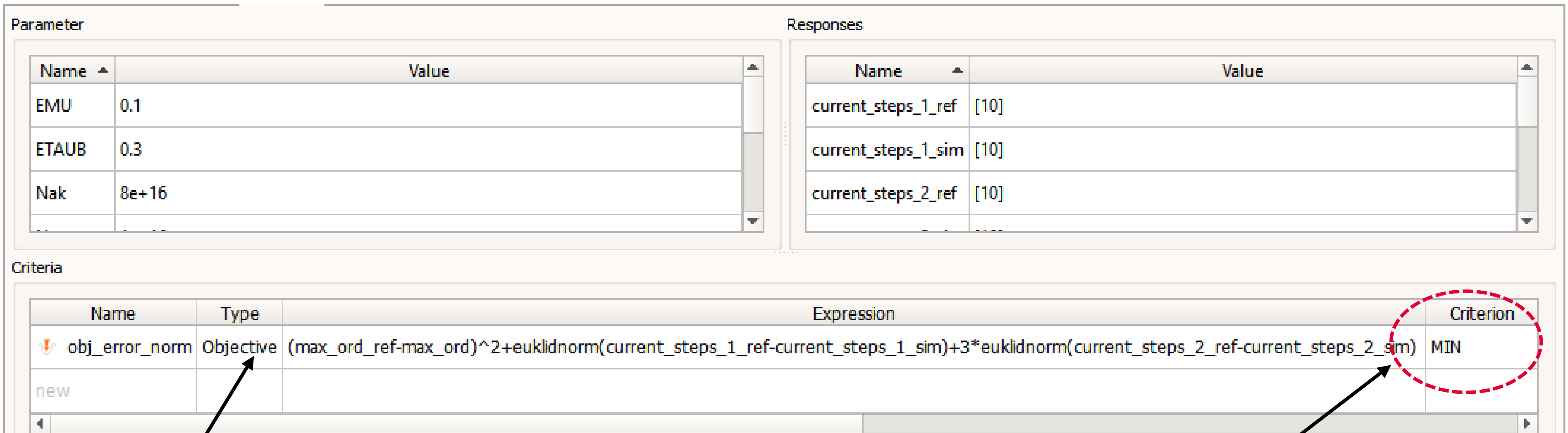
# Calibration objective definition

› Current Maxima




› Two windows defined in turn on and turn off region

# Calibration objective definition contd…




Objective=
(max_curr_ref - max_curr_sim)^2 → Maxima of curve
+euklidnorm(current_steps_1_ref - current_steps_1_sim)
+3*euklidnorm(current_steps_2_ref - current_steps_2_sim)

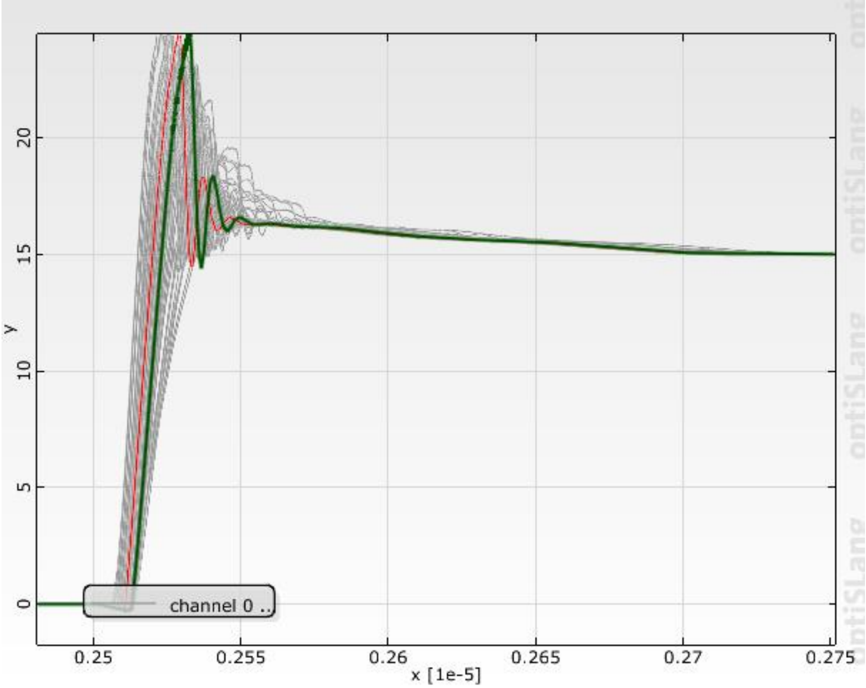
Two windows defined in turn on and turn off region

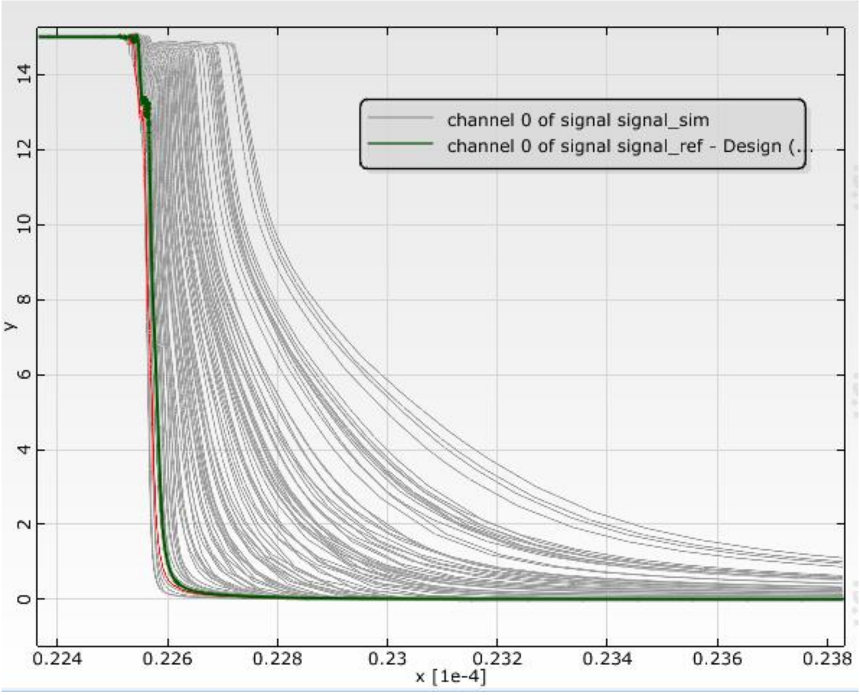
Weightage can be set depending on importance

- Goal is to minimize the objective defined.
- Zero objective would mean that the reference and the simulation are coinciding

# Fit summary after sensitivity analysis

- Green: reference
- Red : best design(sensitivity)

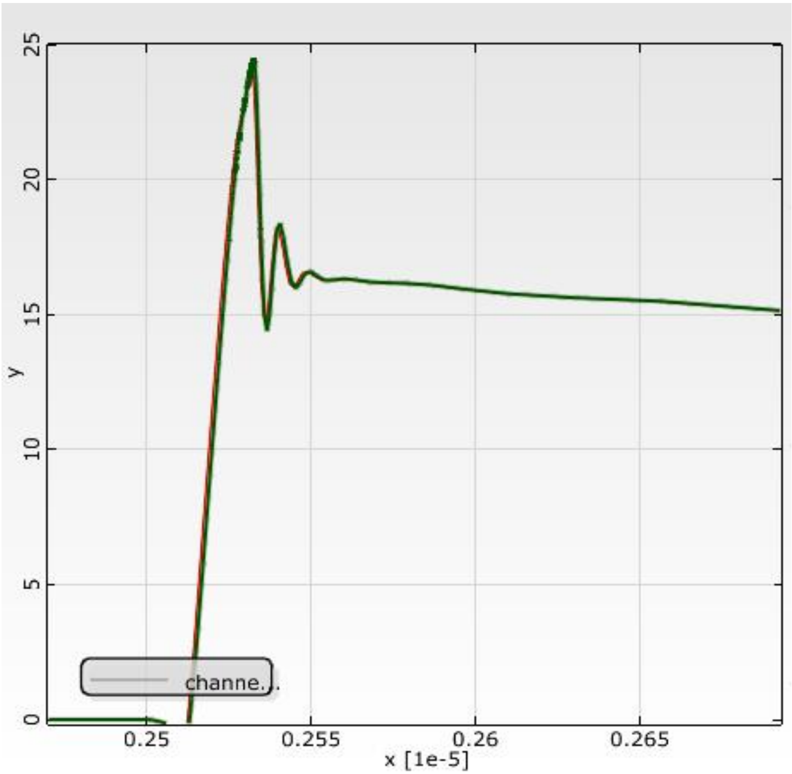


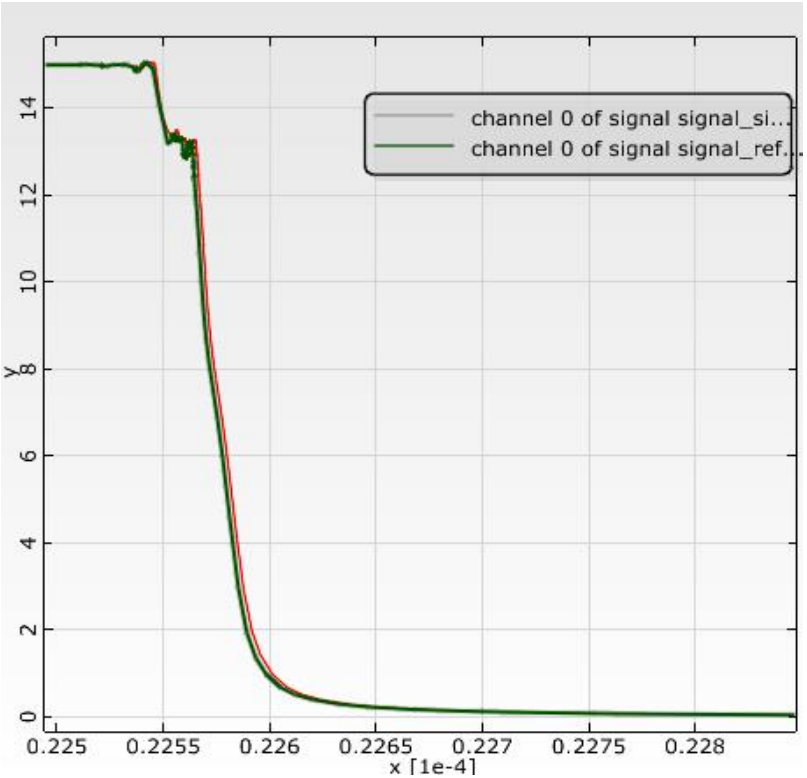




- Grey lines indicate all 100 simulations performed by sensitivity analysis
- Good enclosure of the target curve means that the design space is well defined by the parameter range
  - In case of poor enclosure the parameter ranges need to be redefined and Sensitivity analysis has to be redone

# Fit summary after final optimization

- Green : reference
- Red : best design (optimization)




| Parameter | Nk | Nm | ETB | u_s | Tb | Ng |
|---|---|---|---|---|---|---|
| Optimized Value | 7.78e16 | 3.46e15 | 1.24 | 500 | 2.86e-6 | 1.52e10 |
| Initial Value | 8.5e16 | 2.75e16 | 1.5 | 450 | 2.5-6 | 2.58e10 |

# Agenda

# Example 2 : Two static curves (Transfer and Output)

## Calibration to measured curves:

### Parameter range definition

| | Name | Parameter type | Reference value | Constant | Operation | Value type | Resolution | Range | | Range plot |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Taub | Optimization | 2.5e-05 | | | REAL | Continuous | 1e-06 | 9e-05 | |
| 2 | wfact | Optimization | 1 | | | REAL | Continuous | 0.5 | 5 | |
| 3 | log_Nem | Optimization | 16 | | | REAL | Continuous | 14 | 17 | |
| 4 | u_surf | Optimization | 400 | | | REAL | Continuous | 100 | 600 | |
| 5 | EMU | Optimization | -1.75 | | | REAL | Continuous | -6 | 0 | |
| 6 | log_Ngate | Optimization | 10 | | | REAL | Continuous | 8 | 14 | |
| 7 | log_Nak | Optimization | 16 | | | REAL | Continuous | 14.7 | 17.9 | |
| 8 | Nem | Dependent | 3.4e+16 | | 3.4*10^log_Nem | | | | | |
| 9 | Nak | Dependent | 7e+16 | | 7*10^log_Nak | | | | | |
| 10 | Ngate | Dependent | 2.5e+10 | | 2.5*10^log_Ngate | | | | | |

- Logarithmic parameter definition for wide range of variation
- 7 parameter for variation

# Initial CoP Matrix (Sensitivity analysis)

Transfer curve

Output curve

| Models | Taub | wfact | log_Nem | u_surf | EMU | log_Ngate | log_Na | Total |
|---|---|---|---|---|---|---|---|---|
| obj_error_norm | | 28.5 % | 21.1 % | 19.7 % | | | 69.2 % | 95.3 % |
| force_steps_sim_trans[7] | | 22.0 % | 22.7 % | 14.4 % | | | 71.2 % | 95.1 % |
| force_steps_sim_trans[6] | | 22.4 % | 17.8 % | 14.5 % | | | 75.2 % | 95.2 % |
| force_steps_sim_trans[5] | | 22.3 % | 12.6 % | 14.8 % | | | 77.3 % | 93.7 % |
| force_steps_sim_trans[4] | | 21.3 % | | 15.2 % | | 11.0 % | 78.9 % | 94.1 % |
| force_steps_sim_trans[3] | | 15.7 % | | 15.2 % | | | 87.1 % | 93.8 % |
| force_steps_sim_trans[2] | | 17.0 % | | 20.2 % | | | 86.4 % | 93.2 % |
| force_steps_sim_trans[1] | | | 35.3 % | | | 63.2 % | 80.7 % | 90.3 % |
| force_steps_sim_trans[0] | 99.8 % | | | | | | | 99.8 % |
| force_steps_sim_out[7] | | 6.9 % | 72.2 % | 2.9 % | | | 34.1 % | 93.7 % |
| force_steps_sim_out[6] | | | 74.6 % | | | | 33.1 % | 92.7 % |
| force_steps_sim_out[5] | | | 81.1 % | | | | 30.2 % | 94.3 % |
| force_steps_sim_out[4] | | | 81.6 % | | | | 28.7 % | 95.1 % |
| force_steps_sim_out[3] | | | 83.3 % | | | | 28.0 % | 95.8 % |
| force_steps_sim_out[2] | | | 84.0 % | | 8.6 % | | 28.2 % | 97.8 % |
| force_steps_sim_out[1] | | | 74.7 % | | | | 30.6 % | 90.6 % |
| force_steps_sim_out[0] | 100.0 % | | | | | | | 100.0 % |
| euklidnorm_trans | | 32.7 % | 23.0 % | 20.4 % | | | 65.6 % | 95.3 % |
| euklidnorm_out | | | 68.4 % | | | | 22.1 % | 70.1 % |

Parameter

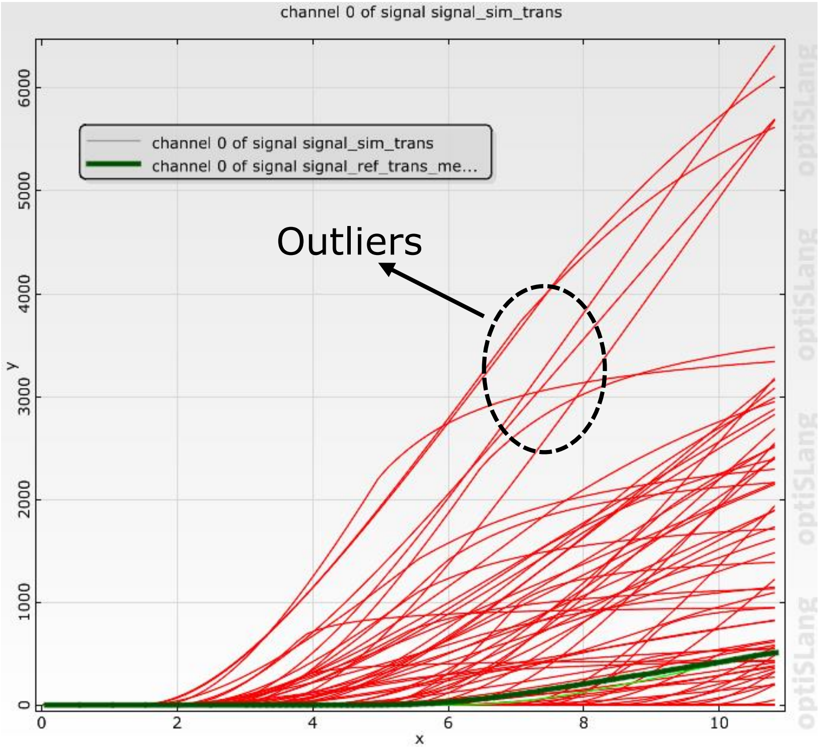
optiSLang

- Taub only has impact in the initial part of the curves
- EMU and Ngate has negligible impact on both curves
- Transfer curve → reduction from 7 to 6 important parameter
- Output curve → reduction from 7 to 3 important parameter

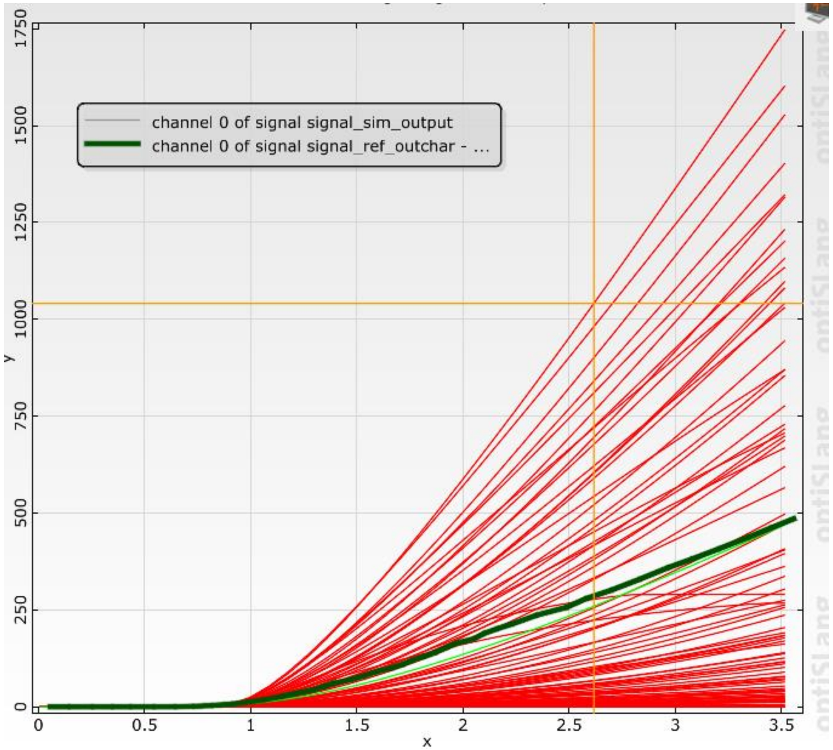
- different CoP value for Transfer and Output curves → Outliers???

# Optimize MOP

Transfer curve

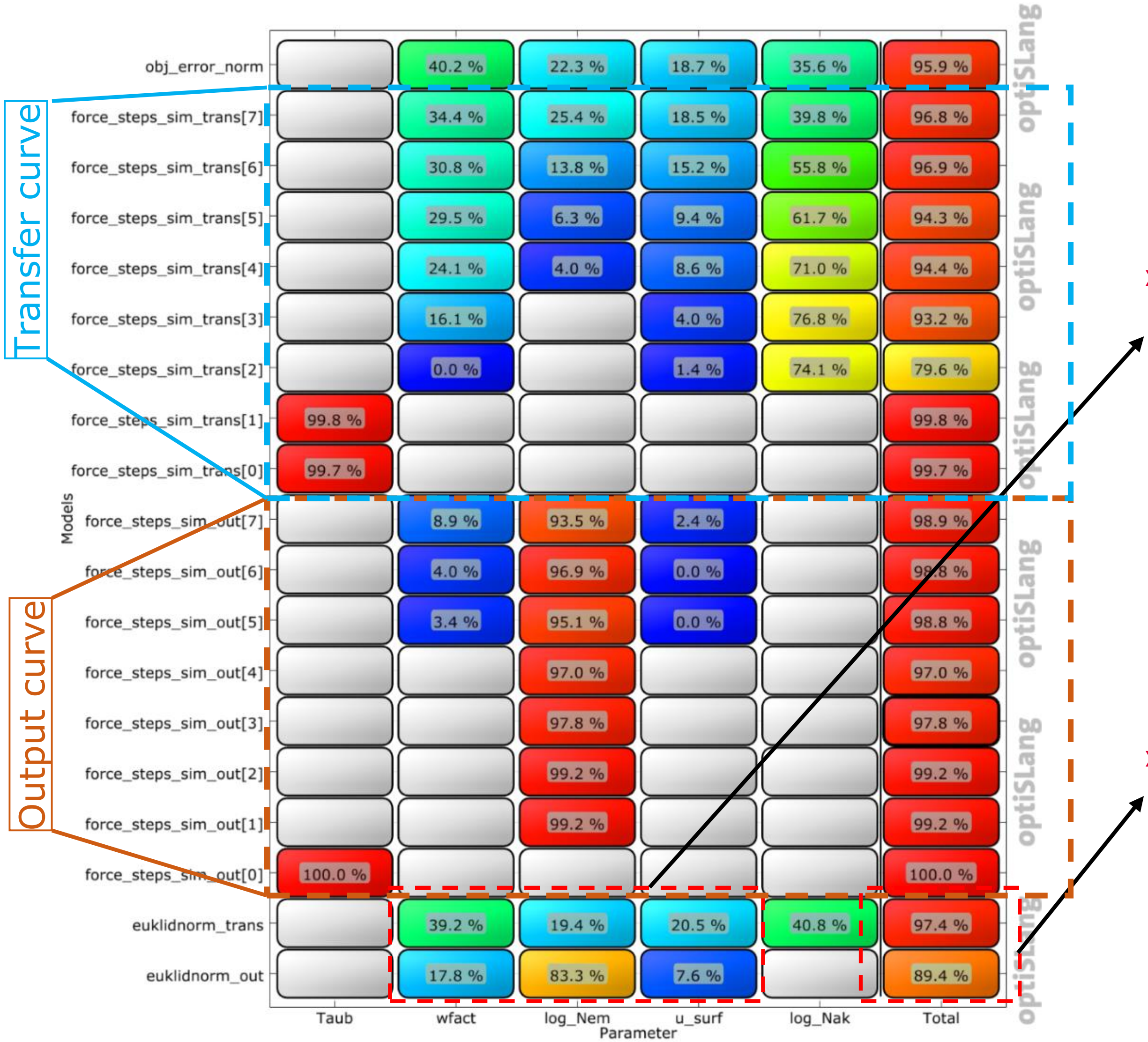



Output curve




- MOP optimization :
  - Filter out negligible parameters manually
  - Deactivate outlier designs manually from the MOP
  - Goal is to increase the total CoP value -> better calibration possible

# Optimized CoP Matrix



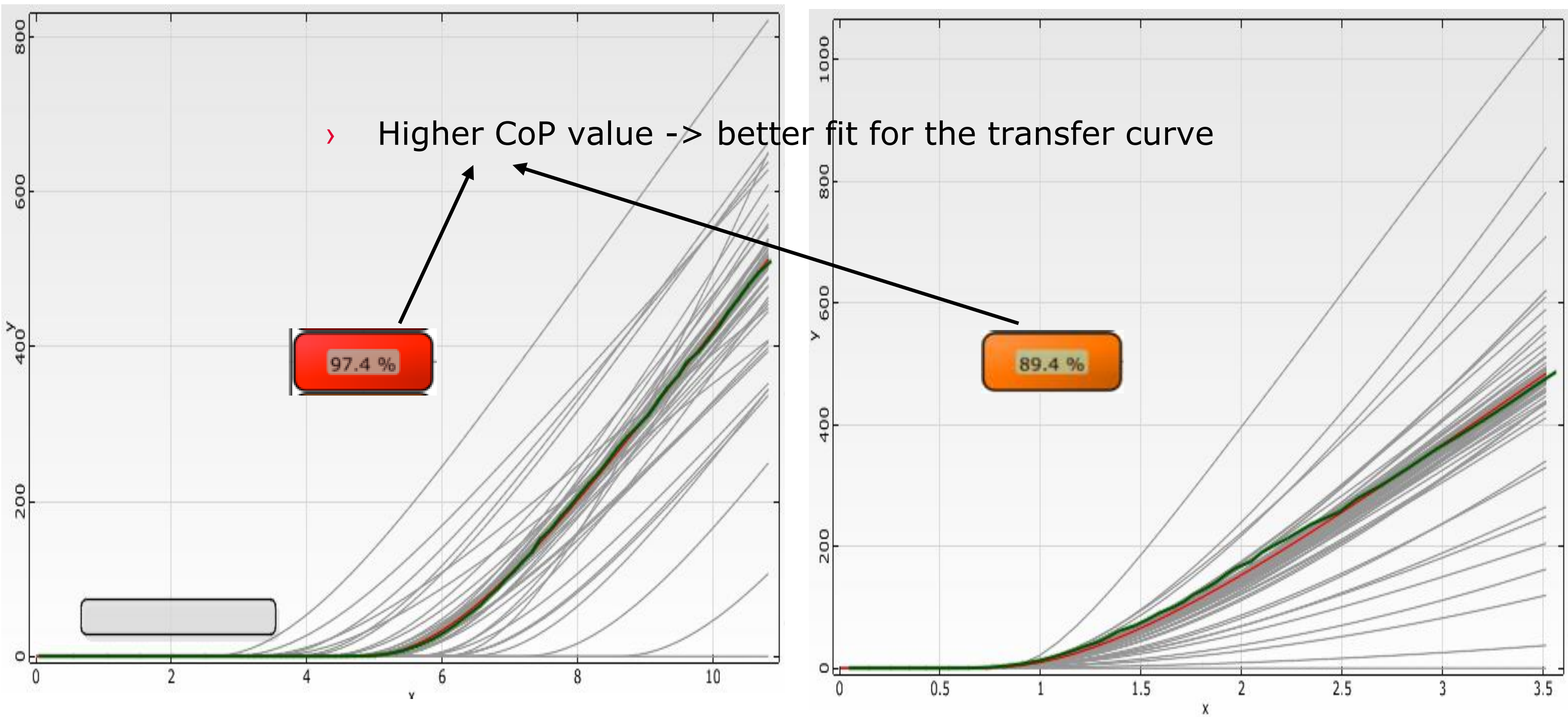

- Parameters having influence on both curves shows the importance of a global calibration

- With MOP optimization we could increase the total CoP value up to 90%

# Fit summary after global optimization

Transfer curve

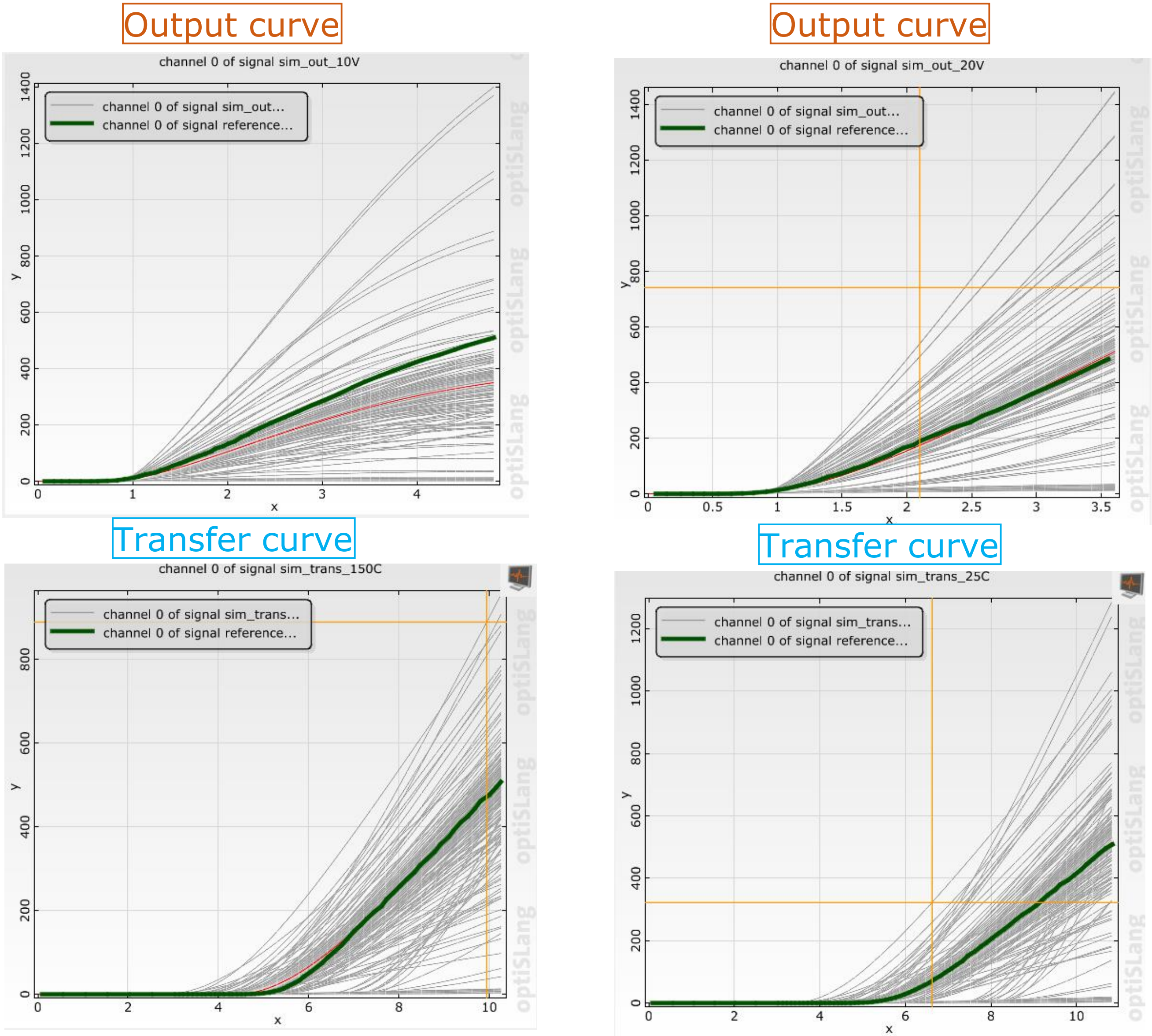
Output curve




› Higher CoP value -> better fit for the transfer curve

- › Green curve indicates the target curve from measurements
- › Grey curves indicate all simulations performed by direct optimization after Opt. on MOP
- › Red curves indicates the final optimizer fit → excellent agreement

# 4 curve system fit summary (2 transfer & 2 output curves)




- Excellent agreement for 3 of 4 curves → weighted objective necessary

# Agenda

# Conclusion/Future Outlook

- Current status
  - optiSLang aided fitting of compact IGBT SPICE model demonstrated
  - Good fit to measurements achieved in the defined parameter range
    - Complex transient curve successfully calibrated
    - Global calibration of upto four static curves (2 transfer & 2 output) demonstrated
  - Greatly reduces the time and effort needed for compact model calibration

- Outlook
  - Evaluation of temperature dependence and transient curves in global calibration
  - Define a standardized calibration flow with IGBT/diode measurements

THANK YOU FOR YOUR ATTENTION

QUESTIONS ?

Part of your life. Part of tomorrow.