presented at the 4th Weimar Optimization and Stochastic Days 2007
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# Robust Design Optimization in forming simulation using adaptive response surface methodology

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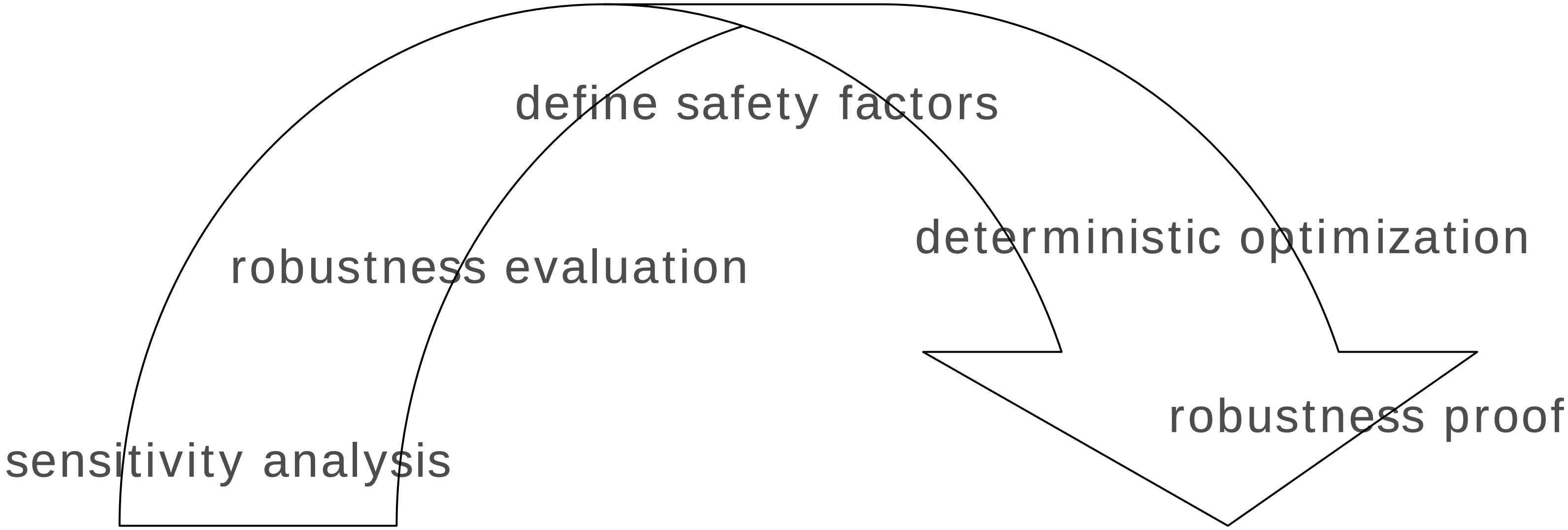
# Iterative RDO procedure

It is absolutely necessary to understand booth domains:

- the design space of optimization
- as well as the robustness/reliability space

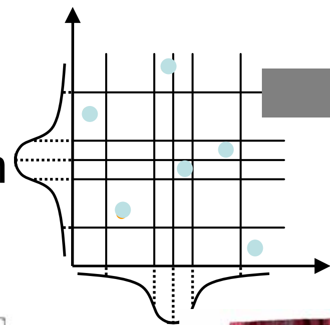
to be able to formulate a successive RDO problem.

- starting with a consecutively approach of using sensitivity analysis, robustness evaluation and deterministic optimization for achieving a robust optimal design is recommended.

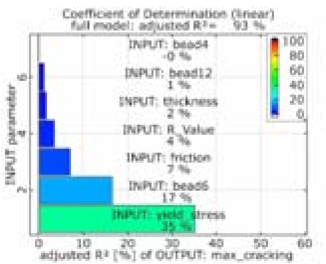


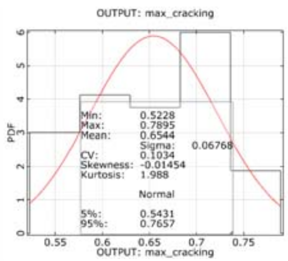
# Example Application
# forming simulation of a small BMW car body part

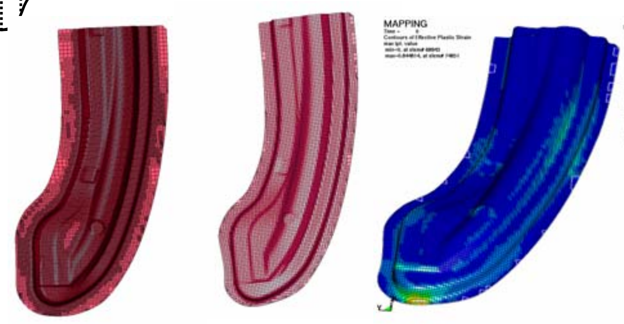
Scanning of design space/robustness domain using LHS Sampling

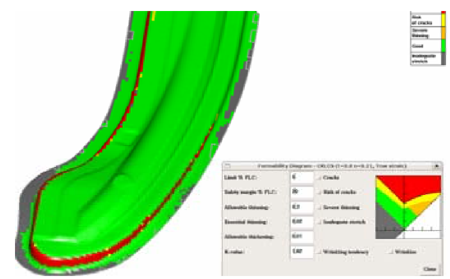


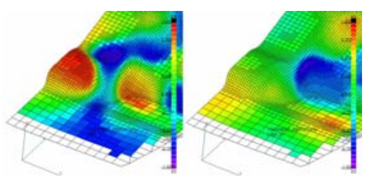
forming simulation (**LS-DYNA**)
- mapping
- FLD evaluation
- meta format extraction

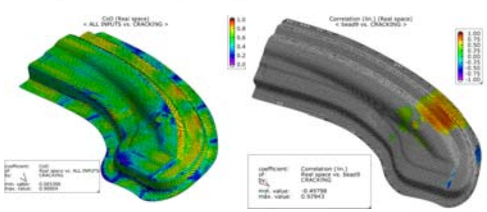


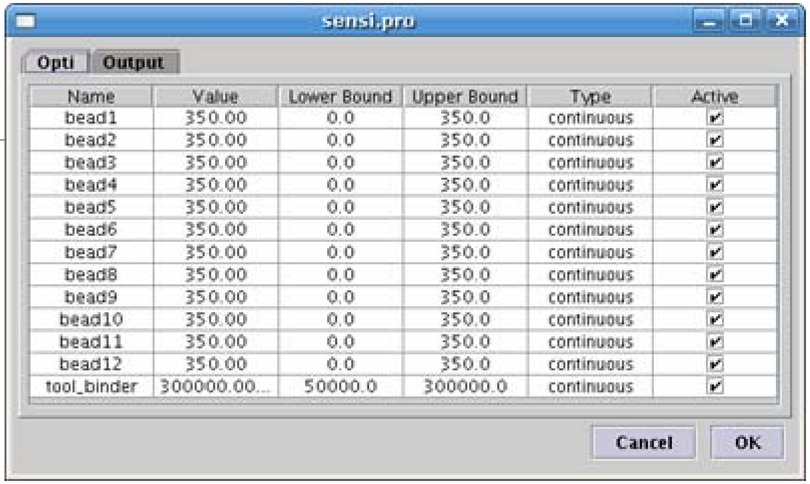




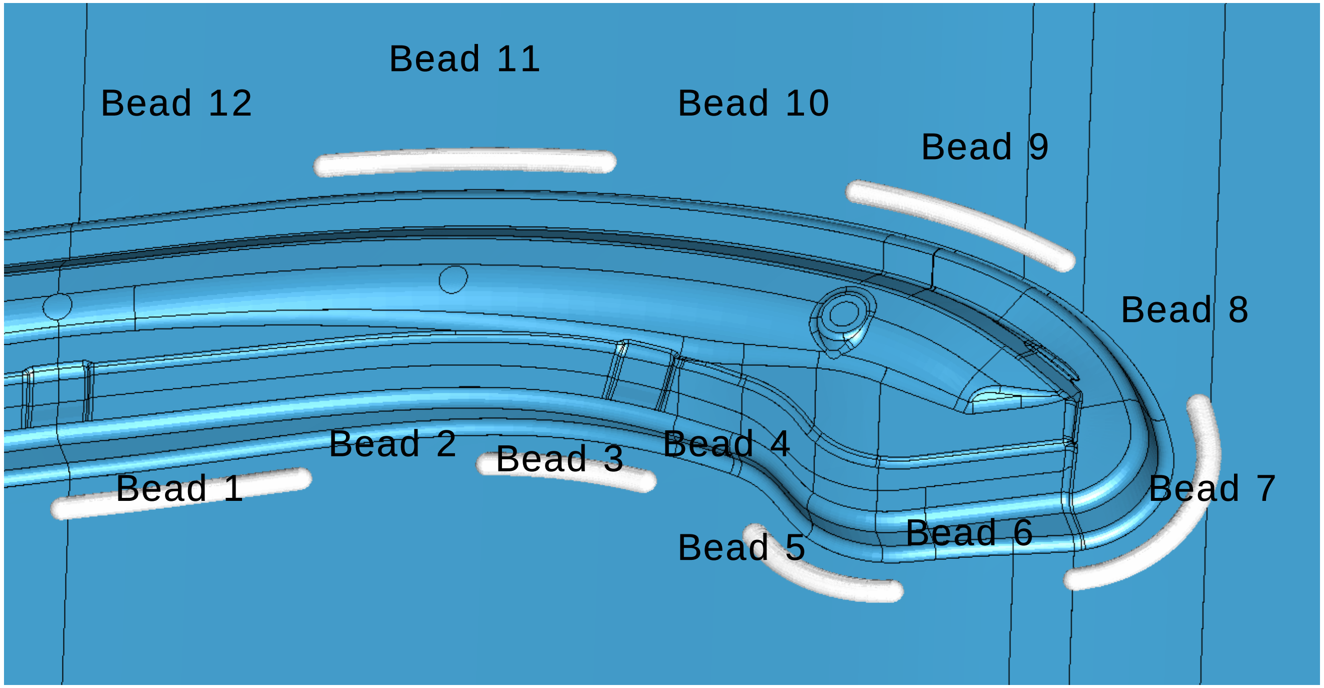
statistical post processing
single values/statistics_on_structure

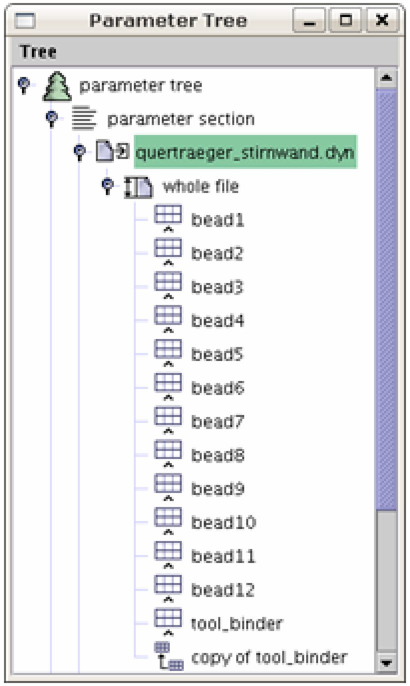
# Optimization domain

- 12 beads forces (0-350 N)
- tool binder force (50-300 KN)




| Name | Value | Lower Bound | Upper Bound | Type | Active |
|---|---|---|---|---|---|
| bead1 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| bead2 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| bead3 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| bead4 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| bead5 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| bead6 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| bead7 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| bead8 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| bead9 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| bead10 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| bead11 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| bead12 | 350.00 | 0.0 | 350.0 | continuous | ✔ |
| tool_binder | 300000.00... | 50000.0 | 300000.0 | continuous | ✔ |

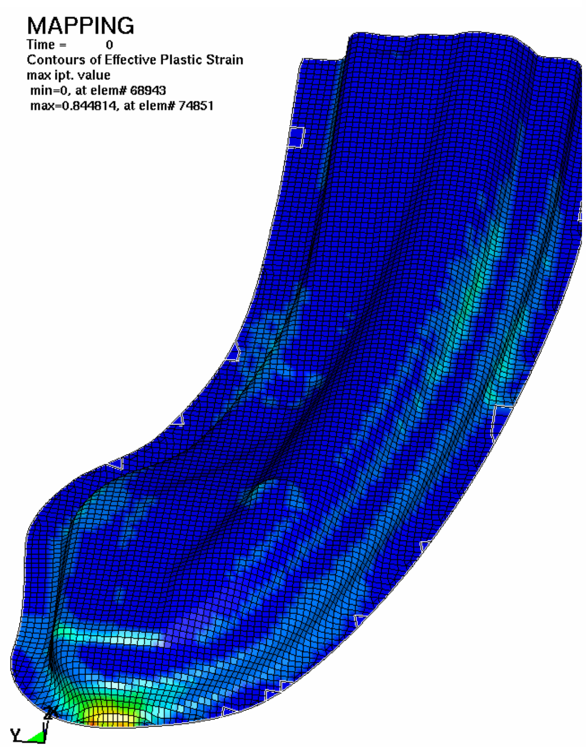


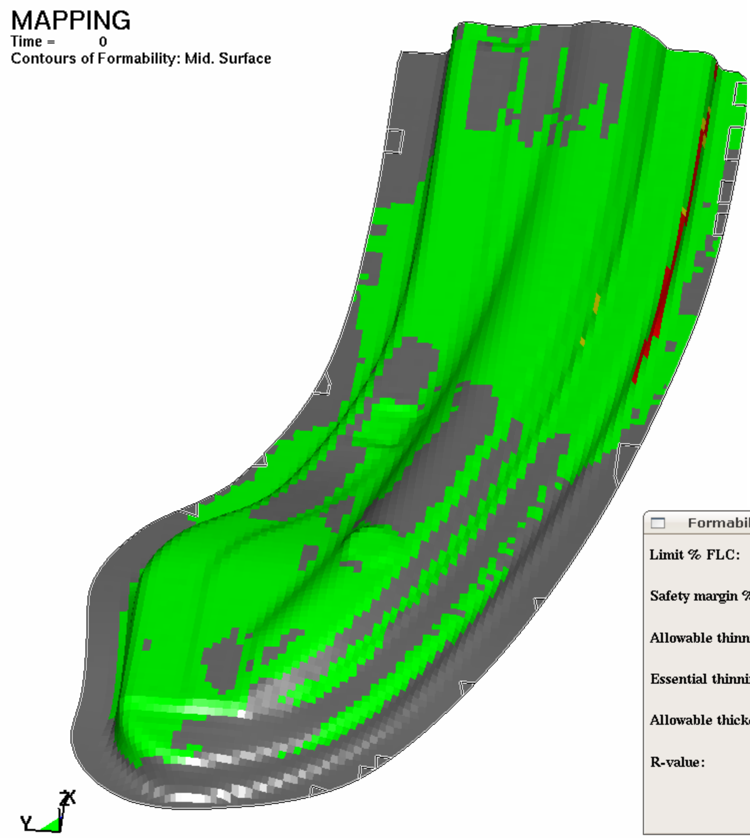



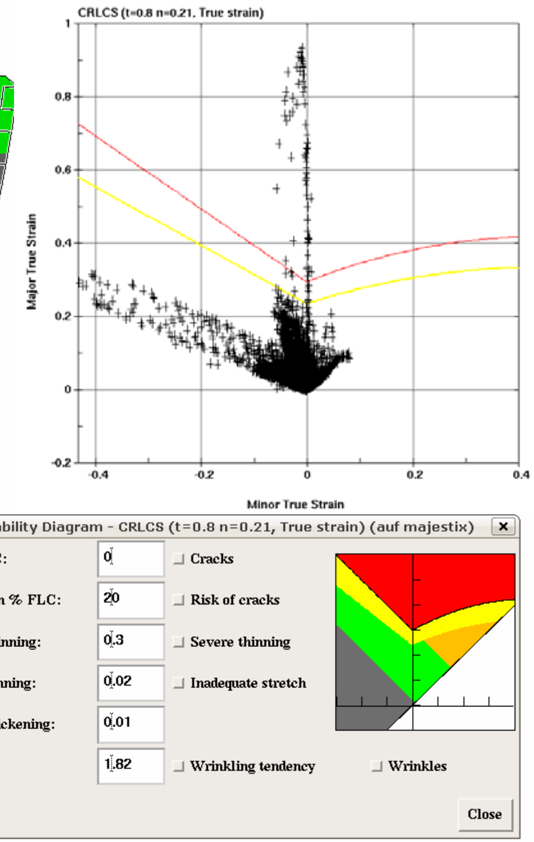
# Sensitivity Analysis with Reference Simulation

Which design parameter, result values and objectives are sensitive ?

- 100 optiSLang Latin Hypercube Sampling

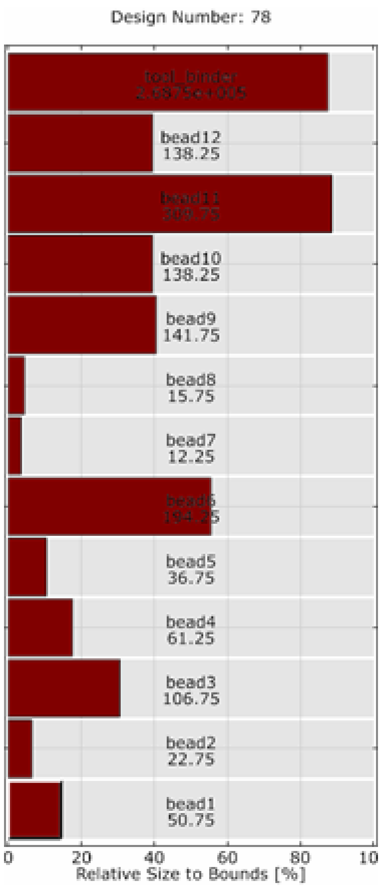


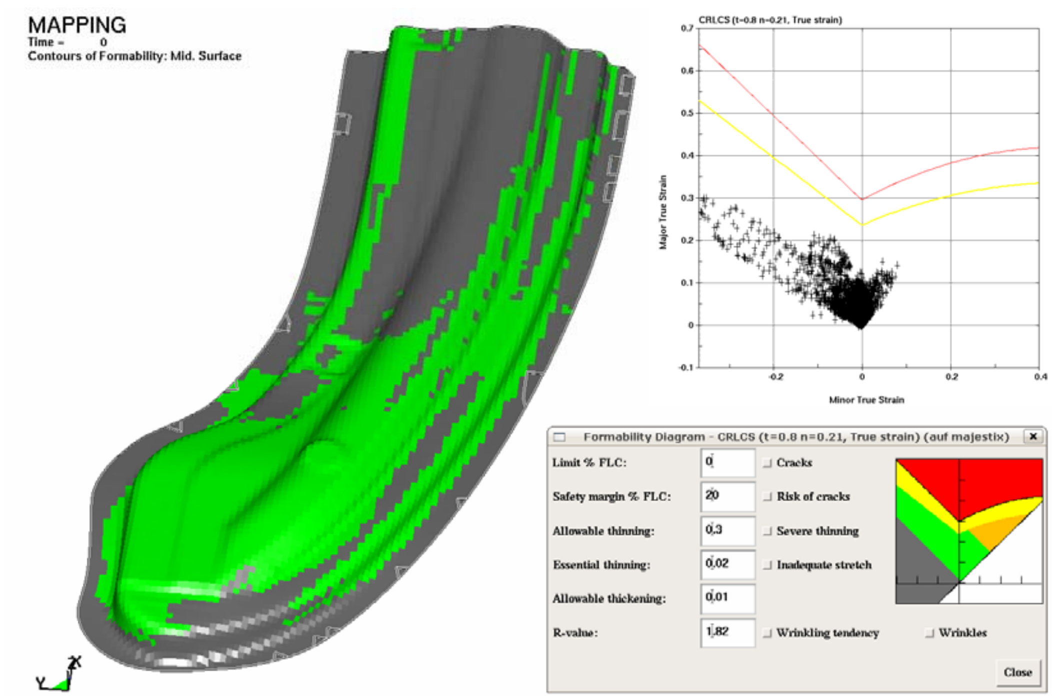



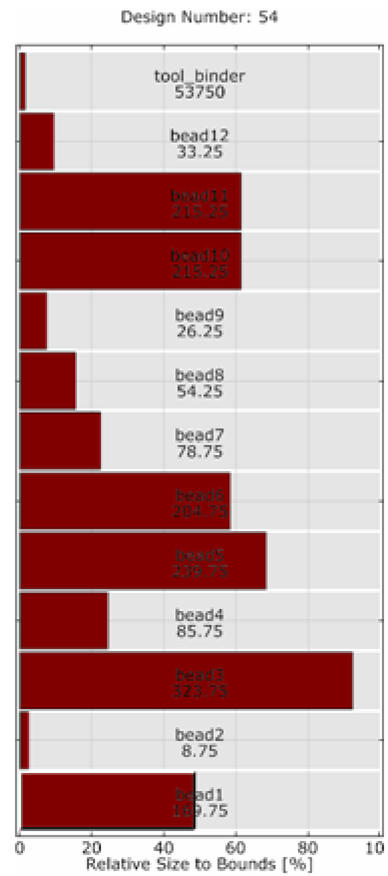



# Sensitivity Study

only two design are admissible regarding the FLD_Crack value

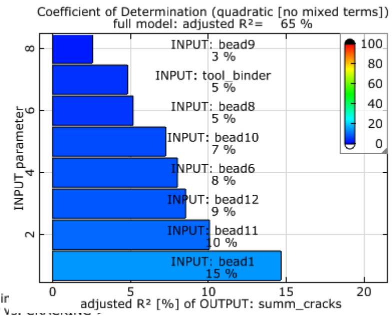


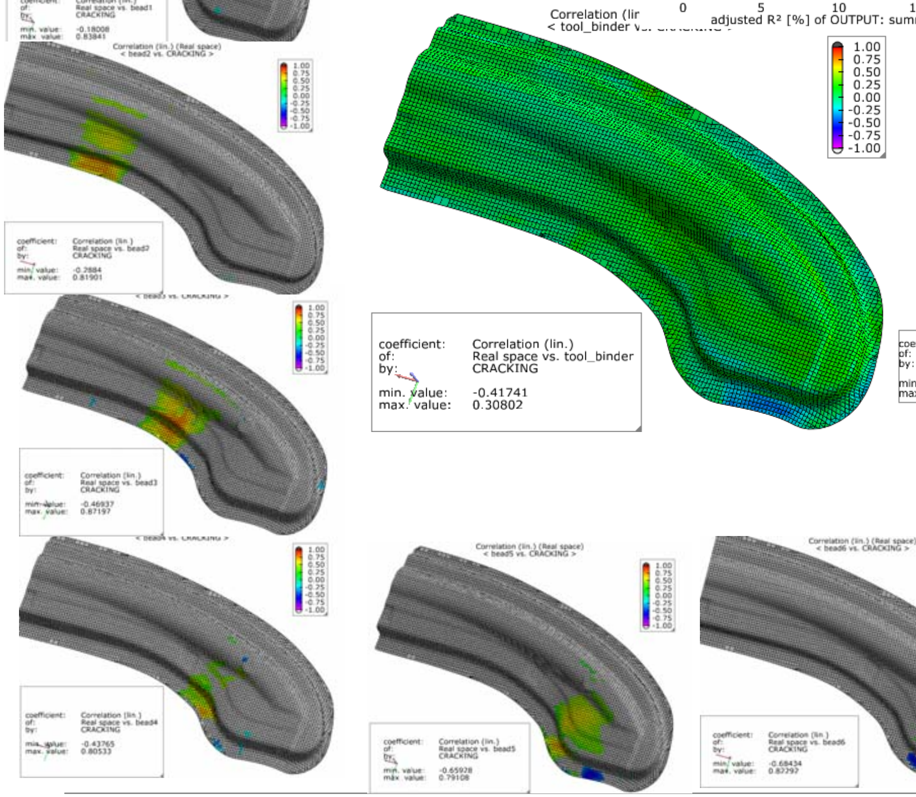



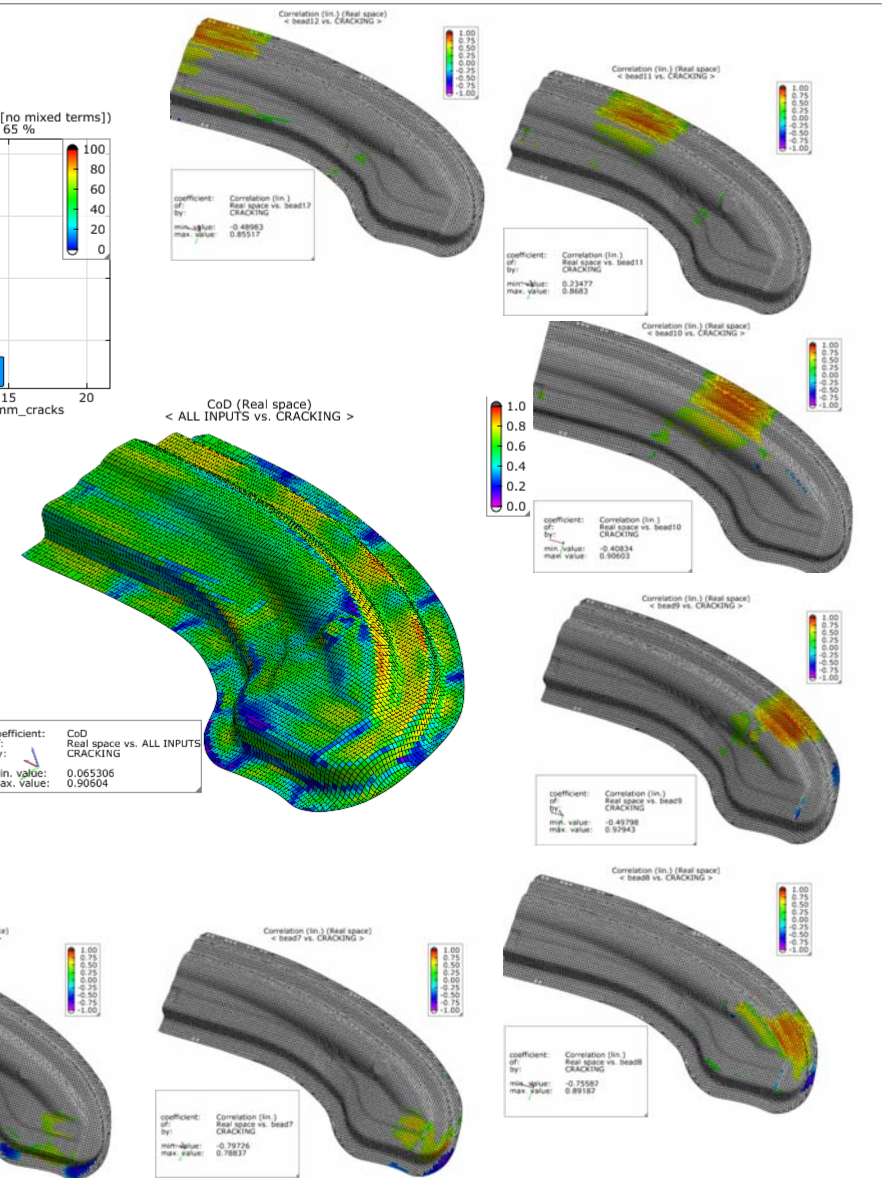



# Sensitivity – Correlation

- no importance ranking possible
- highly non-linear



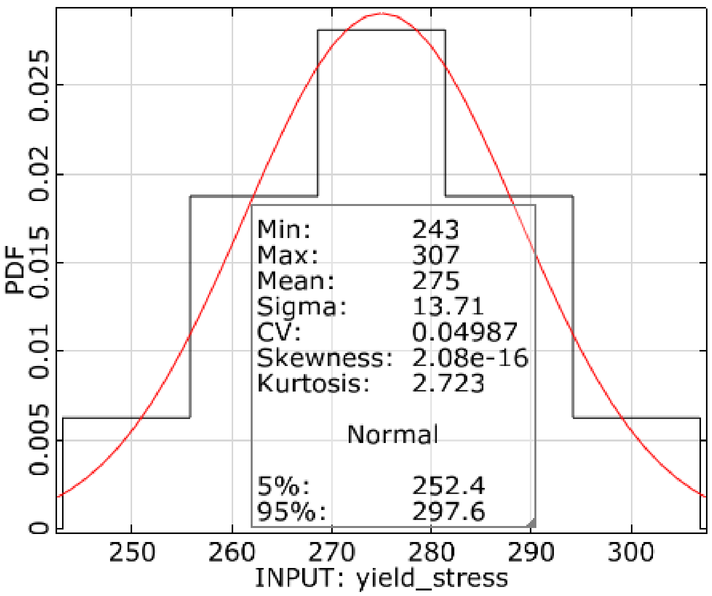



# Robustness Evaluation using 100 LHS Sampling

## Robustness domain

- Scatter of all 12 beads forces
- Scatter of tool binder force
- Scatter of friction (normal
- Scatter of Sheet metal thickness
- Scatter yield stress and plasticity value (R-value)



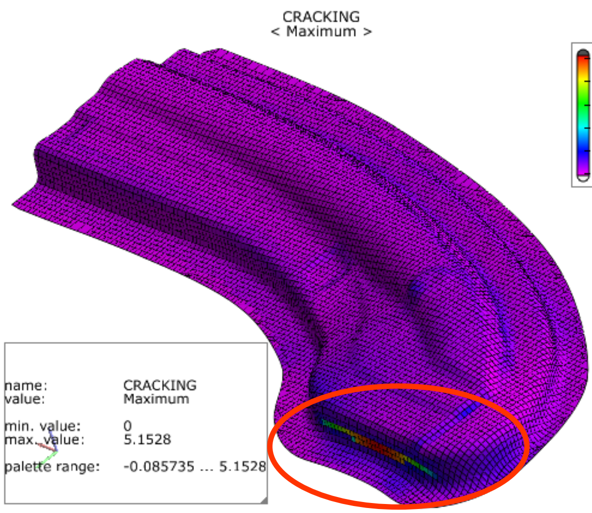

(normal distribution, CoV_0.05)

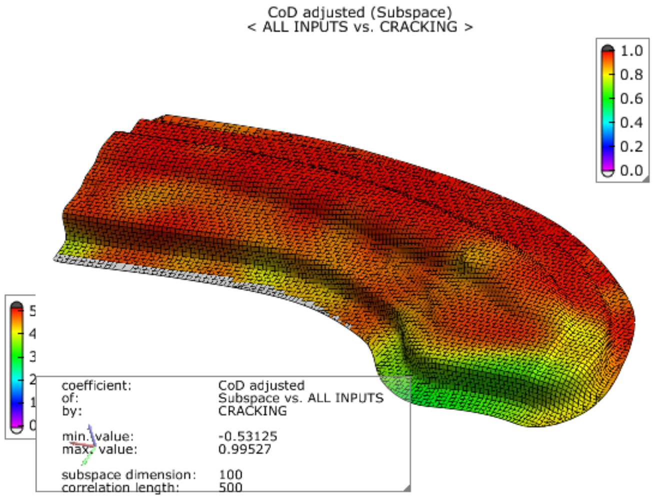
Robustness evaluation for the best_Design of the Sensitivity study (max. FLD_crack=0.73)

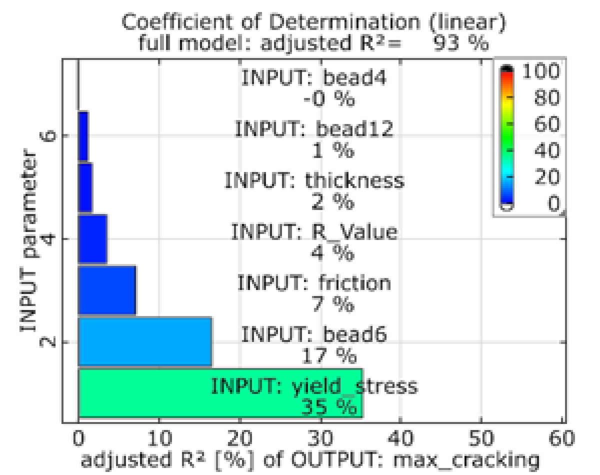
Does the safety distance ensure Robustness ??

# Robustness Evaluation

- 6% failure (maximum FLD_crack > 1.0)
- high coefficients of determination (93% linear correlation base)
- clear ranking (only scatter of yield stress, bead 6 force and friction has important correlation to FLD_crack scatter)



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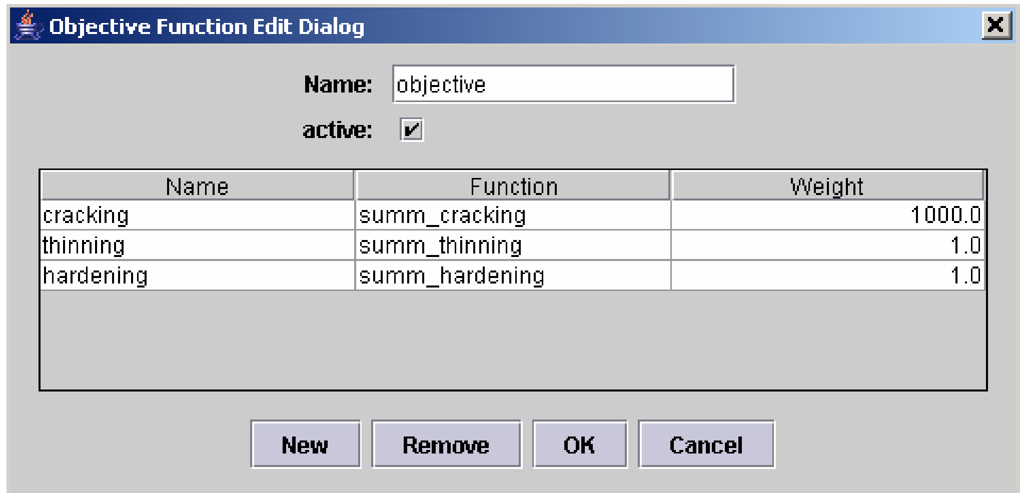
# Deterministic Optimization

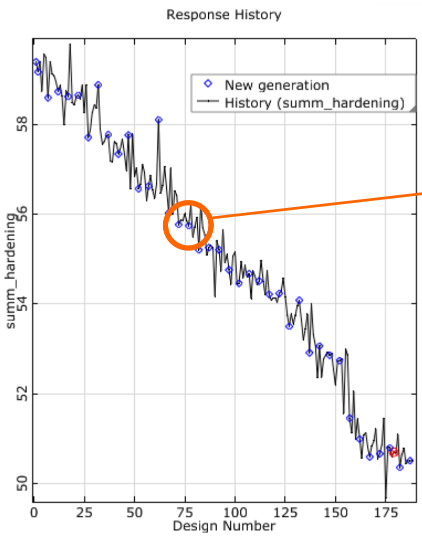
- design improvement from two admissible sensitivity study designs
- increase if safety distance (max. FLD_crack<0.70)
- weighted objective

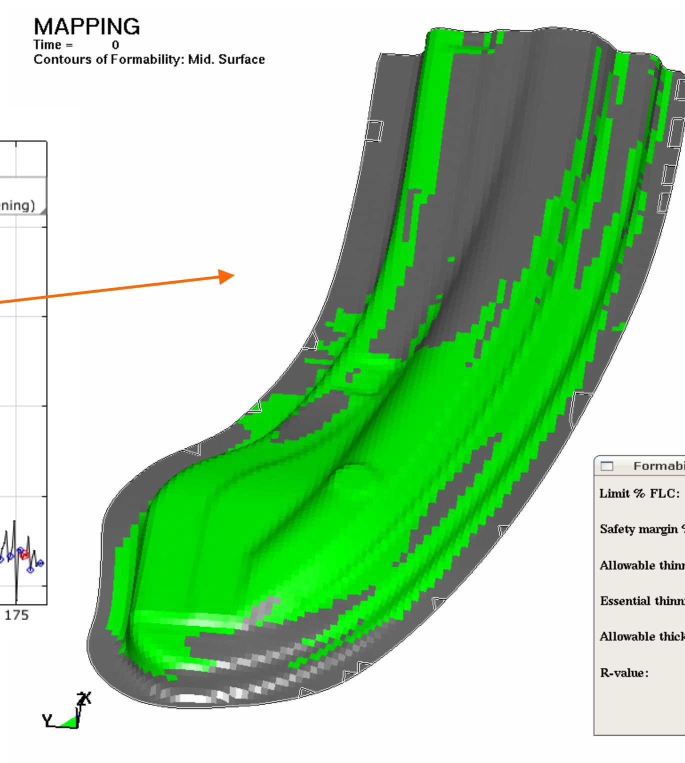


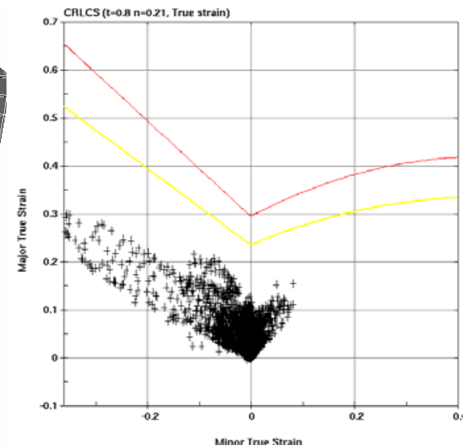

- optiSLang Default setting of evolutionary design improvement

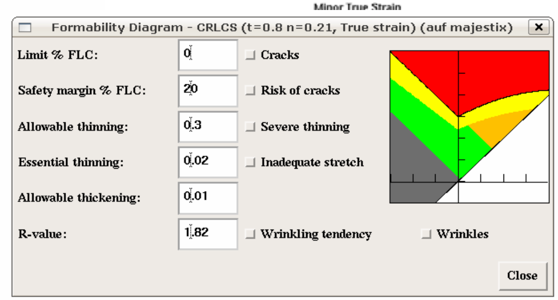
# Evolutionary optimization

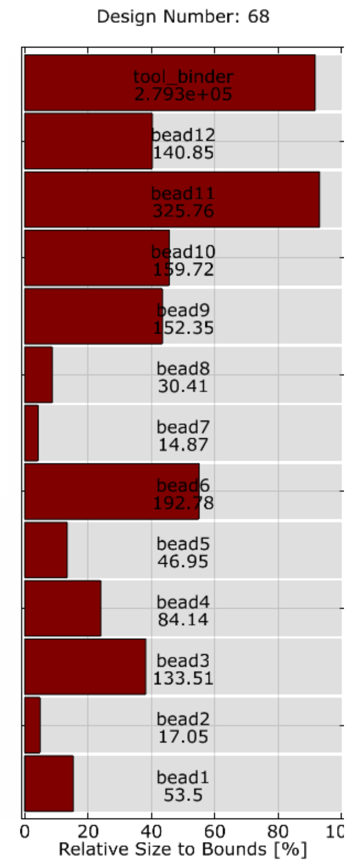
- stop after 80 design evaluations
- max. FLD_crack value =0.68



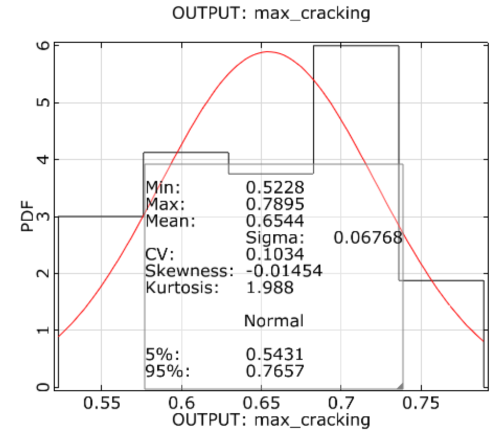



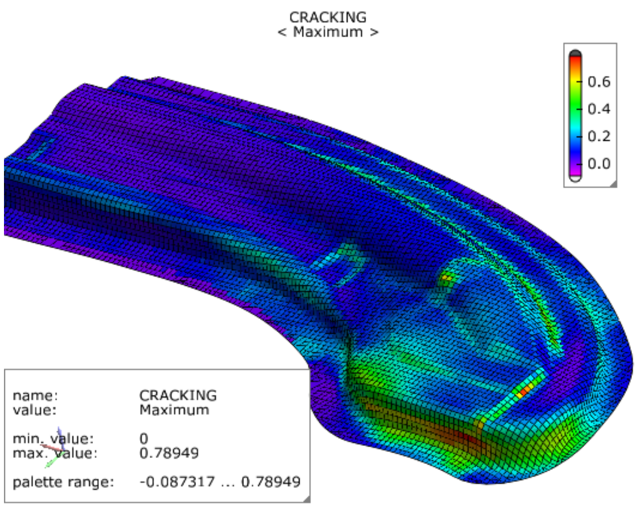
# Robustness Check

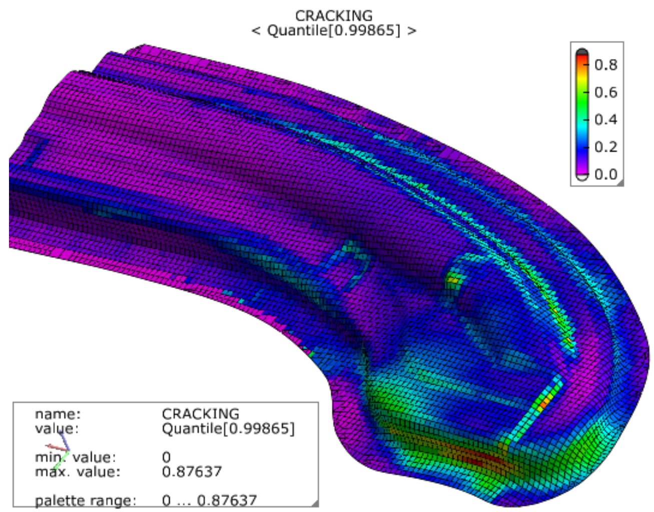
Robustness evaluation for the Design 78_68 (max. FLD_crack=0.68)

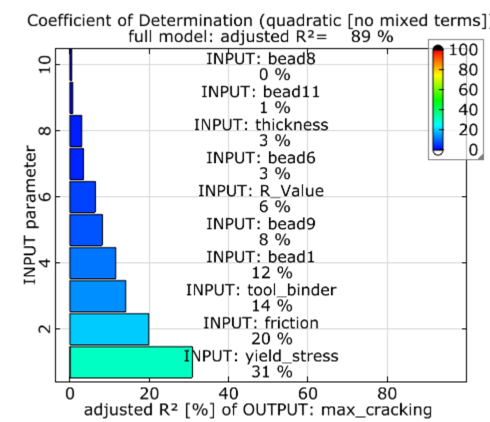
Does the safety distance ensure Robustness ??

- no failure within 50 design realizations
- max. FLD_crack value =0.80
- max. 3-Sigma FLD_crack value =0.88



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# Example Iterative RDO procedure (300 solver runs)

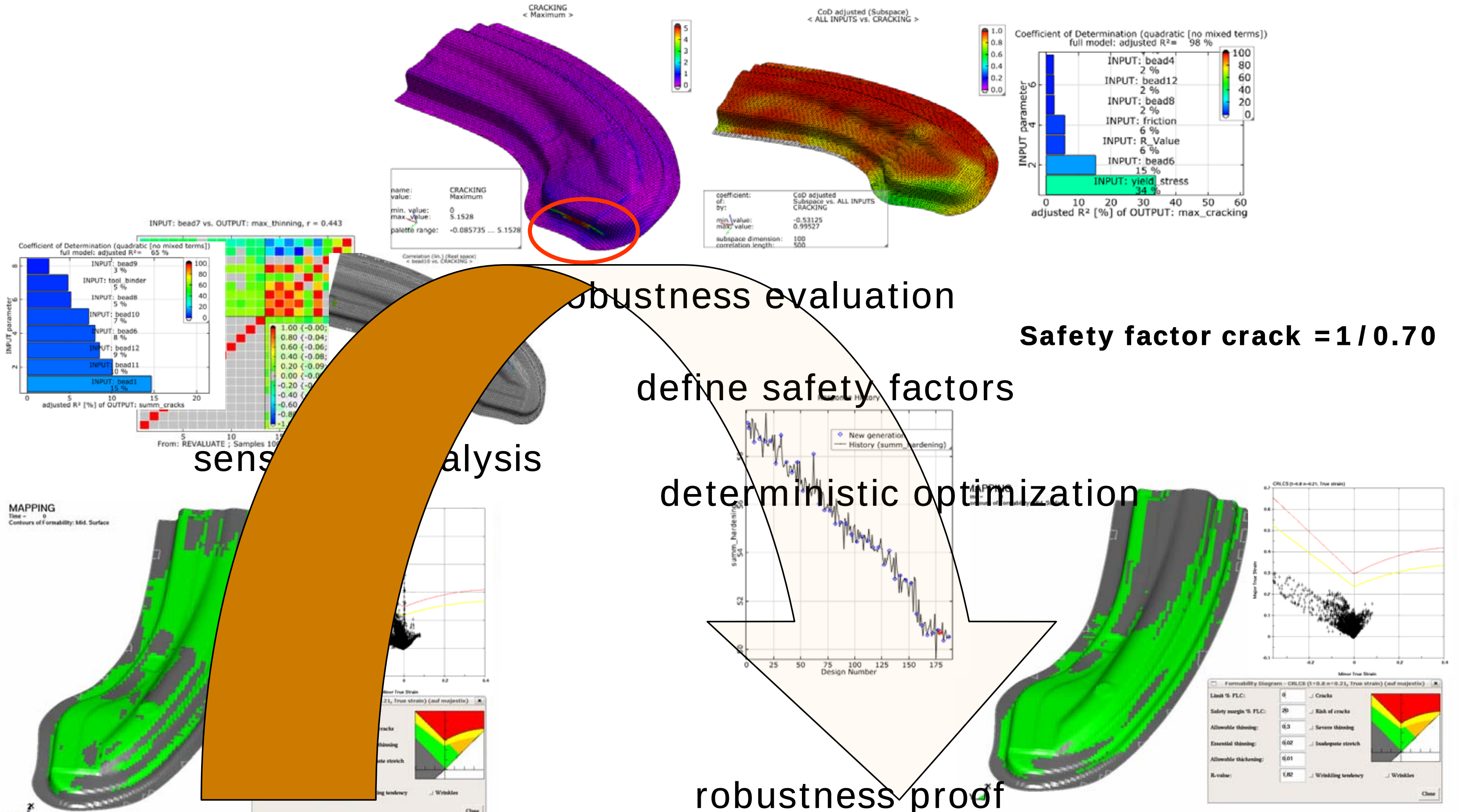


Figure: FLD plot and diagram start design

Figure: optimized robust final design



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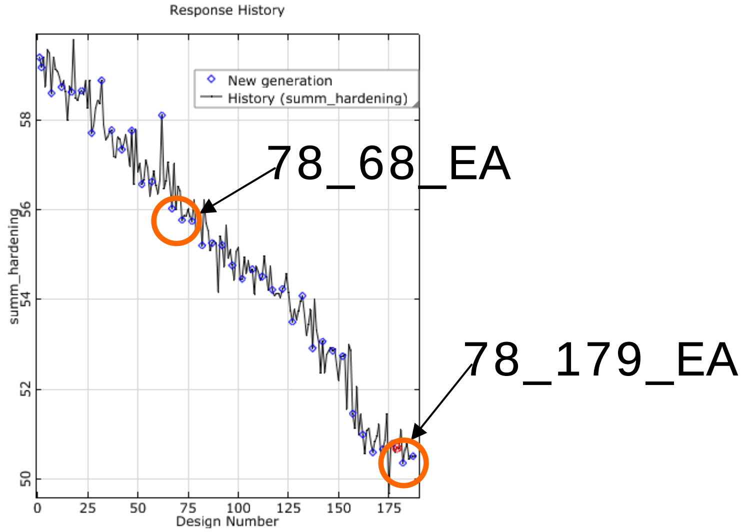
# How robust is the iterative RDO procedure?

| Design | maximum FLD_crack optima candidate | Robustness evaluation FLD_crack value |
|---|---|---|
| 78_sensitivity | 0.73 | 6 % failure |
| 78_68_EA | 0.68 | no failure at 50 designs<br>max. FLD_crack=0.80<br>max. 3Sigma value=0.88 |
| 78_179_EA | 0.70 | 19 % failure |
| 78_200_ARSM | 0.64 | 23 % failure |
| 54_58_EA | 0.685 | 50% failure |

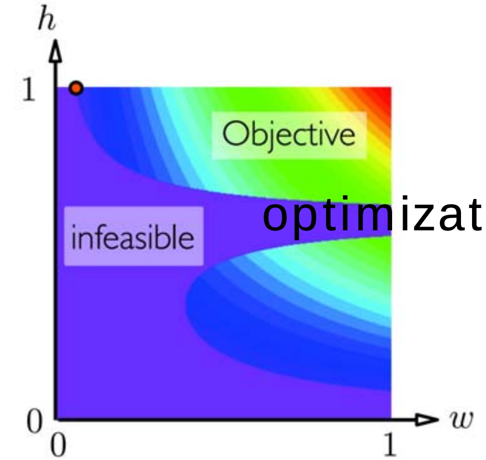
- effect is highly nonlinear
- no “constant” safety distance



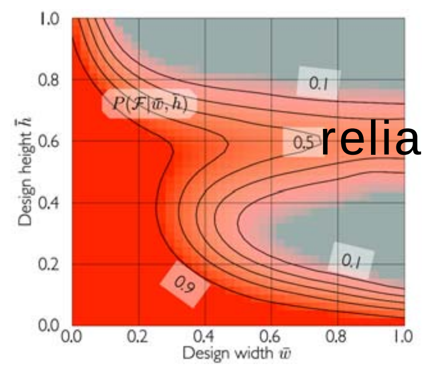
# (simultaneously) RDO methodology

Because of the highly nonlinear robustness behaviour an automatic Robust Design Optimization procedure with simultaneously dealing with optimization and reliability domain is the final dream.

Because RDO simultaneously deals with optimization and robustness analysis computational effort becomes very high. Therefore the challenge in applying RDO is to find a payable balance between effort and reliability of the robustness measurements.




Co-simulation of optimization and reliability analysis like doing a Latin Hypercube Sampling for every optimization design is possible, but the effort multiplies.



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# RDO (EA/LHS)

Spending 330 runs using EA/LHS

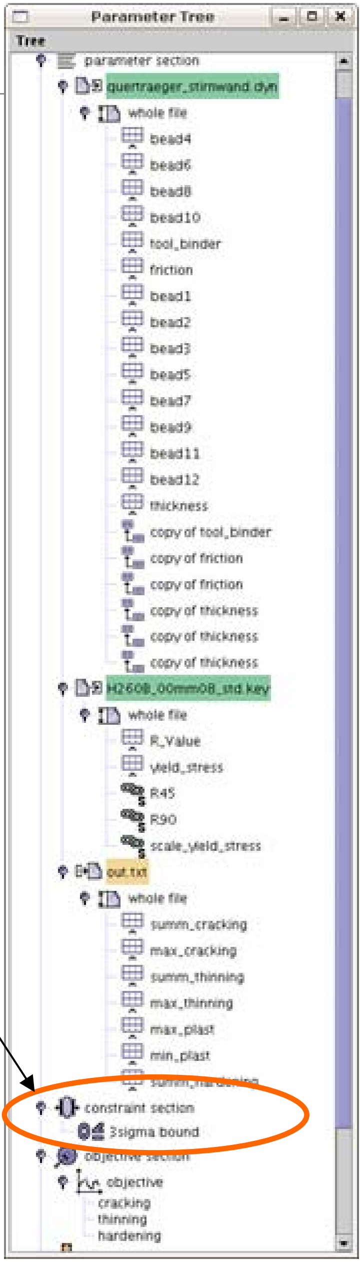
That approach try to automate the manual iterative process

RDO using evolutionary alrorithm in the optimization domain and Latin Hypercube Sampling in Robustness is used.

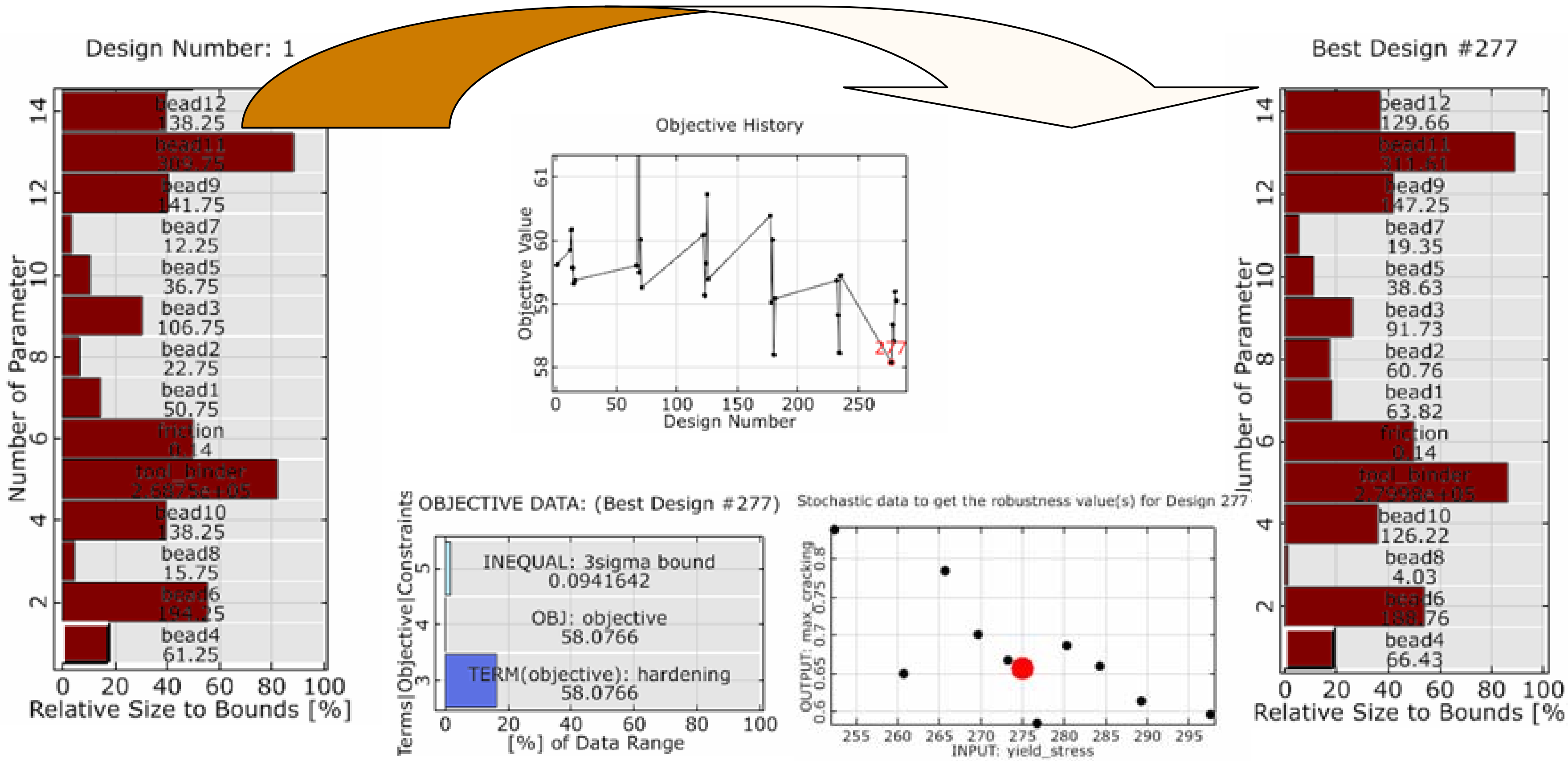
Robustness within the optimization is introduced using a 3-sigma-bound at the max. crack value. The 3-sigma bound is checked with estimation of standard variation using 10 LHS samplings.

Start Design of optiSLang evolutionary Design Improvement is Design_78_Sensitivity

(6 Generations =6*5*11 LHS=330)



# RDO (EA/LHS)




After 6 generations the objective is improved from 59.6 auf 58.08 with a deterministic max. cracking value of 0.656 and a estimated 3-sigma-value of 0.90.



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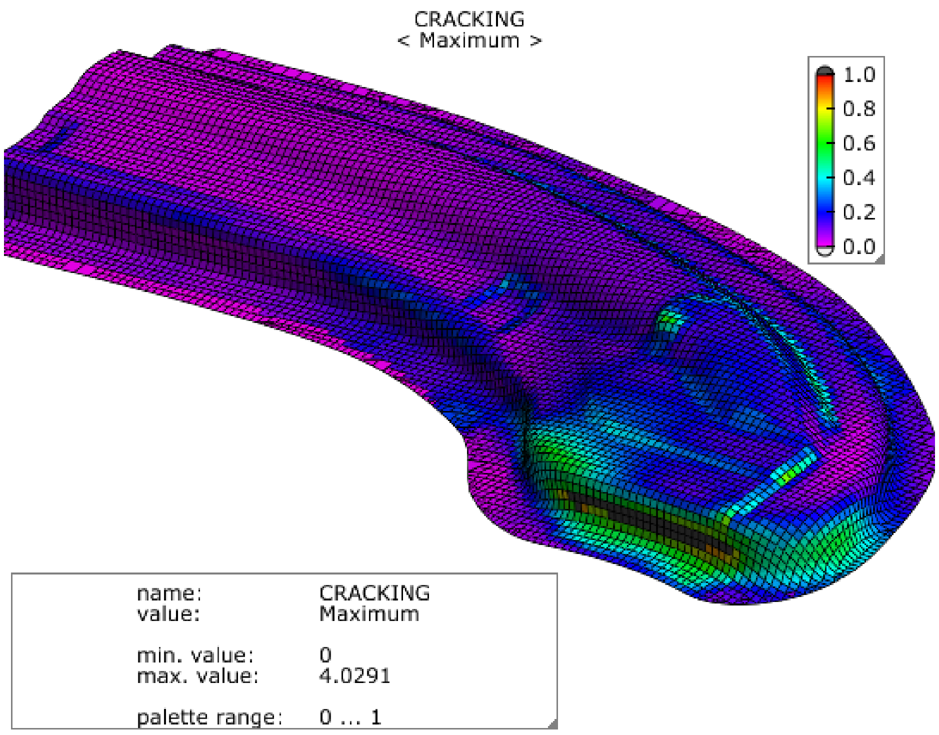
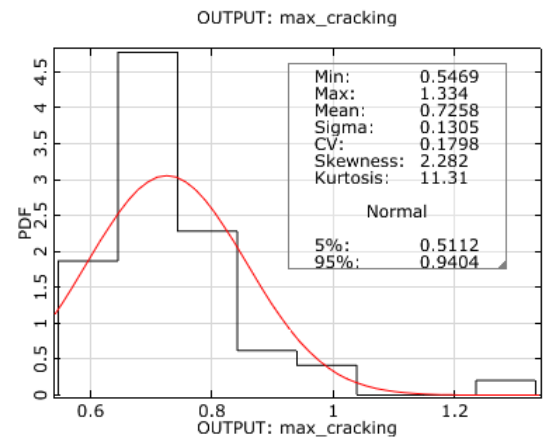
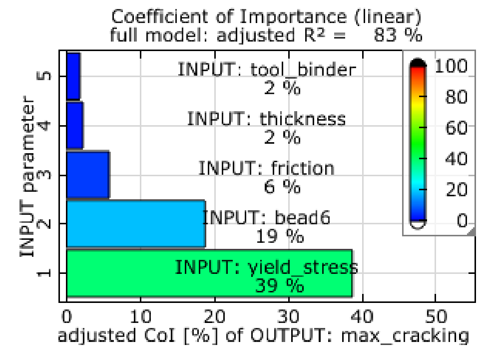
# Robustness Check

Robustness evaluation for the Design 78_RDO_233 (max. FLD_crack=0.68)

- two failure within 50 design realizations (4% failure)
- max. FLD_crack value > 1.00



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# RDO (adaptive RSM/LHS)

Spending 300 runs using ARSM/LHS

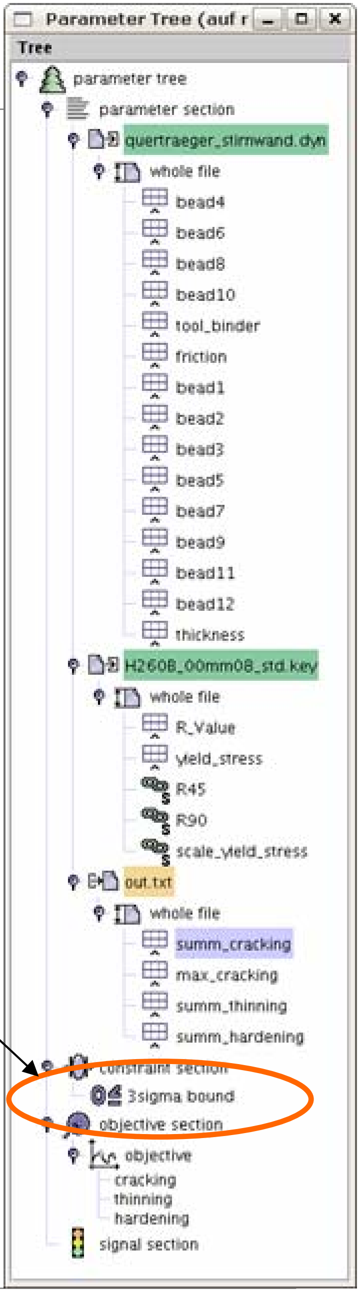
Using the experience from the sensitivity study and the deterministic optimization we reduce the design space of optimization to 5 variables (4 beads and the tool binder).

RDO using adaptive (local) RSM in optimization domain and Latin Hypercube Sampling in Robustness is used.

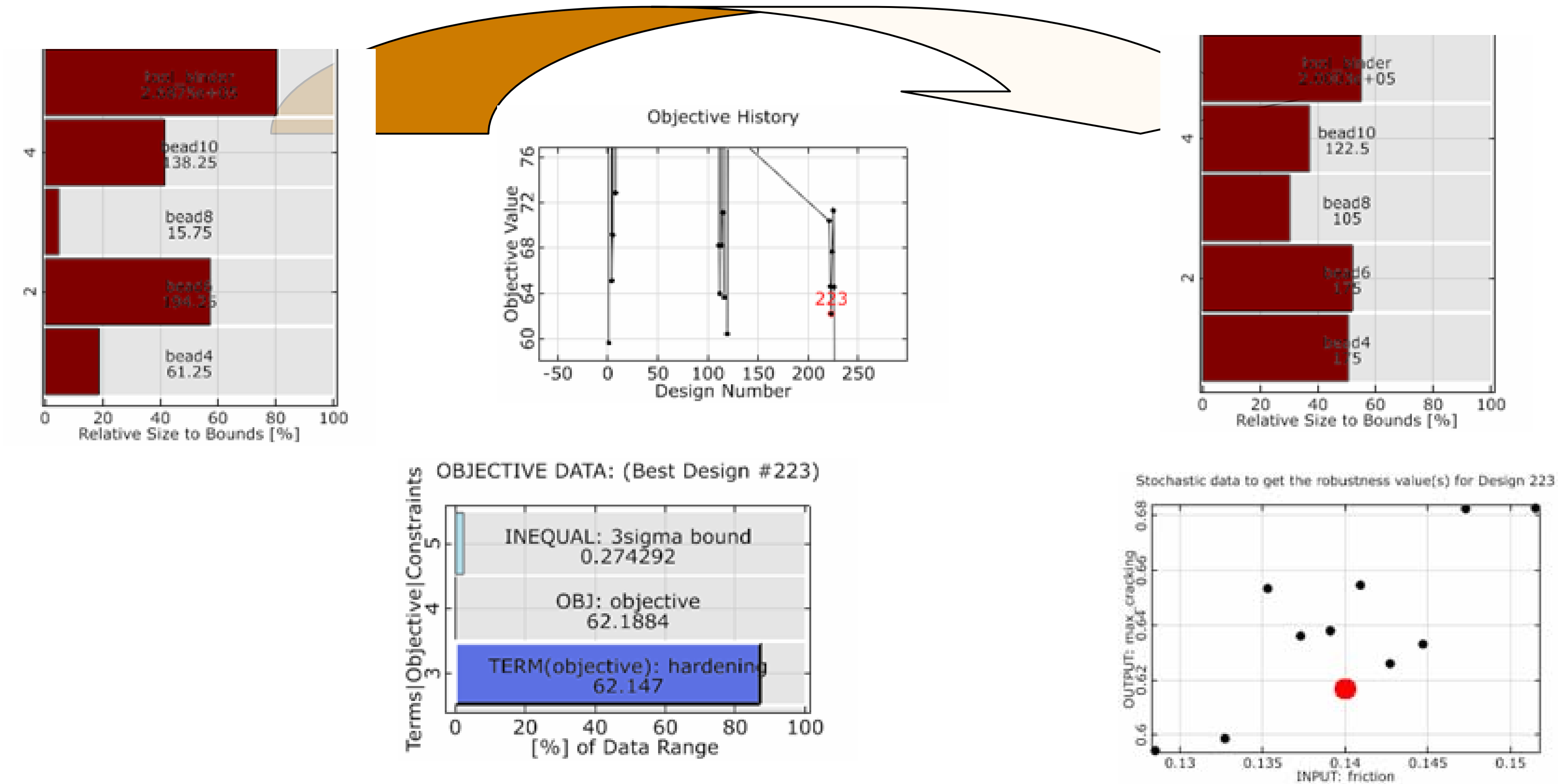
Robustness within the optimization is introduced using a 3-sigma-bound at the max. crack value. The 3-sigma bound is checked with estimation of standard variation using 10 LHS samplings.

With that strategy 3 RSM Iterations are possible!

(3 Iterations*10 optimal DOE *11 LHS=330)



# RDO (adaptive RSM/LHS)

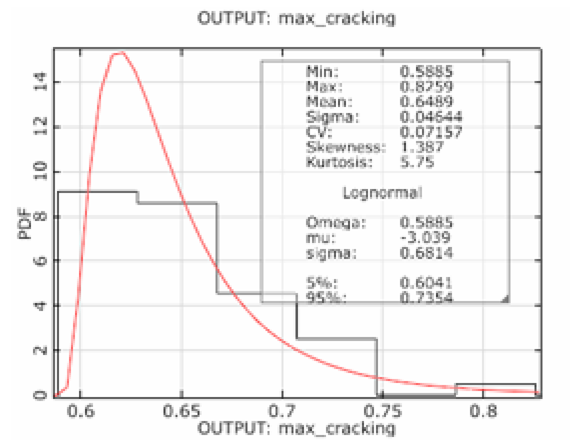


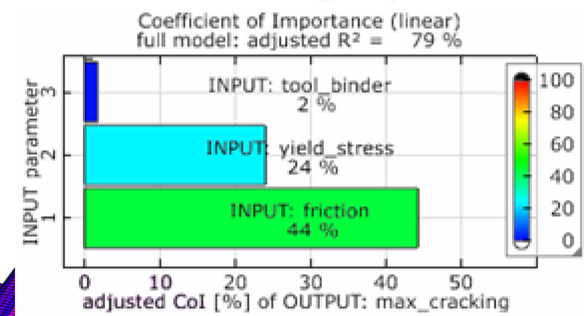

After three iterations the objective is increased from 59.6 auf 62.15 with a deterministic max. cracking value of 0.62 and a estimated 3-sigma-value of 0.73.

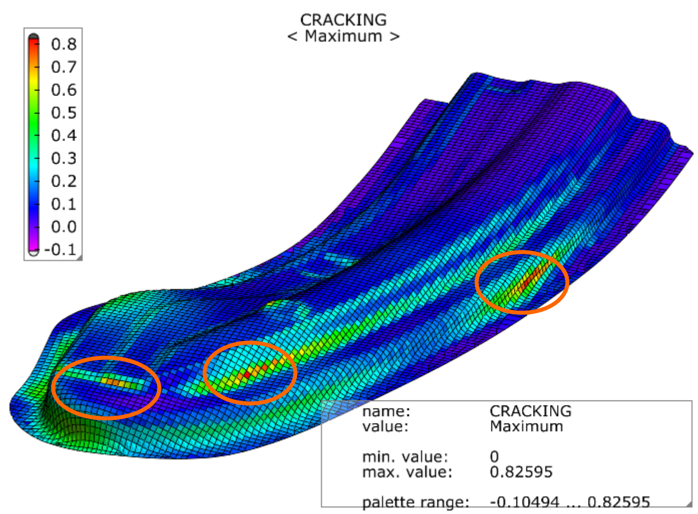
# Robustness Check

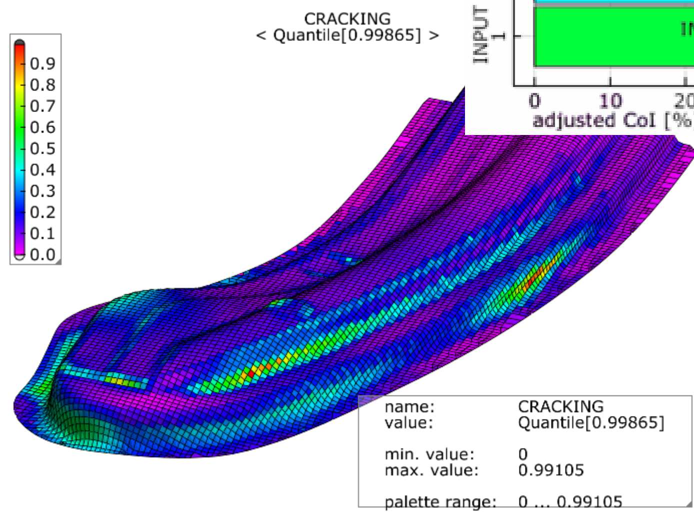
Robustness evaluation for the Design 78_RDO_233 (max. FLD_crack=0.68)

- no failure within 50 design realizations
- max. FLD_crack value =0.83
- max. 3-Sigma FLD_crack value =0.99
- scatter of process forces insignificant for FLD scatter
- highest FLD-values now at different locations



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# How robust is the automatic RDO procedure?

| Design | Deterministic max. FLD_crack | Summ Hardening | 3-Sigma-Bound | Failure at Robustness Check using 50 LHS | Number of Solver Runs |
|---|---|---|---|---|---|
| **Sensitivity Analysis** | | | | | |
| Design_78_Sensitivität | 0.73 | 59.6 | -- | 6 % | 200 |
| **iterative RDO procedure using safety distance** | | | | | |
| Design_68_EA | 0.68 | 58.62 | 0.88 | 0 % | 320 |
| Design_179_EA | 0.70 | 52.29 | -- | 19 % | 430 |
| Design_200_ARSM | 0.64 | 53.68 | -- | 23 % | 450 |
| **automatic RDO procedure using 3-sigma-bounds** | | | | | |
| Design_RDO_223_ARSM_LHS | 0.68 | 62.15 | 0.99 | 0 % | 530 |
| Design_RDO_277_EA_LHS | 0.656 | 58.08 | 0.92 | 4 % | 530 |

- robustness evaluation of final designs very important
- the 3-sigma-bound (estimated with 11 LHS) was not sufficient
- challenge of RDO is the balancing of improvement (optimization) and level of reliability (robustness)

# Summary

- Sensitivity Study and Robustness evaluation are very helpful to define and run a iterative or simultaneously RDO
- In practical applications the design space and robustness space are different with some overlap

- Effort for iterative RDO high (300-500 runs)
- Effort for simultaneously RDO higher effort >500

- Improvement of RDO algorithms regarding number of runs and reliability/robustness measurements still necessary
- Balance of most efficient optimization algorithms in reduced design spaces combined with sufficient robustness measurements promising

- Robustness evaluation of the final design absolutely necessary