Sensitivity analysis of forming process parameters regarding the shape accuracy of single and assembled parts

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The best or nothing.

Outline

1. Motivation

2. S-rail forming and joining process chain – sensitivity analysis and optimization

3. Results of the analysis of forming process parameters – sensitivity and RDO

4. Optimization of framing station parameters

5. Enhancement of the optimization possibilities using SOS

6. Summary and Outlook

1. Motivation

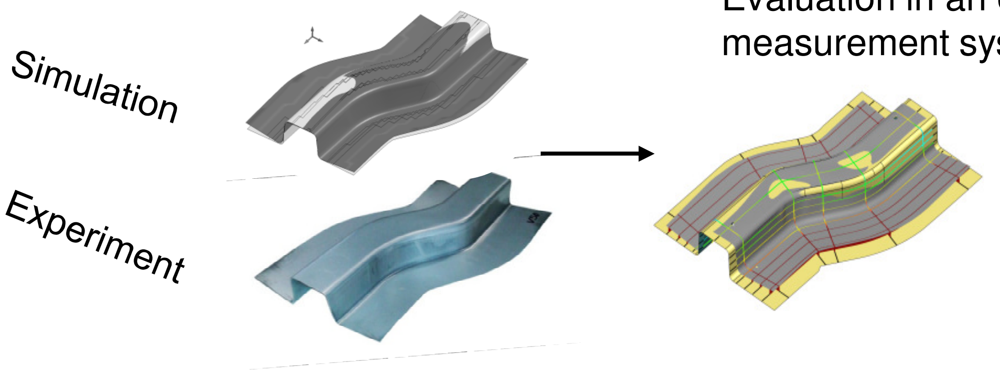
Analysis of the shape accuracy of single and assembled parts

Analyzing the dimensional accuracy of process chains

Aim: Shortening of product development cycles and prediction of the dimensional accuracy at an early product development stage

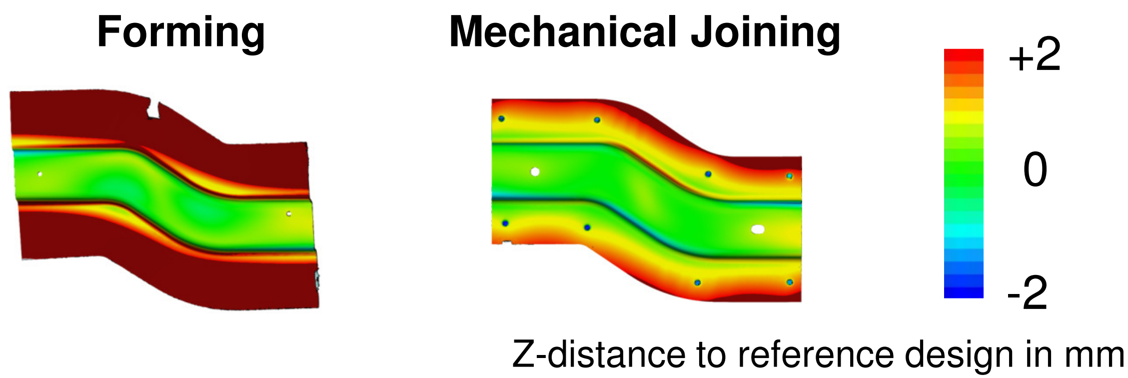
→ Simulative investigations instead of an hardware phase

Evaluation parameters dimensional accuracy



- X, Y, Z-Displacement
- Sheet Thickness

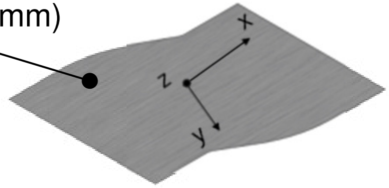
Dimensional accuracy after different process chain steps



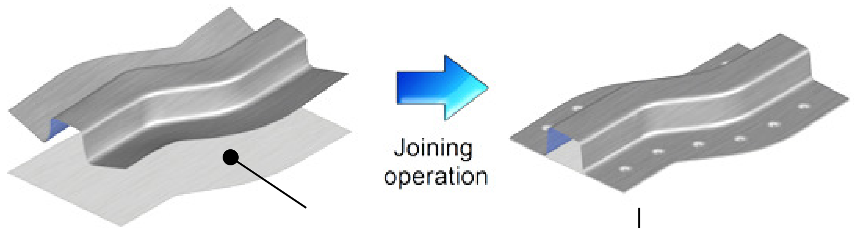
2. S-rail forming and joining process chain

Analysis of the sensitivity of forming (and joining) parameters

Outer part (1.0 mm)
AA 6014



Deep drawing operation



Joining operation

Inner part (1.0 mm), AA 6014

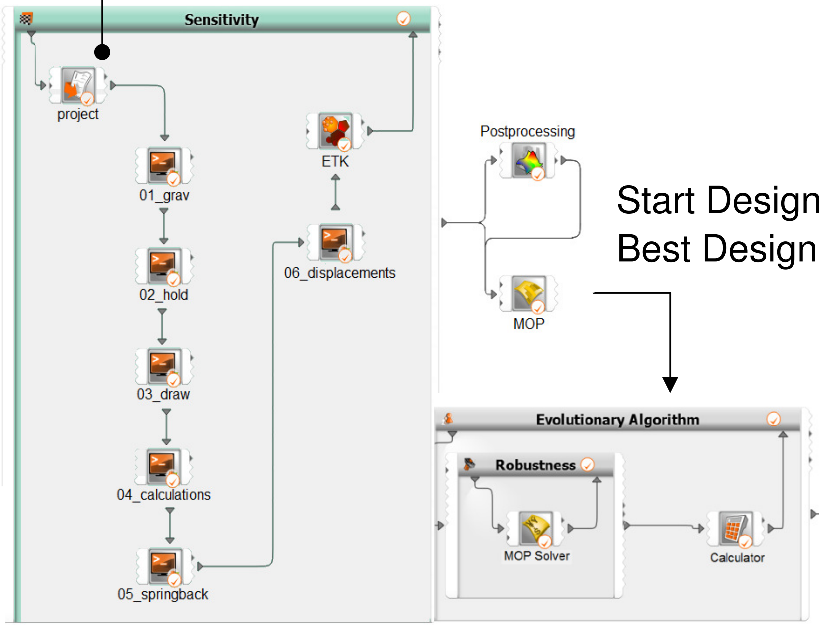
Blank thickness tblank : 0.95 – 1.05 mm

Blank translation (x/yvers): -10 to 10 mm

Blankholder forces bf4: 30 kN – 150 kN

Clamps: X, Y- und Z-position of the 6 clamps

Clinching points: X- and Y-position

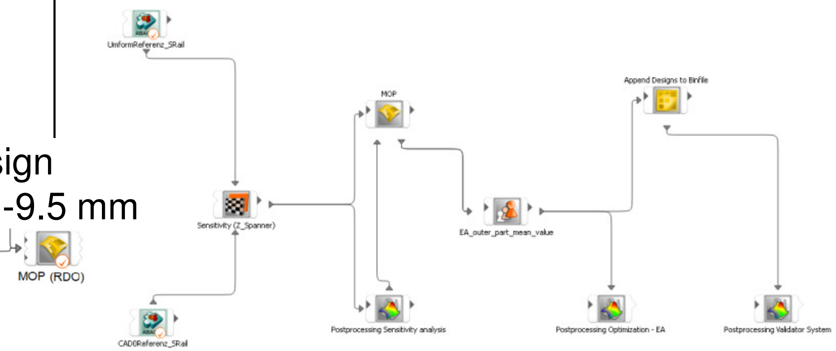


Start Design = Best Design

Best Design x/yvers= -9.5 mm

Sensitivity analysis of the joining conditions

Sensitivity analysis of the clamping conditions



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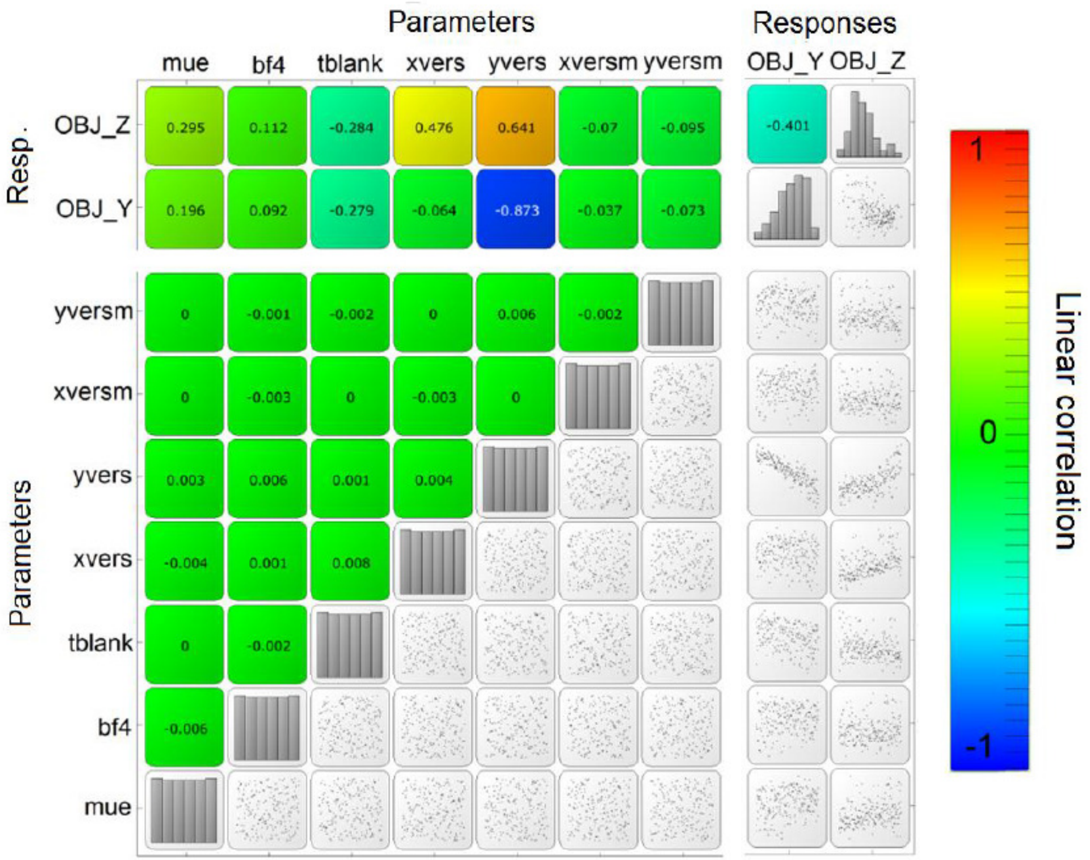
3. Results of the analysis of forming parameters

OptisLang results - Linear correlation matrix



<u>Definition of the objectives:</u>

Value = Mean value x standard deviation

↓

OBJ_x : ***value*** of all nodes' displacement in x-direction

OBJ_y : value of all nodes' displacement in y-direction

OBJ_z : value of all nodes' displacement in z-direction

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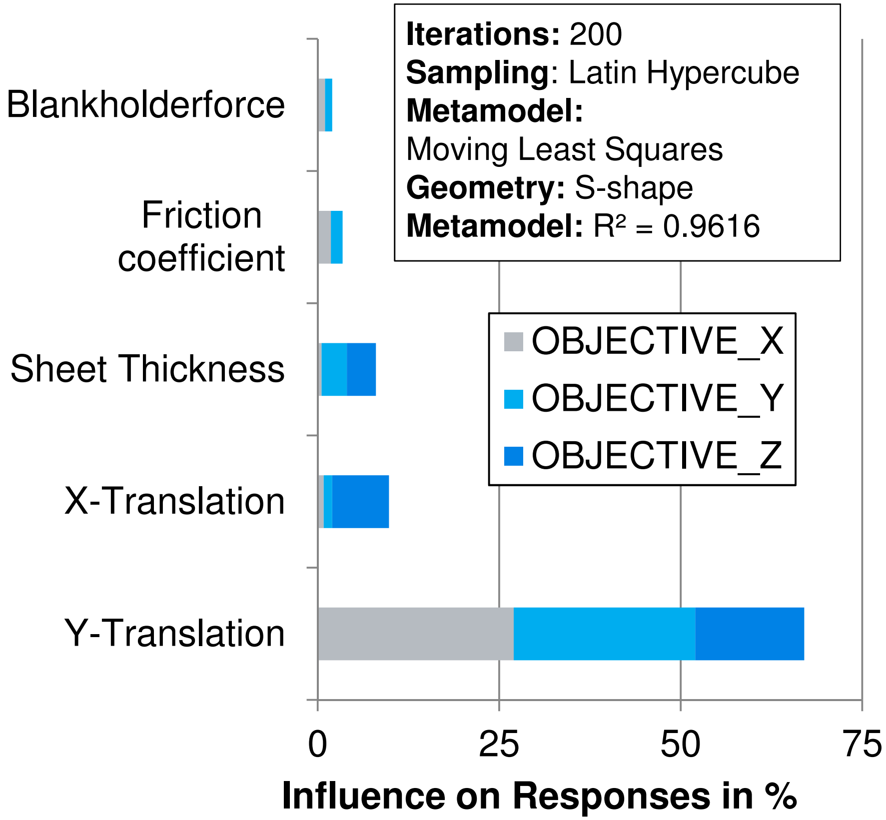
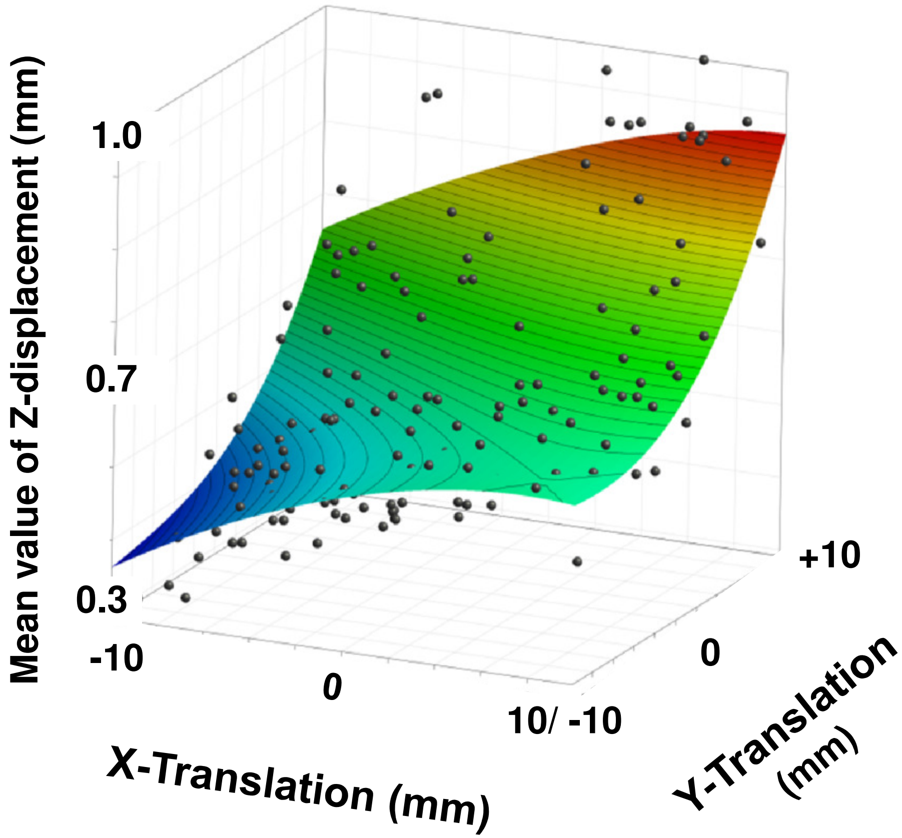
- ➢ The influence of y-translation has a comparatively higher influence on the OBJ_Y (-0,873) compared to its influence on the OBJ_Z (0,641)
- ➢ Blankholder force (bf4) and the friction coefficient (μ left out for the **Robust Design Optimization)**

3. Results of the analysis of forming parameters

OptisLang results– Global Sensitivities and metamodel





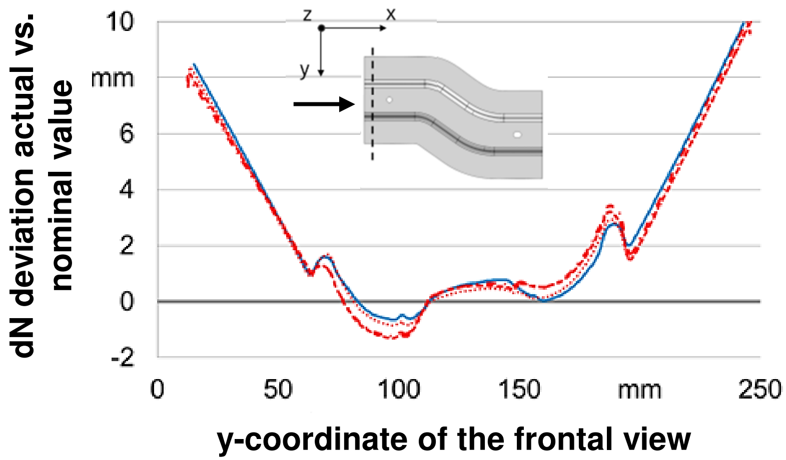
- Y-Translation in reference to its initial plate position with highest influence on x-, y- and z-displacement
- 89 % of the parameter influence on the nodal displacements dedicated by three control / noise variables

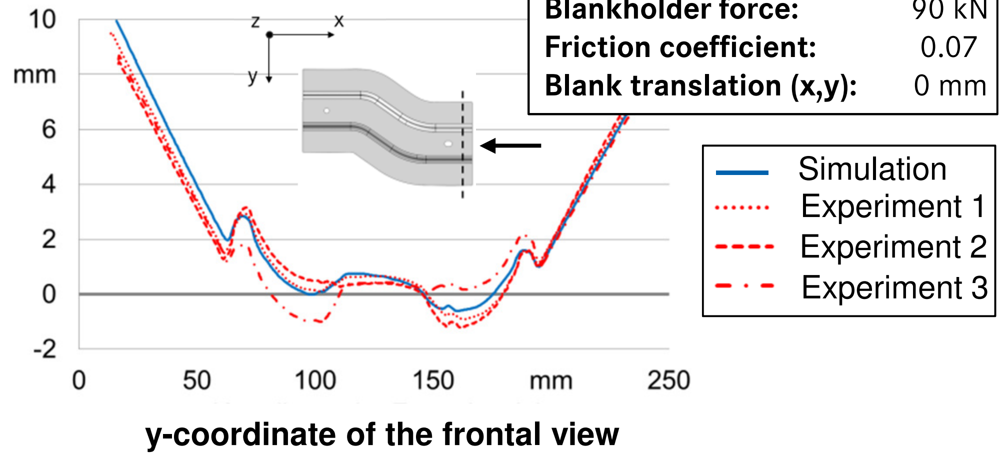
3. Results of the analysis of forming parameters

Comparison of simulation and experiments

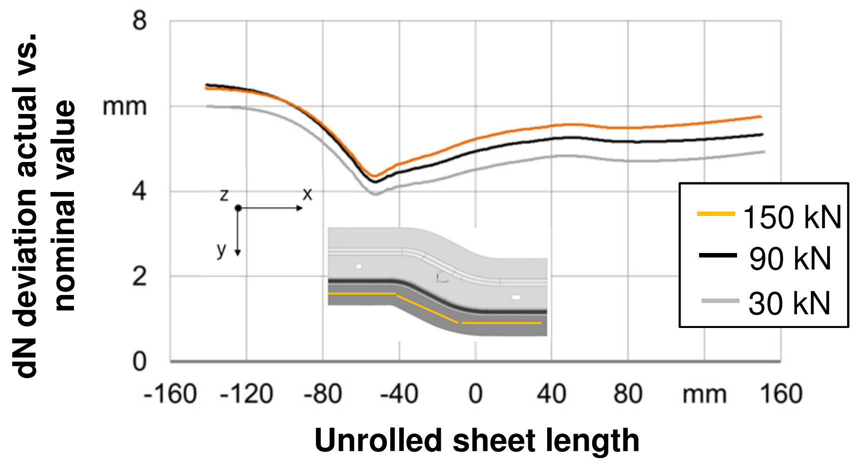
Material	AA 6014
Shape:	S-Form (A)
Thickness outer part:	1.0 mm
Blankholder force:	90 kN
Friction coefficient:	0.07
Blank translation (x,y):	0 mm

Deviation between simulation and experiment:

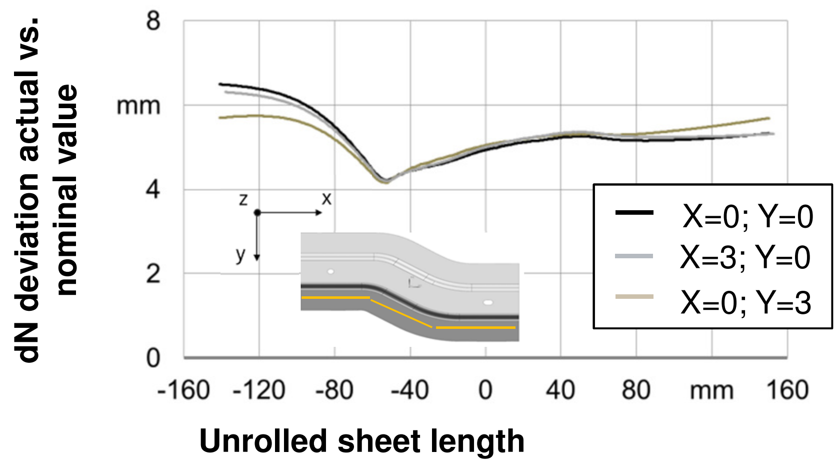




Blankholder forces:



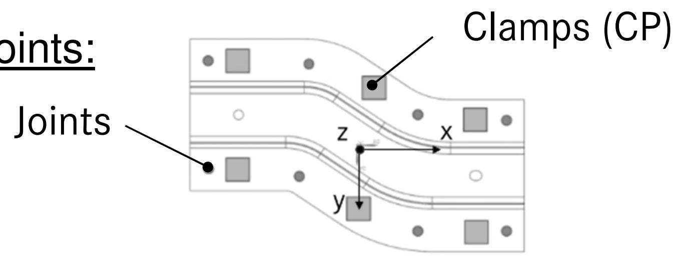
Initial blank x-y-positions:

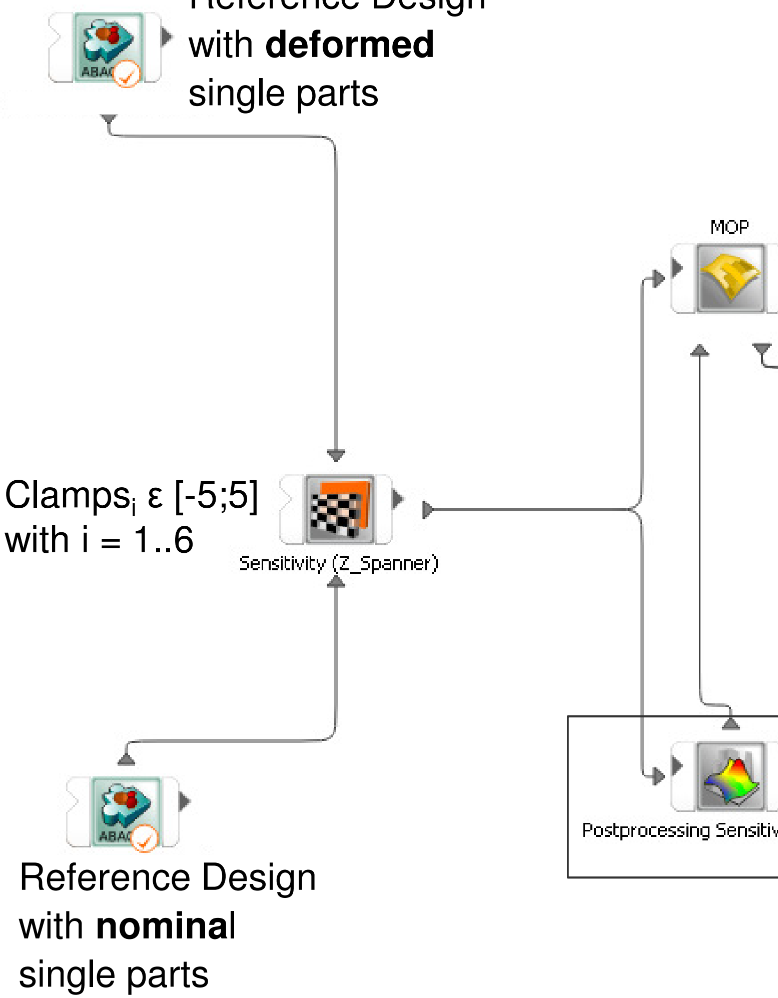


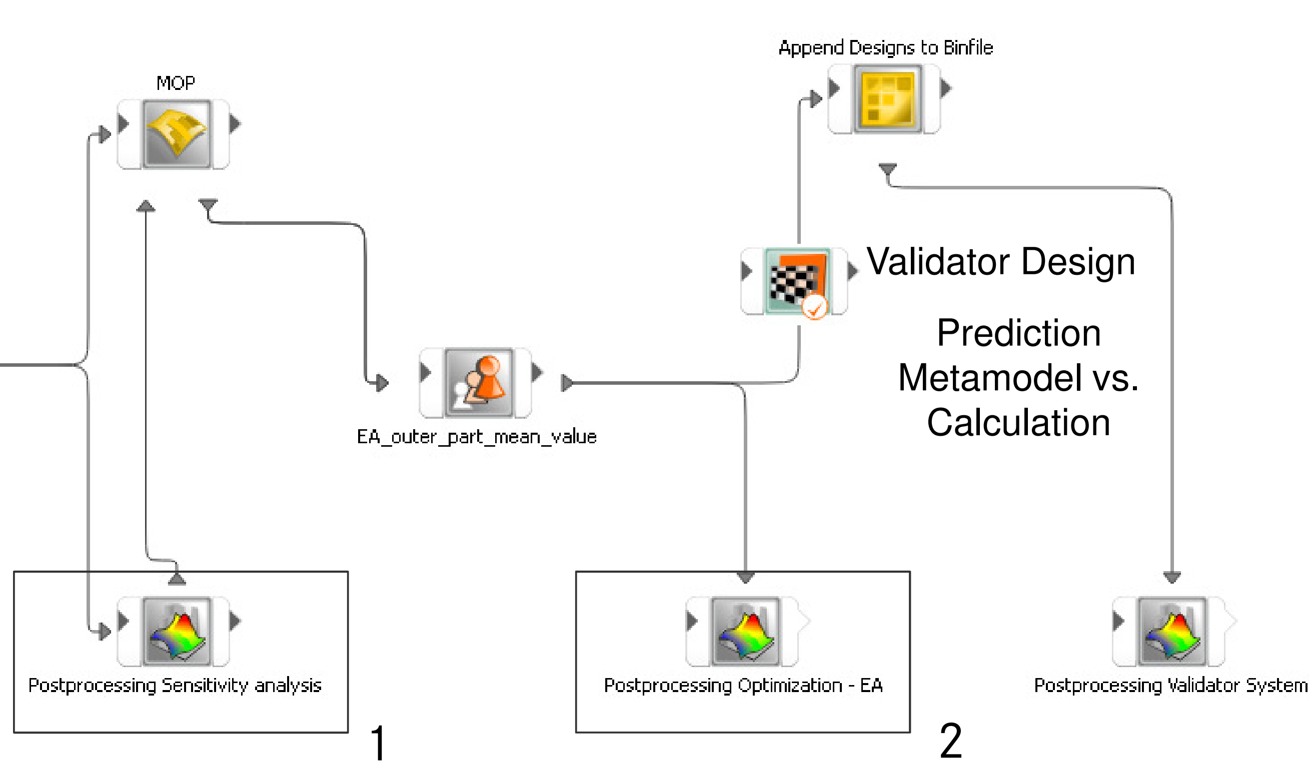
4. Optimization of framing station parameters

Sensitivity analysis and optimization of framing station parameters

<u>Model with parametrized clamps and joints:</u>

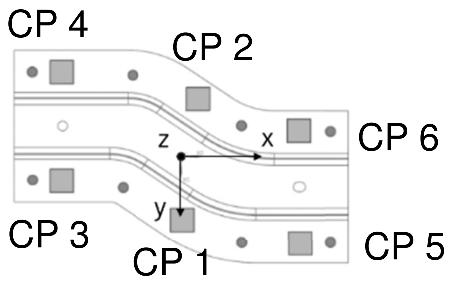






4. Optimization of framing station parameters

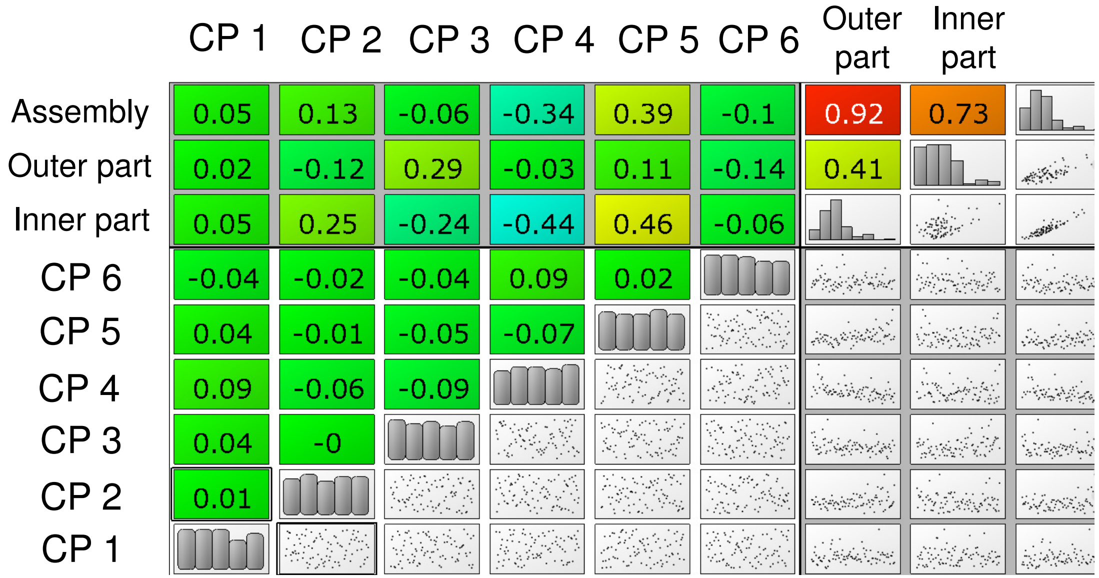
Sensitivity results of z-positions of the clamps



Varied parameter space:

Six z-positions of the clamps (# CP = clamping sequence)

Linear correlation matrix:



Metamodel - CoP:

	CP1	CP2	CP3	CP4	CP5	CP6	Total
Outer part	7.6	9.0	37.5	36.5	21.4	34.4	**84.6**
Inner part	0	4.5	28.6	21.6	26.8	32.3	**82.9**

4. Optimization of framing station parameters

Optimization objectives and results

Objectives (according to the Euclidian Norm:)

Objective scalar value **a** = **min** $\frac{1}{\dim(R^n)} \sqrt{\left\{ \begin{pmatrix} node\ 1_z \\ node\ 2_z \\ node\ i_z \end{pmatrix} + \begin{pmatrix} u\ 1_z \\ u\ 2_z \\ u\ i_z \end{pmatrix} - \begin{pmatrix} node\ 1^*_z \\ node\ 2^*_z \\ node\ i^*_z \end{pmatrix} \right\}^2}$

Annotations:

node 1_z : z-Coordinate joining deformed meshes

u 1_z : z-displacement of the node

node 1^*_z : z-Coordinate joining nominal meshes

Optimization strategies:

- Evolutionary algorithm for minimizing *a* for the **whole** outer part (OP) ("OP all")
- Evolutionary algorithm for minimizing *a* for the **right and left flanges** of the outer part ("OP right-left")

Optimization results

Reference

Notation	Z-value [mm]
CP1	0
CP2	0
CP3	0
CP4	0
CP5	0
CP6	0

EA - "Outer part all"

CP1	CP2	CP3	CP4	CP5	CP6
-1.4	-1.5	-4.5	-5.0	1.6	1.9

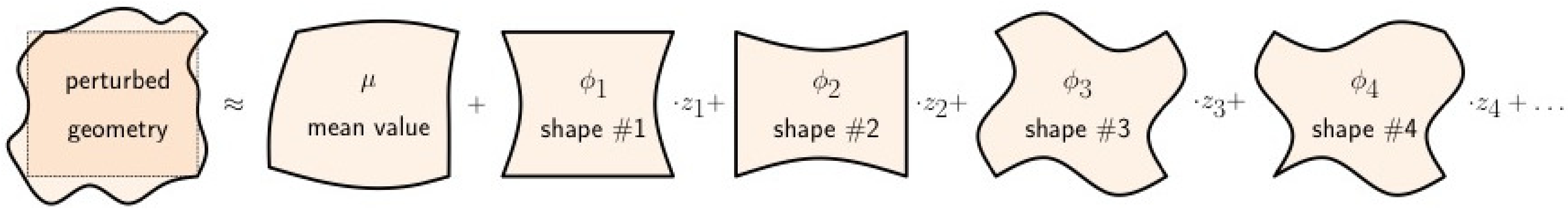
EA -"Outer part right-left"

CP1	CP2	CP3	CP4	CP5	CP6
-0.7	-4.1	1.7	-0.9	1.1	-4.1

5. Enhancement of the optimization possibilities using SoS – Random Field Model

Approximation of a **random design** with

- mean value + standard deviation of the nodes' displacement **(x, y, z and normal direction)**
- linear combination of deterministic "scatter shapes" multiplied with random coefficients ("amplitudes")

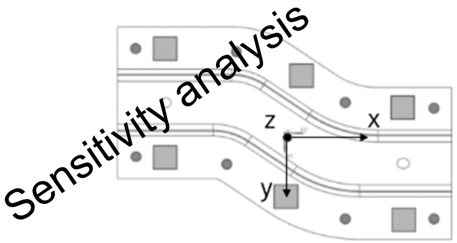


Accurately resembles

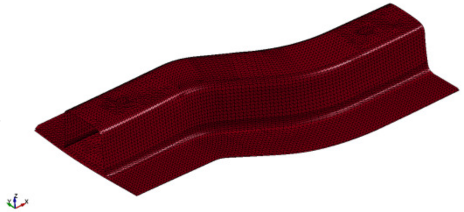
- Statistical moments (mean, standard deviation…)
- Spatial correlations (anisotropic, inhomogeneous…)

Use in optimization: Representation of field variations as found in DoE; Combination with MOP to approximate field variations based on input parameters

5. Enhancement of the optimization possibilities using SoS – Process flow

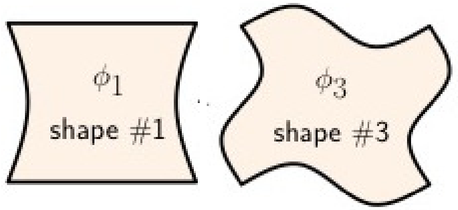


Six z-positions of clamps [-3, 3]



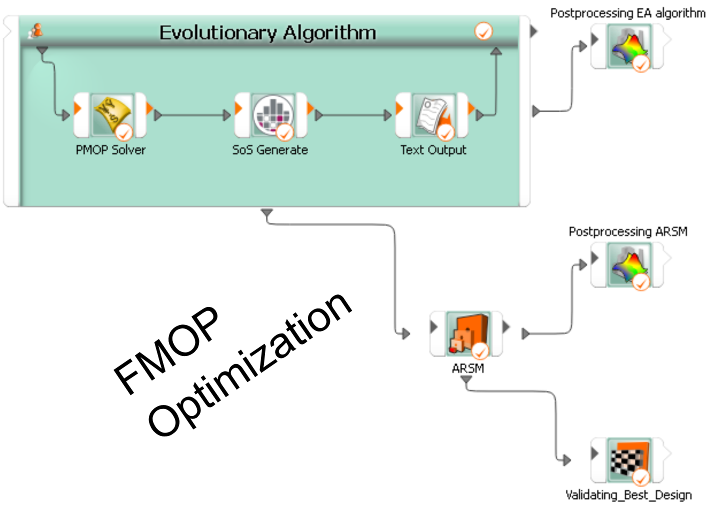
100 deformed meshes (.stl)

1 nominal mesh/assembly (.stl)



Generation of shapes

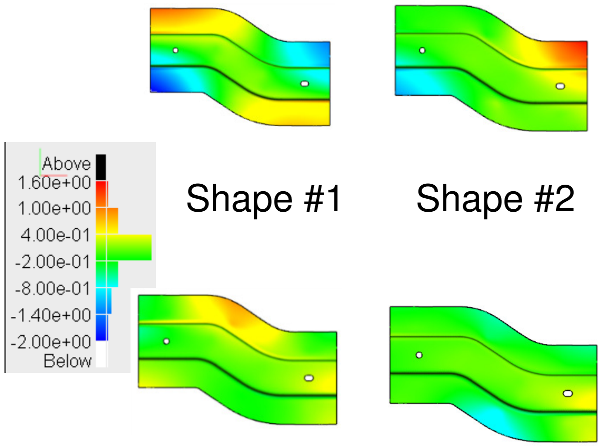
Statistical moments



Coordinate deviation in normal direction

	CoorDeviation[3]
shape[1]	53.5595 %
shape[2]	78.6645 %
shape[3]	87.7746 %
shape[4]	96.0643 %
shape[5]	98.4415 %
shape[6]	99.298 %
variation	99.298 %

Variation (cumulative)



Shape #3 Shape #4

5. Enhancement of the optimization possibilities using SoS – Results

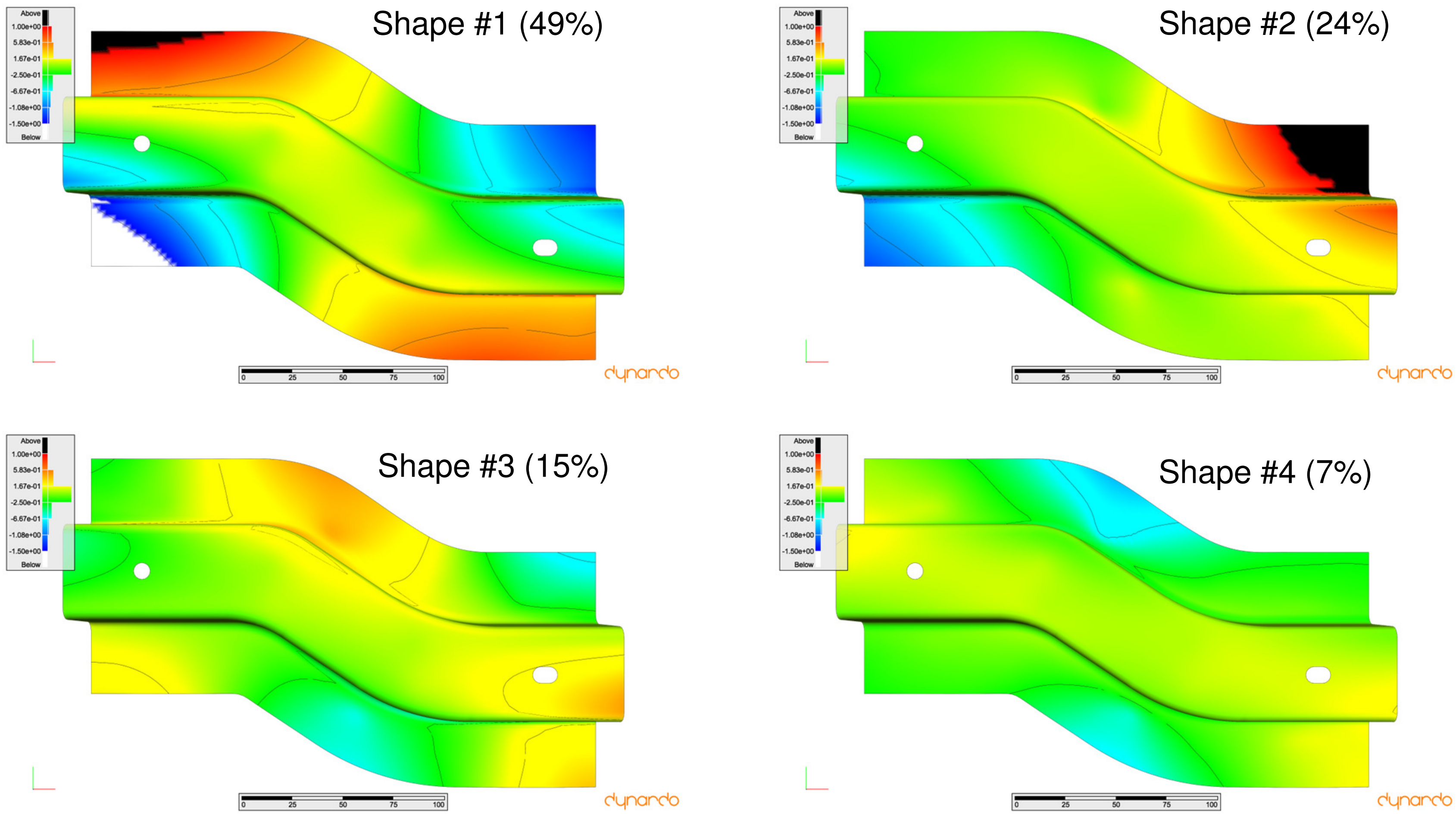
<u>Evaluation possibilities:</u>

[Check plausibility of random field model]

1) Accuracy of CAE process (a priori)
   Analyze how well the CAE process can resemble the target solution
2) Accuracy of F-MOP (a priori)
   Show F-CoP for whole model
   Show and rank F-CoP (sensitivity) of individual input parameters onto different mesh locations
3) Accuracy of F-MOP solution (a posteriori)
   For coordinate deviation, compare prediction of F-MOP with true solution at best design

5. Enhancement of the optimization possibilities using SoS – Results

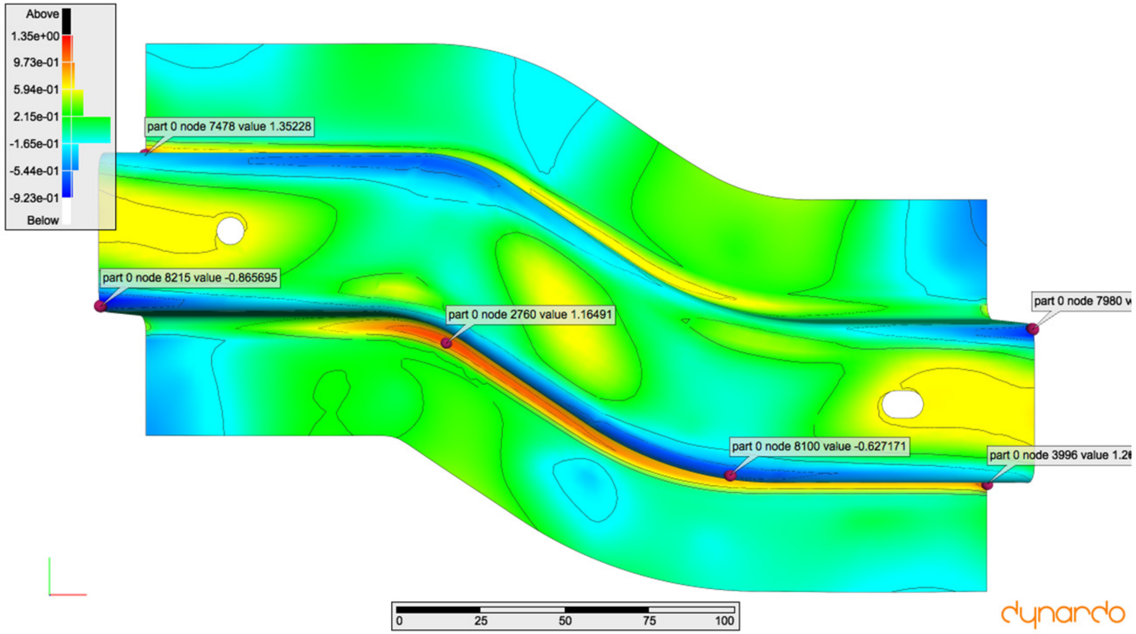
0) Plausibility test of random field model: Check scatter shapes



5. Enhancement of the optimization possibilities using SoS – Results

1) Accuracy of CAE process (a priori)

- Analyze how well the CAE process can resemble the target solution
- Strategy: Analyze the variation shapes found in the DoE and check how well they can represent a zero deviation from the CAD0 geometry



Best possible solution of the CAE process (Z-axis)

Best possible solution:
- maximum positive deviation: 1.35 mm
- maximum negative deviation: -0.93 mm

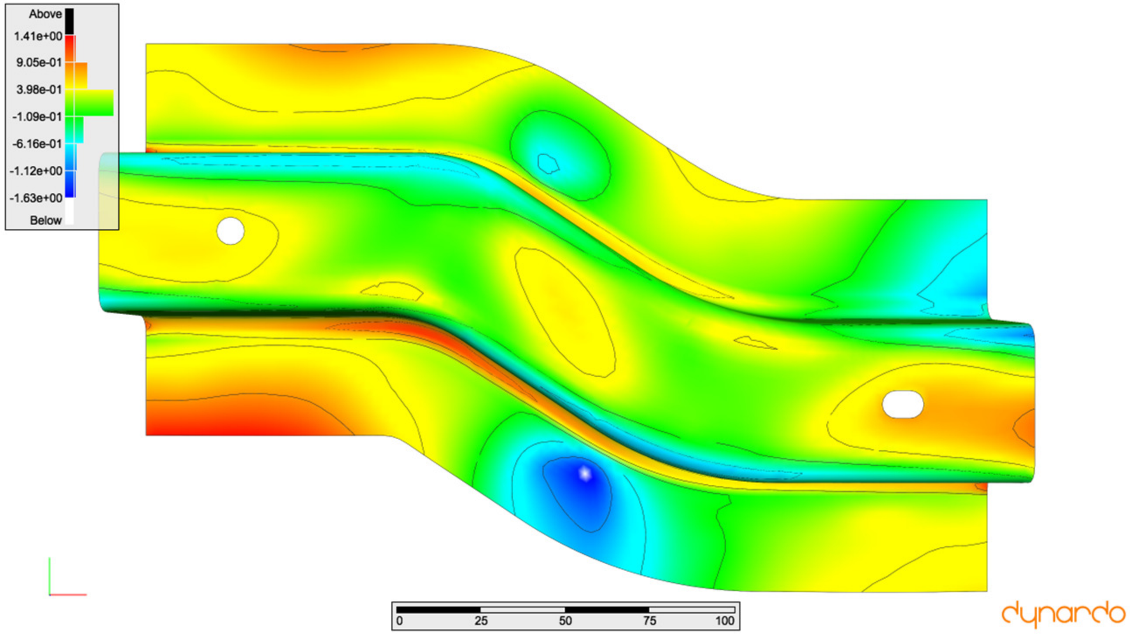
But:
- corresponding random field amplitudes outside of DoE value range
- optimum expected to be worse

5. Enhancement of the optimization possibilities using SoS – Results

1) Accuracy of CAE process (a priori)

Correct amplitude values of zero design to amplitude bounds in DoE

This roughly approximates how well the CAE process can reproduce the target solution within the value bounds of the DoE



Best possible solution of the CAE process (Z-axis)

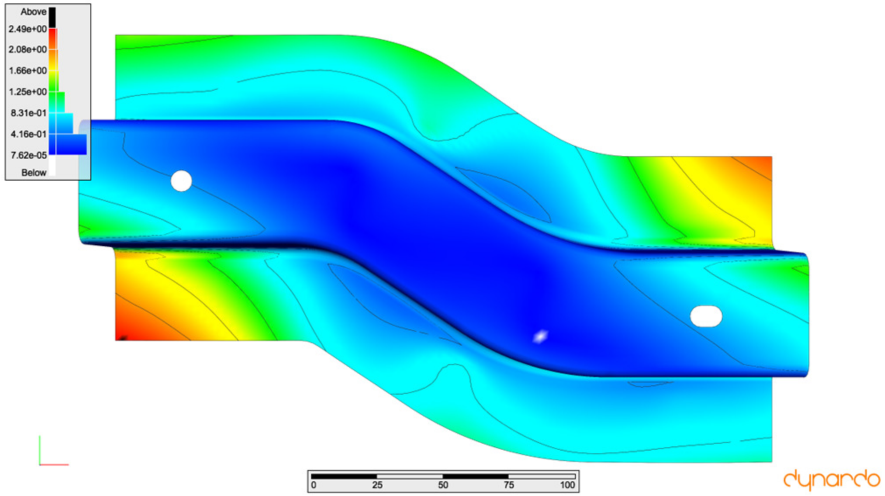
Best possible solution
within DoE value bounds:

- maximum positive deviation: 1.41mm
- maximum negative deviation: -1.63mm

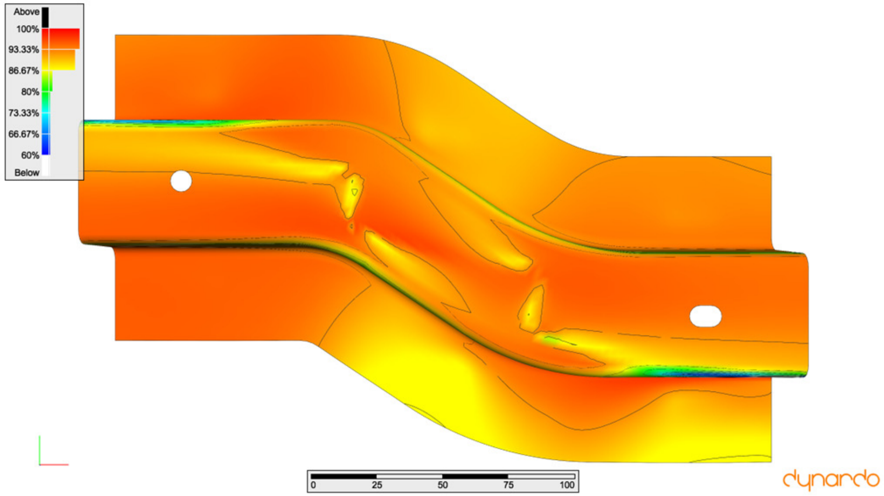
5. Enhancement of the optimization possibilities using SoS – Results

2) Accuracy of F-MOP (a priori)

Standard deviation



F-CoP (Total), average: 94%



F-CoP should be 90-100% at positions of interest, in particular in regions with large variation

May be less at locations that are not critical (e.g. at folds, corners or seams)

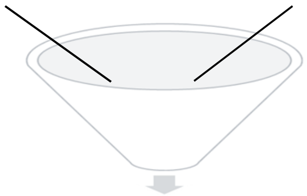
Ergo: suitable for optimization on field meta model

5. Enhancement of the optimization possibilities using SoS – Results

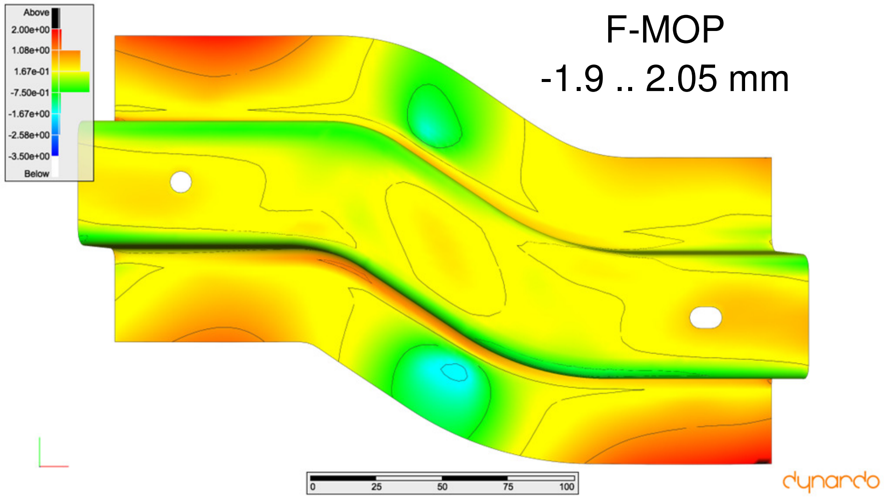
3) Accuracy of F-MOP solution (a posteriori)

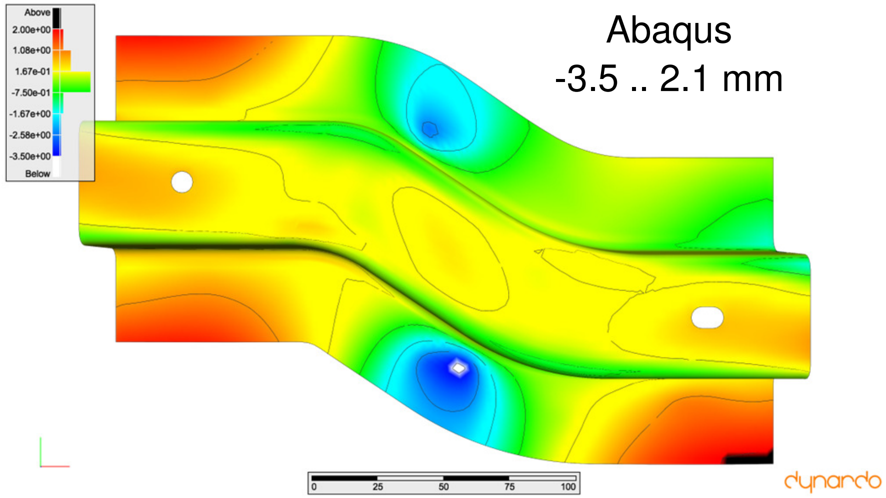
Nominal geometry of the assembly (calculated)

Verification run with best/ optimized design in SoS



Comparison of coordinate deviation along z axis with respect to CAD0 geometry





Discussion: F-MOP underestimates deviation. Most input parameters at DoE value ranges

Changes: 1. Enhance DoE bounds, 2. Direct optimization

6. Summary and Outlook

Summary

- Y-translation of the S-rail plate with a higher influence on the dimensional accuracy compared to the x-translation in simulation and experiment
- Usage of metamodels of the sensitivity analysis (high accuracy) to reduce the calculation times of the Robust Design Optimization of **forming** and **framing station** parameters
- SOS as an enhancement or supplement (vector values / FMOP) → FMOP approximates well qualitative distribution of geometric deviation

Outlook

- Automatic translation and rotation of sheets matching the target geometry
- Robustness analysis with SoS: Analyze influence and sensitivity of uncertain input parameters onto joining process

→ Uncertain a) clamp positions

b) initial geometries resulting from deep drawing process