



Dynamore Express



Robustness in (Sheet) Metal Forming with LS-OPT

Mathias Merten, Katharina Liebold

DYNAmore GmbH

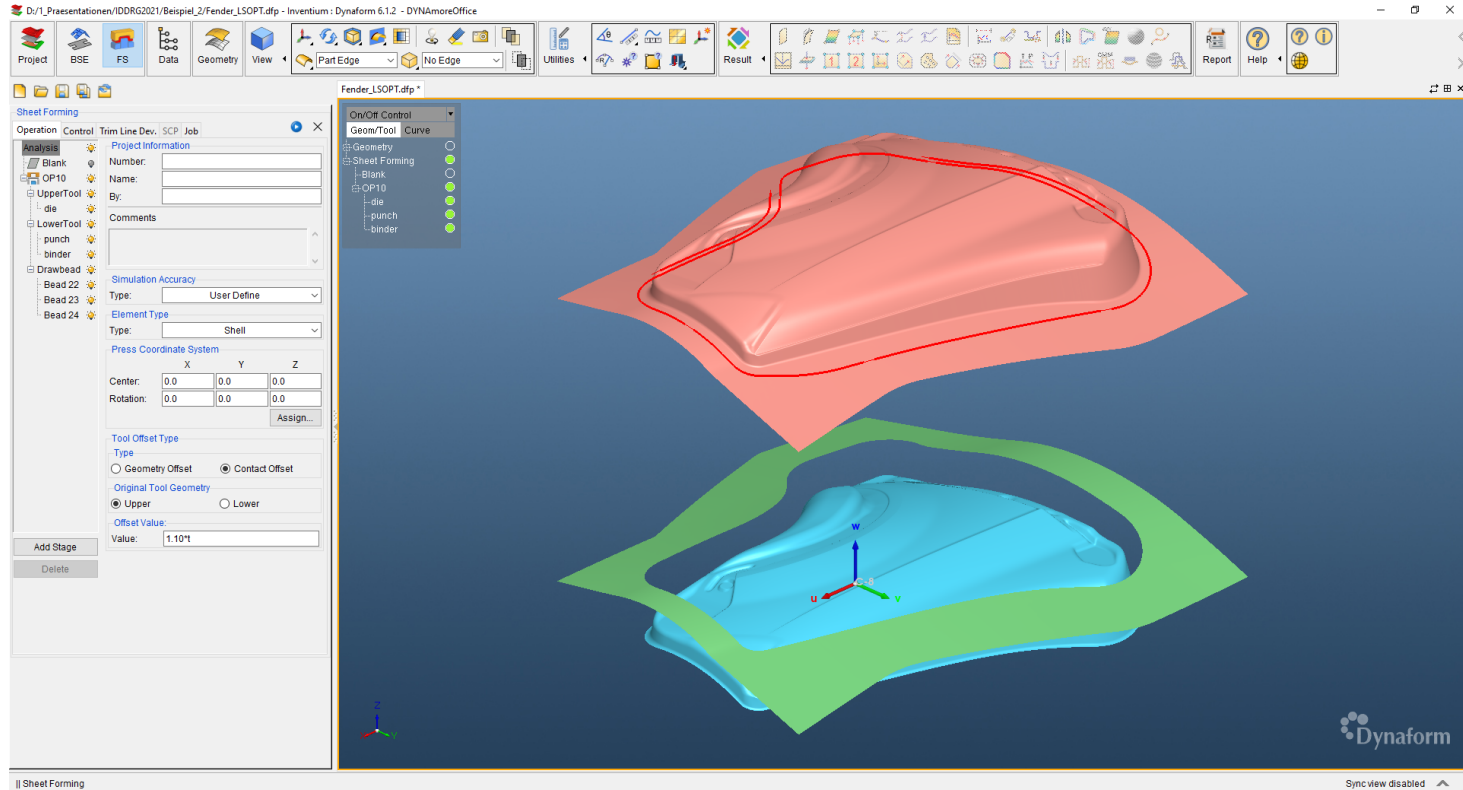
July 17th, 2021, Berlin/Stuttgart



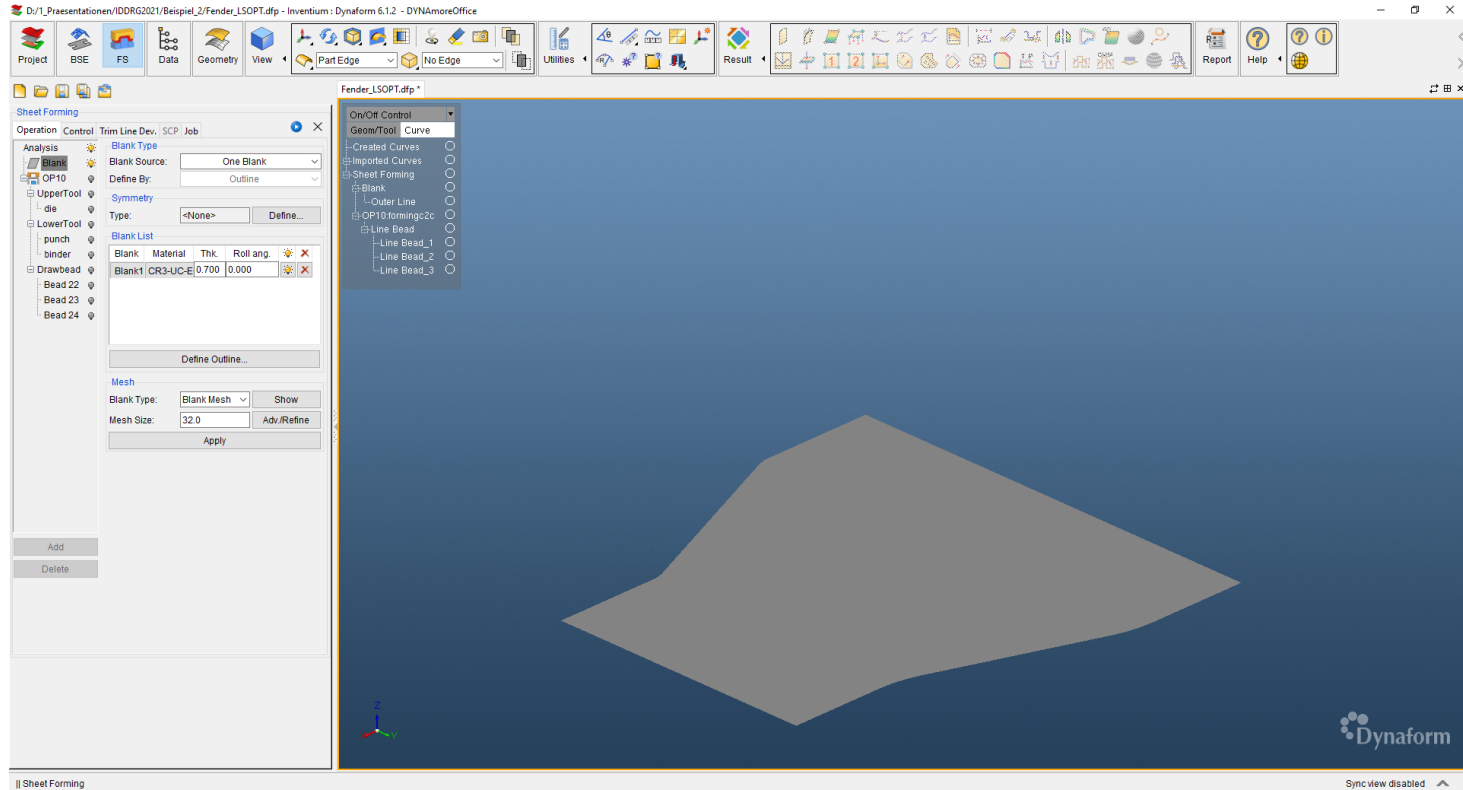
Outline

1. Motivational Introduction Example
2. Metamodels and Classifier
3. Results and Visualization
4. Summary and Outlook

Sheet Metal Forming Simulation with Dynaform® (eta)



Sheet Metal Forming Simulation with Dynaform® (eta)



Sheet Metal Forming Simulation with Dynaform® (eta)

Material Library

Library: voestalpine2019

Name: CR3-UC-EG_ISO_0.80_mm

Type: Steel

Mass Density: 7.9e-09

Young's Modulus: 210000.0

Poisson's Ratio: 0.3

Remark: EN label: DC04
VDA label: CR3
voestalpine label: DC04
Common label: DC04
Coating: UC (uncoated), EG (electrogalvanized)
FLD: thickness 0.80 mm - ISO 12004-2 Transverse

Material Model: 3-Parameter_Barlat's 89

Hardening Curve

Yield Surface: Barlat's 89

Forming Limit Curve

Type: Load Curve

Curve in 00 Direction: Define

Young's Modulus Change Define

Consider Strain Rate

M: 6

R00: 1.81 Curve

R45: 1.35 Curve

R90: 2.03 Curve

Type: User Define

T: 0.7 Define Curve

Formability Index

Import OK Cancel

Material Database available via DYNAmore sales team

The screenshot shows a web browser window displaying the DYNAmore website. The browser's address bar shows the URL <https://www.dynamore.de/en/products/materialcards>. The website header features the DYNAmore logo and a navigation menu with links for Products, Services, Training, Company, and News. Below the header, a breadcrumb trail indicates the current location: Home / Products / Material Cards. The main content area is titled "Material Cards" and contains the following text:

In cooperation with the Austrian steel producer voestalpine, DYNAmore has created a material database for over 60 different steel types for metal forming simulations.

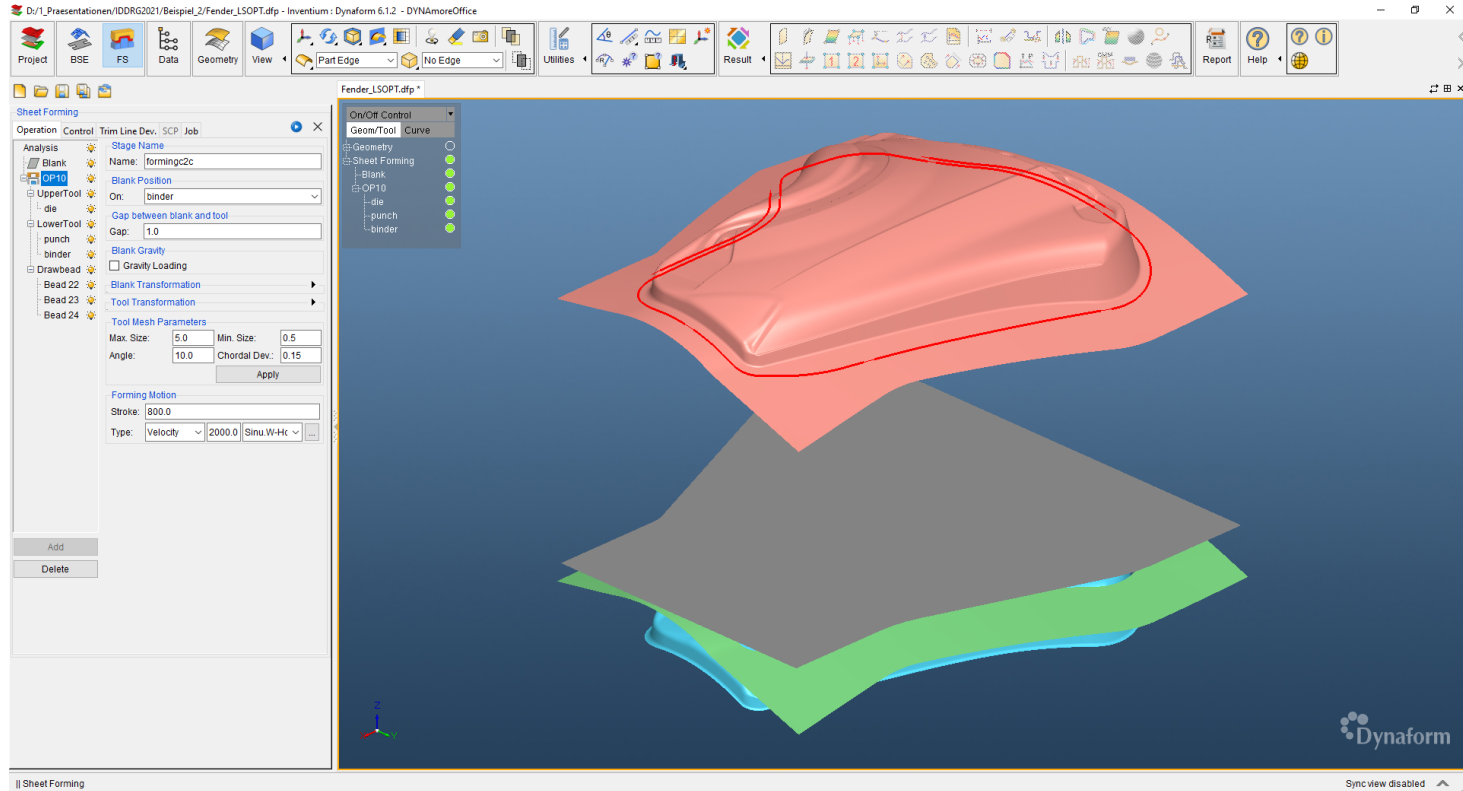
In cooperation with the Austrian steel producer voestalpine, DYNAmore has created a material database for over 60 different steel types. The data is based on tests carried out by voestalpine. DYNAmore has converted the data into the LS-DYNA Keyword format for metal forming simulations. These material cards are also available as material libraries for Dynaform 5.9.4 and 6.0.5. We provide the user license free of charge to our customers. If you are interested, please contact our sales staff.

On the right side of the page, there is a "Contact" section with two entries:

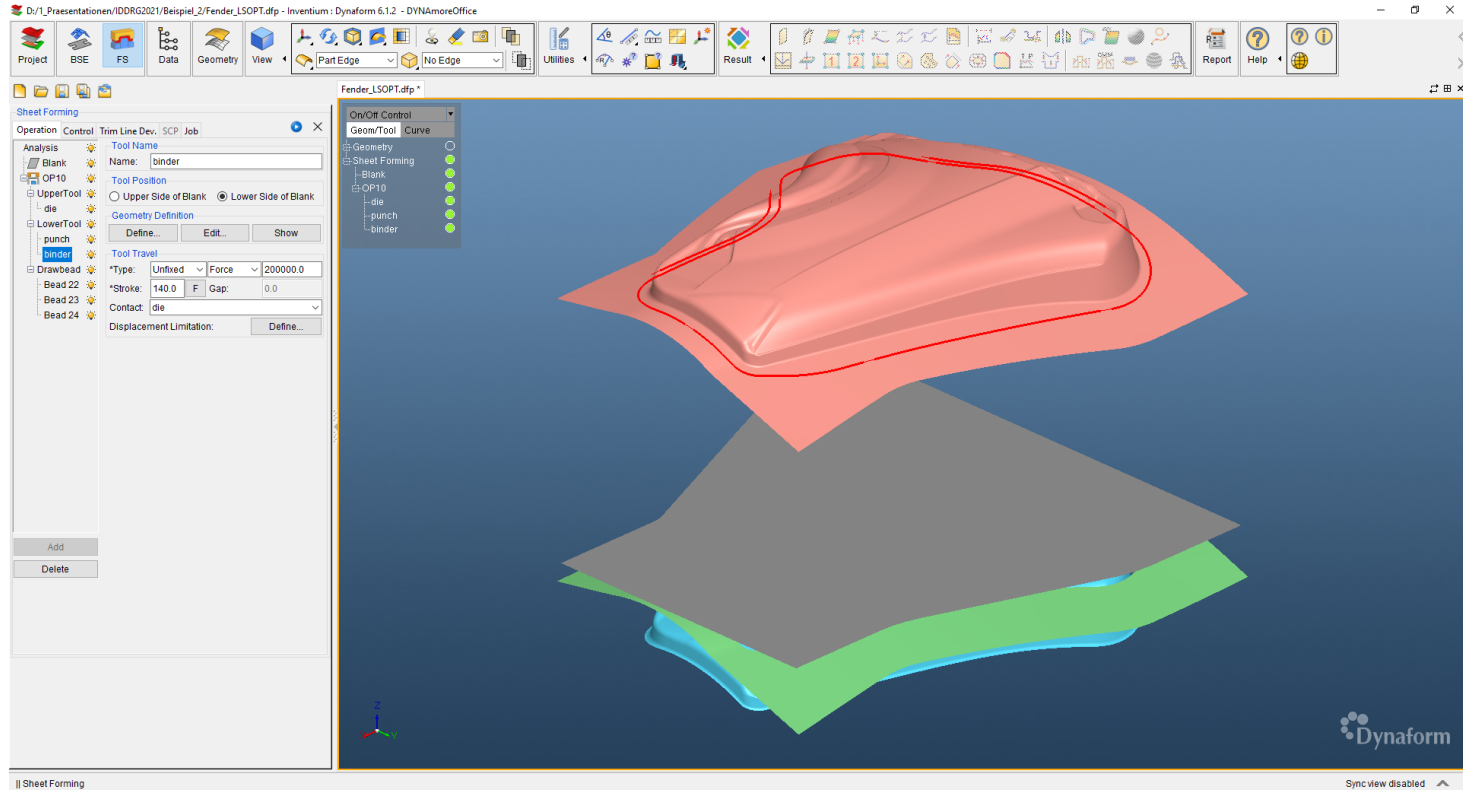
- Kathleen Fritz**
@ Kathleen Fritz
t +49 711 459600273
f +49 711 45960029
- Kathrin Faas**
@ Kathrin Faas
t +49 711 459600274
f +49 711 45960029

The footer of the website contains a grid of links for Products, Services, Training, Company, News, and Downloads. A cookie notice is visible at the bottom of the page.

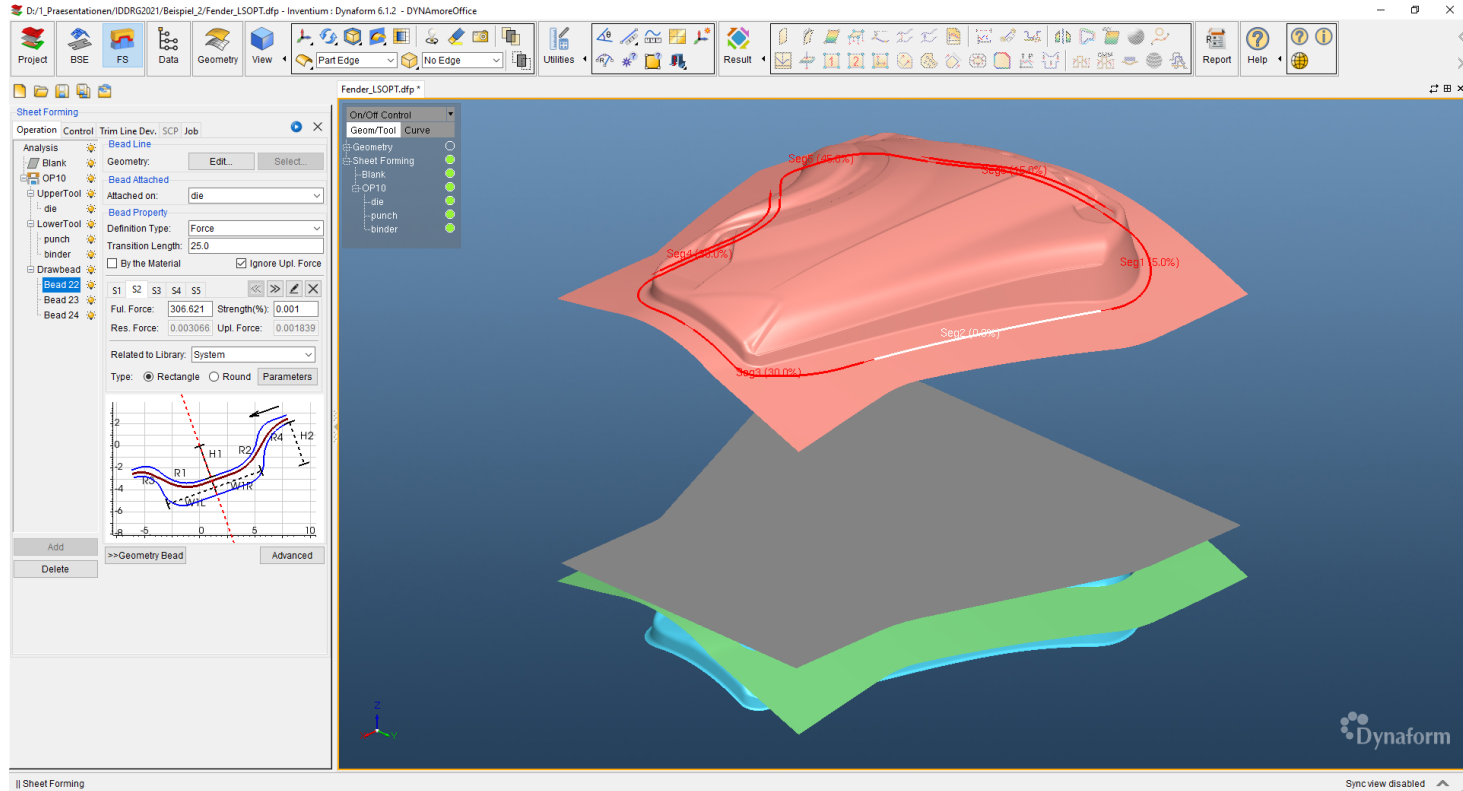
Sheet Metal Forming Simulation with Dynaform® (eta)



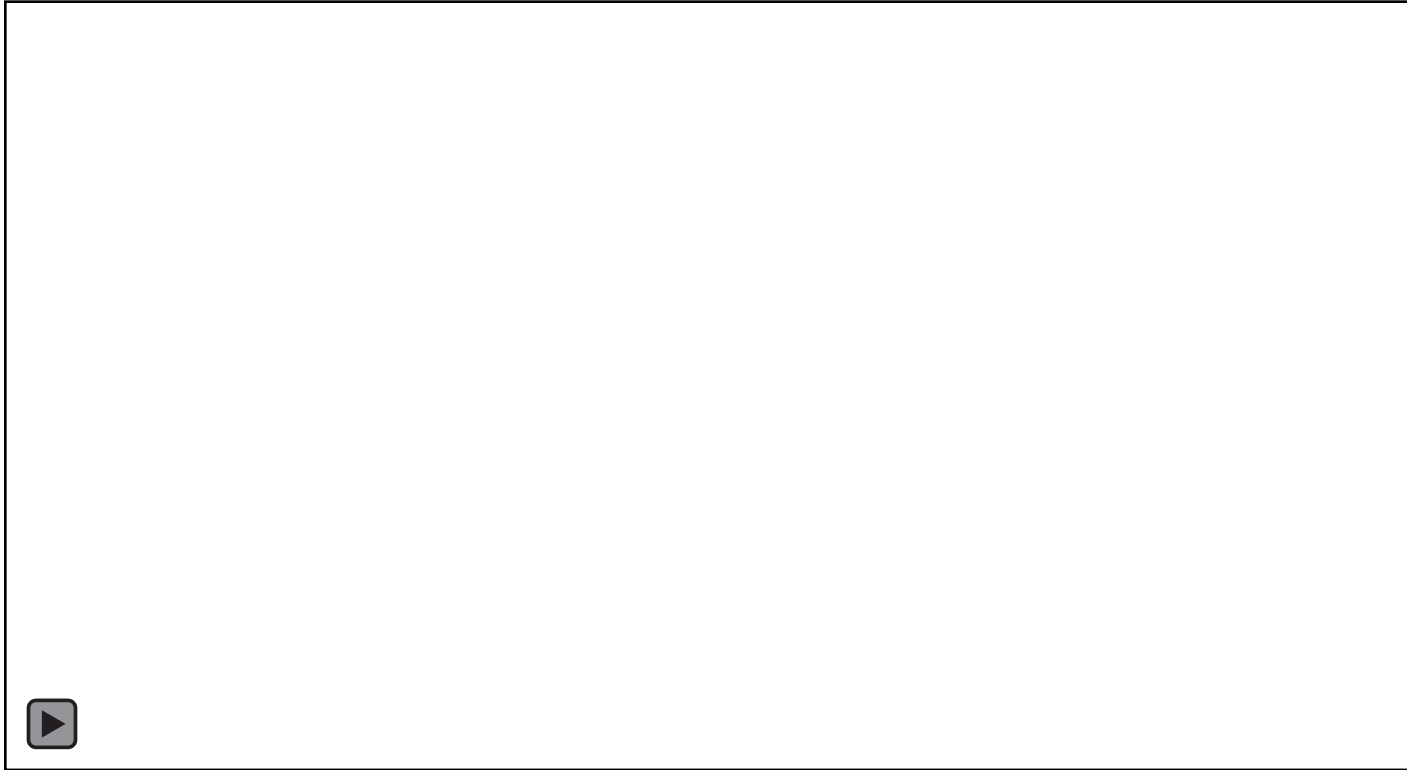
Sheet Metal Forming Simulation with Dynaform® (eta)



Sheet Metal Forming Simulation with Dynaform® (eta)

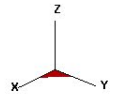
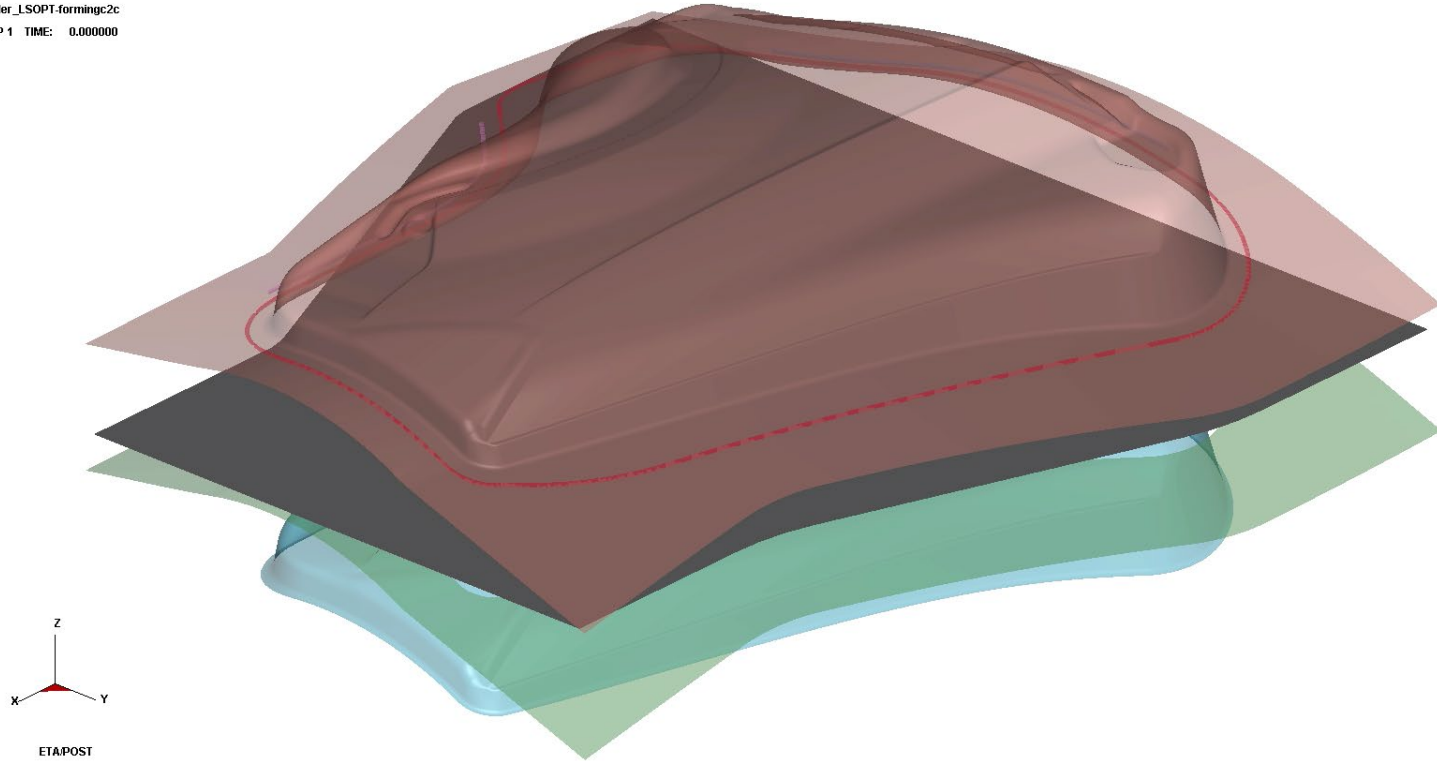


Sheet Metal Forming Simulation with Dynaform® (eta)



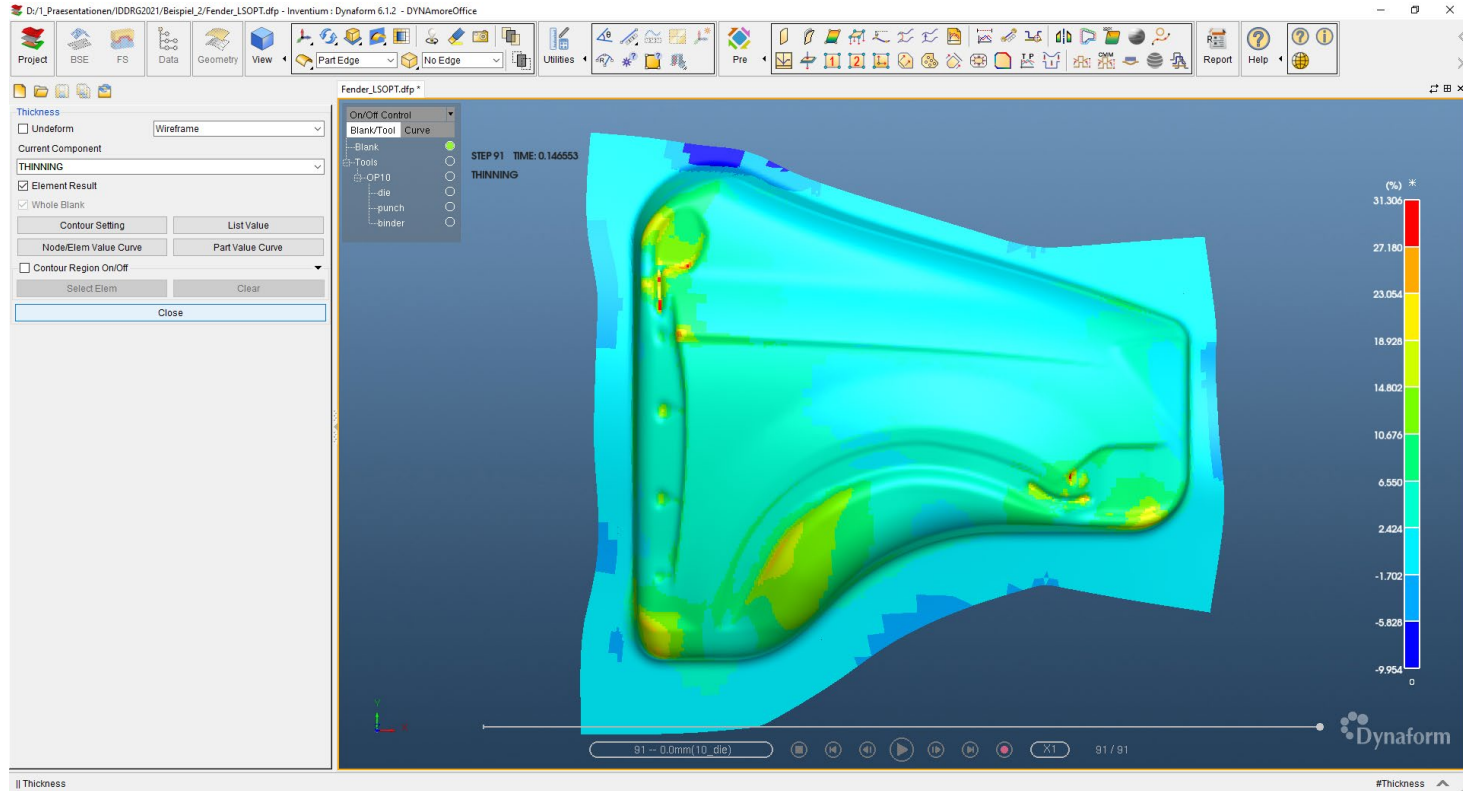
Case Study – Process

Fender_LSOPT-forming2c
STEP 1 TIME: 0.000000

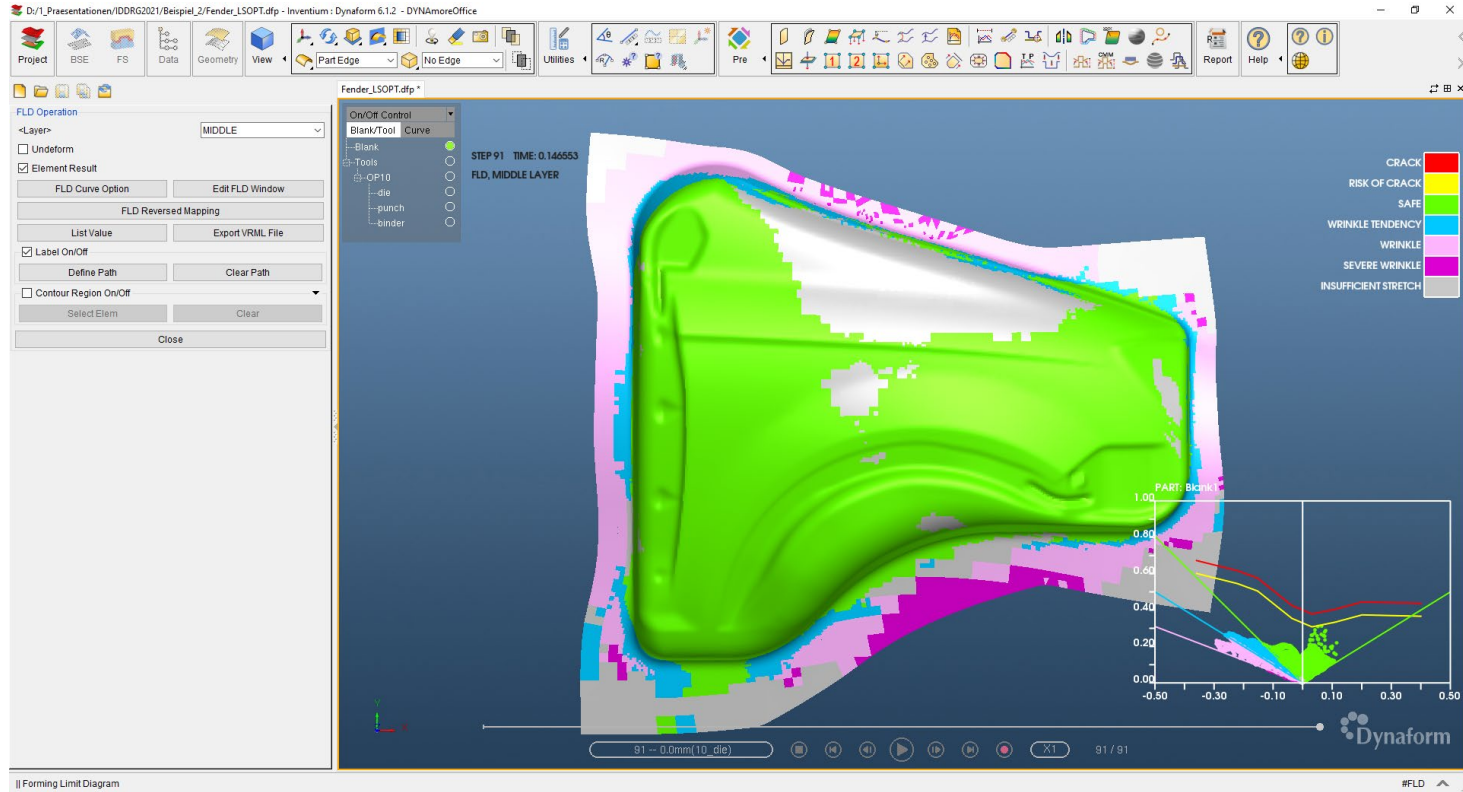


ETAPOST

Sheet Metal Forming Simulation with Dynaform® (eta)



Sheet Metal Forming Simulation with Dynaform® (eta)



Sheet Metal Forming Simulation with Dynaform® (eta)

***MAT_3-PARAMETER_BARLAT_{OPTION}**

This is Material Type 36. This model was developed by Barlat and Lian [1989] for modeling sheets with anisotropic materials under plane stress conditions. Lankford parameters may be used to define the anisotropy. This particular development is due to Barlat and Lian [1989]. *MAT_FLD_3-PARAMETER_BARLAT is a version of this material model that includes a flow limit diagram failure option.

Available options include:

<BLANK>

NLP

The NLP option estimates failure using the Formability Index (F.I.), which accounts for the non-linear strain paths seen in metal forming applications (see the [Remarks](#)). The NLP field in Card 4b *must* be defined when using this option. The NLP option is also available for *MAT_037, *MAT_125, and *MAT_226.

Sheet Metal Forming Simulation with Dynaform® (eta)

- Scalar measurement for formability in case of nonlinear strain paths

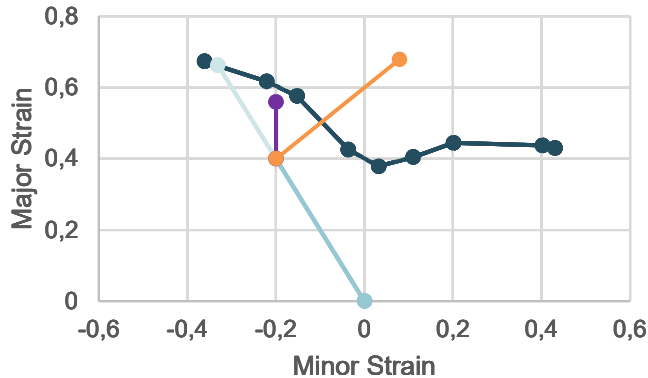
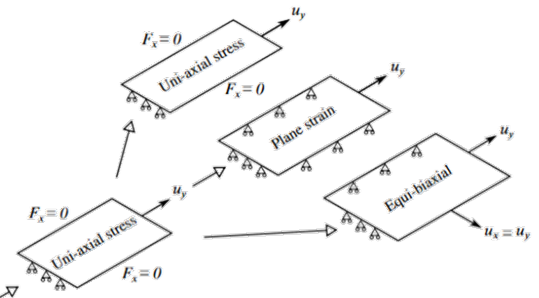
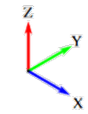
- Based on converted FLC

- Example:

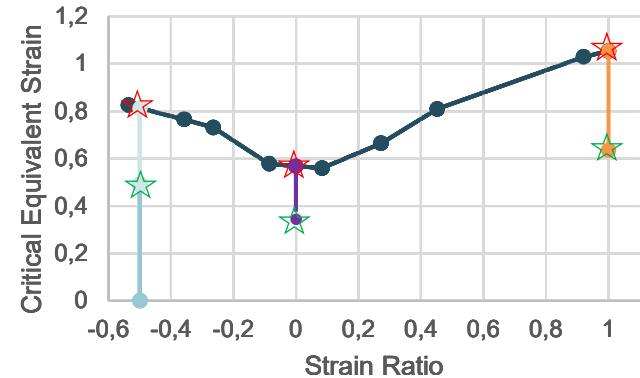
- uni-axial pre-strain

- followed by uni-axial, plane strain, bi-axial

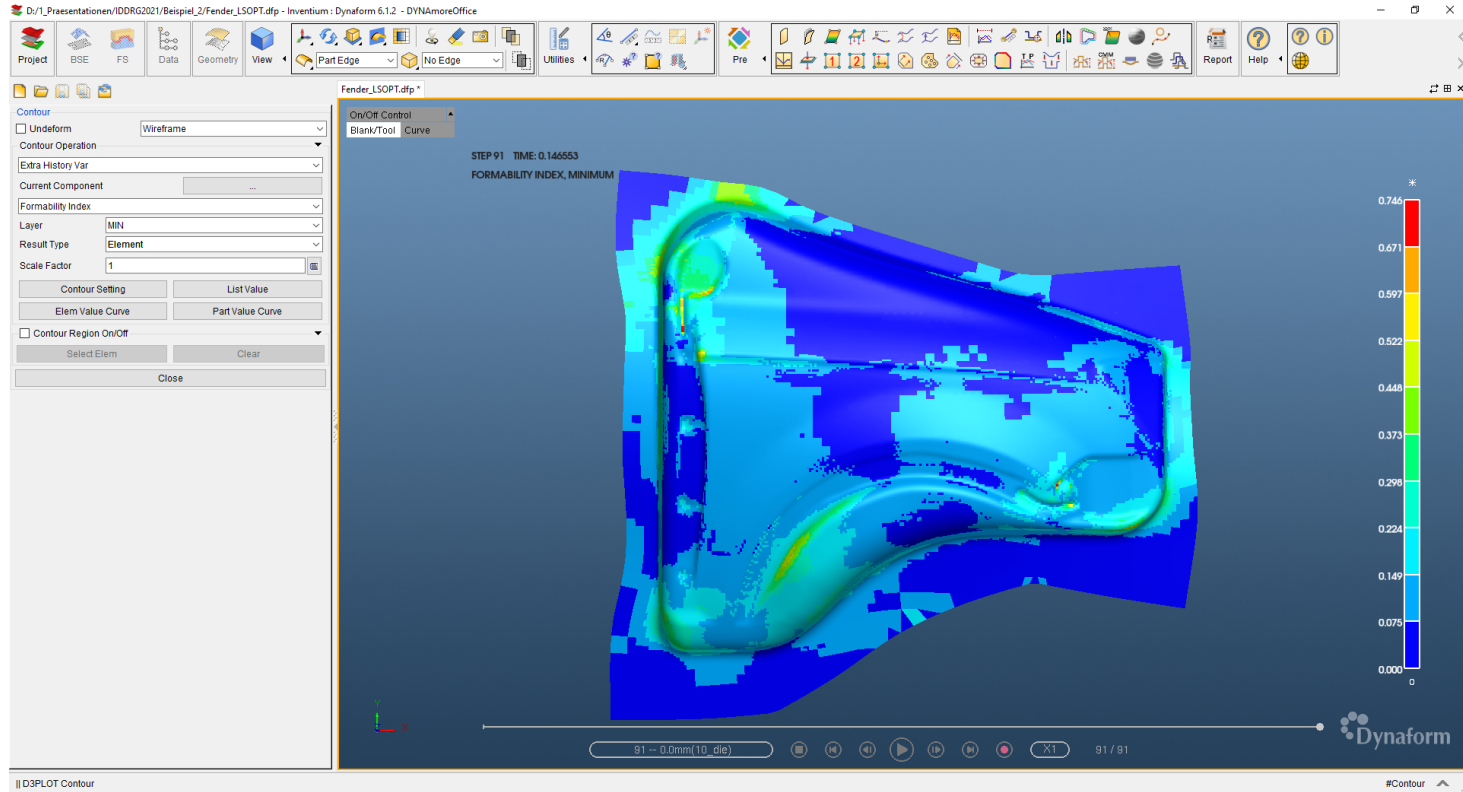
$$FI = \sum_i^n \frac{\Delta \varepsilon_{eq}^i}{\varepsilon_{eq}^{fail} \left(\frac{\Delta \varepsilon_2}{\Delta \varepsilon_1} \right)} < 1$$



☆ FI ~ 0.6
 ☆ FI = 1.0



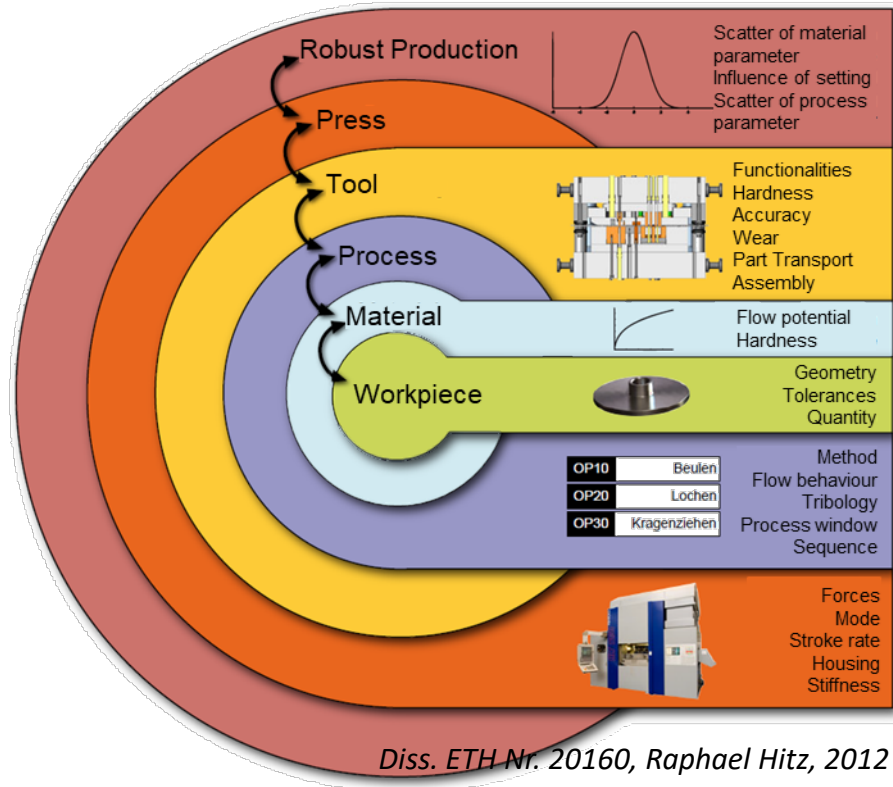
Sheet Metal Forming Simulation with Dynaform® (eta)



Sheet Metal Forming Simulation with Dynaform® (eta)

- Everything within specifications
 - (Of course: Depends on the specification in the showcase)
- Let's start production!
- What could go wrong?

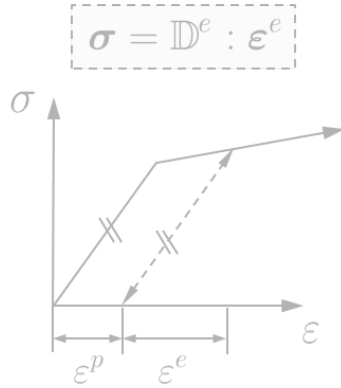
Robustness and Numerical Process Simulation



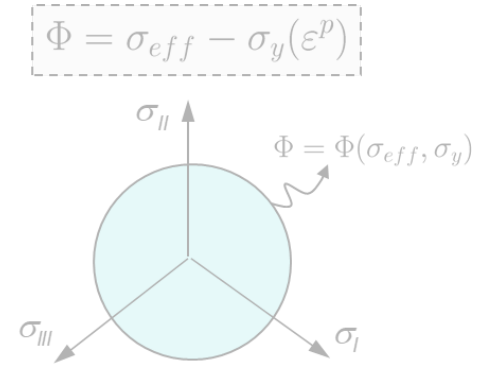
- Workpiece
 - CAD discretization during meshing
- Material
- Process
 - Operation sequences / method
 - Boundary conditions
- Tool
 - Working surface
- Press
 - Generally neglected
- Scatter of all parameters
 - Generally neglected

Robustness and Numerical Process Simulation

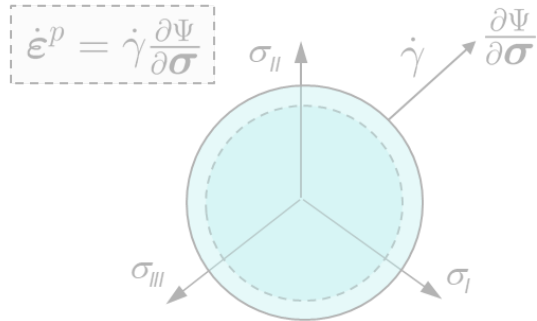
ELASTIC LAW



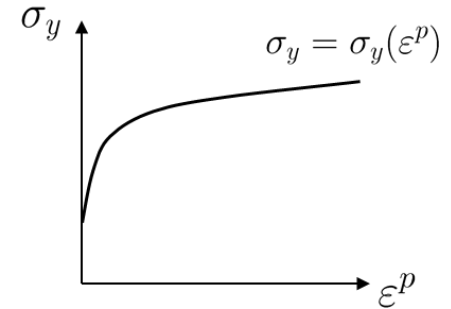
YIELD CRITERION



PLASTIC FLOW



HARDENING LAW



Robustness and Numerical Process Simulation

■ Literature study for DC04

■ Gosh-type hardening

$$\sigma_y(\varepsilon_p) = k(\varepsilon_0 + \varepsilon_p)^n - p$$

$$k = \frac{R_m(A_g+1) - R_{p0.2}}{[\varepsilon_0 + \ln(A_g+1)]^n - \varepsilon_0^n}$$

$$p = k\varepsilon_0^n - R_{p0.2}$$

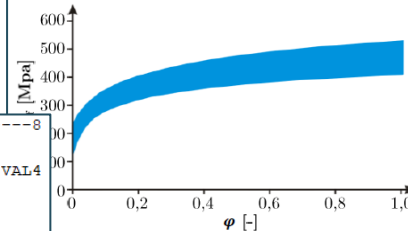
■ ε_0, A_g, n fixed

```

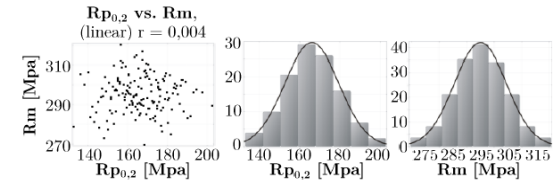
$-----1-----2-----3-----4-----5-----6-----7-----8
*PARAMETER
$  PRMR1      VAL1      PRMR2      VAL2      PRMR3      VAL3      PRMR4      VAL4
R    HR        5.0
R  n_Gosh    -0.137766
R  Re0_Gosh  0.0325023
R    ag       0.24
R   rp02     166.0
R    rm      295.0
$
*PARAMETER_EXPRESSION
$  PRMR1
R  k_Gosh    (xm*(ag+1.0)-rp02)/((e0_Gosh+log(ag+1.0))*n_Gosh-e0_Gosh**n_Gosh)
R  p_Gosh    k_Gosh*e0_Gosh**n_Gosh - rp02
$-----1-----2-----3-----4-----5-----6-----7-----8
    
```

	$R_{p0.2}$	R_m	ε_0	m
Minimum	130 MPa	263 MPa	-	-
Maximum	225 MPa	328 MPa	-	-
Mittelwert	166 MPa	295 MPa	0,0325023	-0,137766
Standardabweichung	13,5 MPa	9,5 MPa	-	-
Verteilungsfunktion	Normal	Normal	-	-

Tabelle 2.4.: Verwendete Parameter für DC04. k und p wurden jeweils gemäß der Gleichungen [2.15](#) und [2.16](#) berechnet.



(a) NLO-Hüllkurven für DC04.

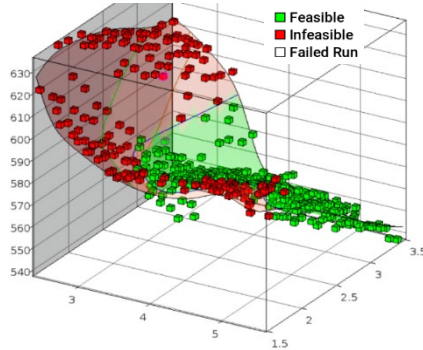


(b) Materialparameterstreuungen und Histogramme für DC04.

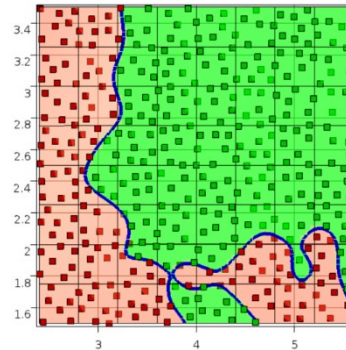
DISS. ETH Nr. 24853, FLORIAN QUETTING, 2018

Virtual Robustness Analysis

- Highly nonlinear finite element simulations are computationally expensive
→ metamodel or classifier approximations are used to evaluate statistics



Metamodel
Approximation of response



Classifier (Support Vector Classification)

Approximation of constraint boundary

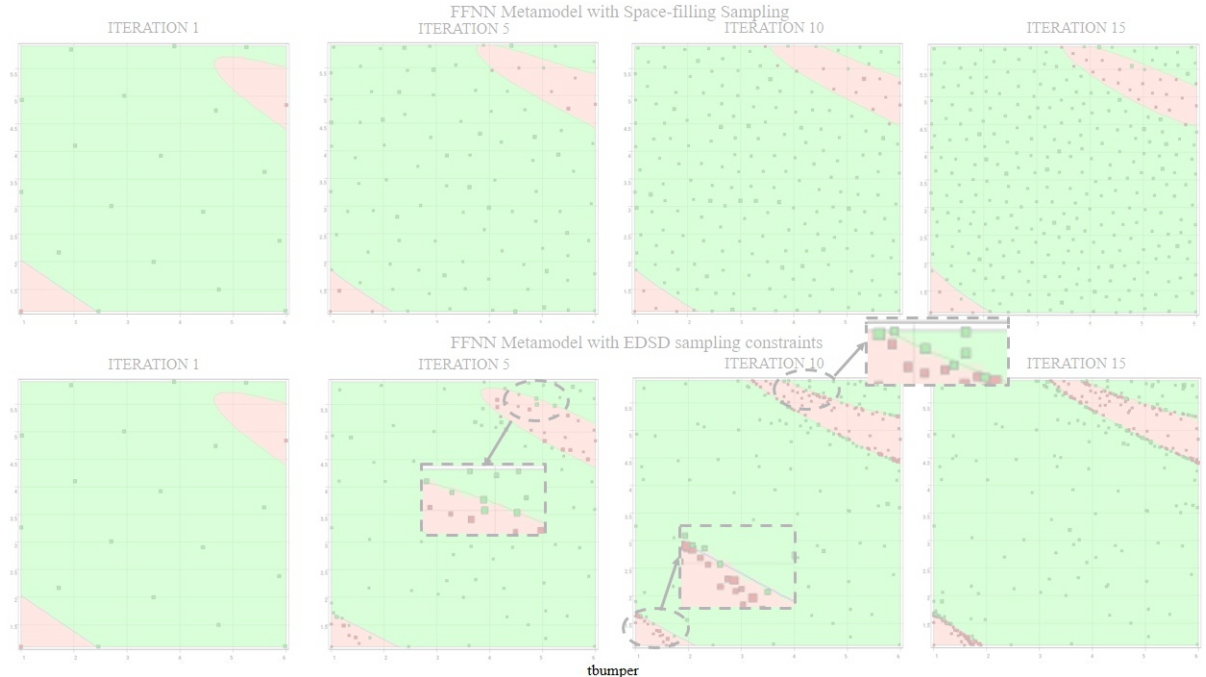
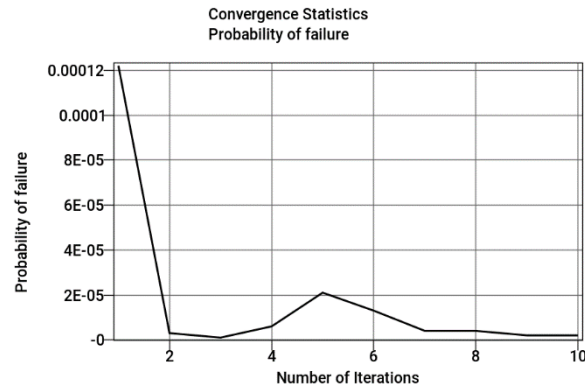
- Feasibility of each design
→ Constraints for optimization or reliability analysis
→ Adaptive Sampling

Sequential Monte Carlo Analysis

- Iteratively add space-filling or adaptively selected samples

- Convergence

- metamodel accuracy
- probability of failure



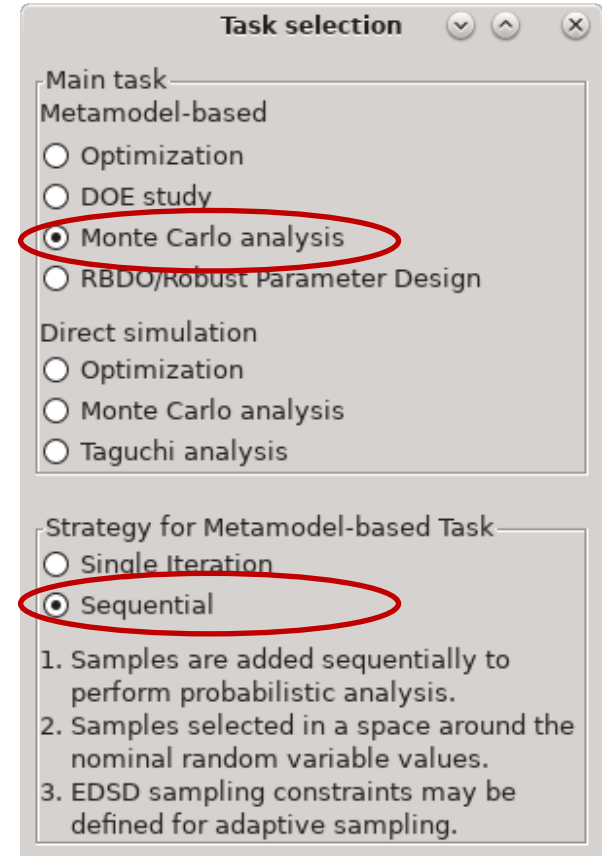
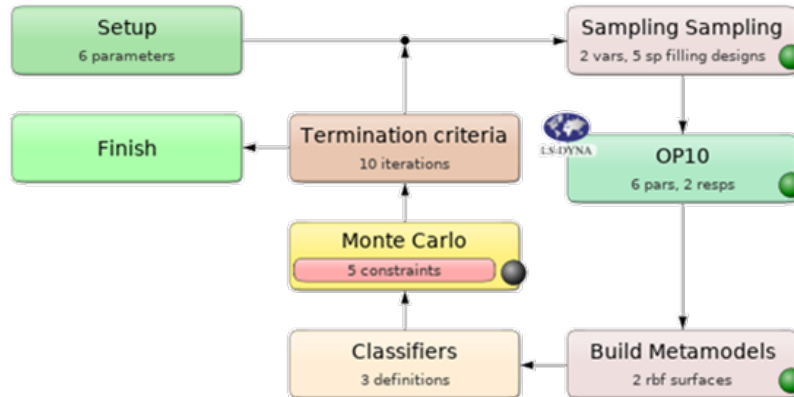
Case Study – Setup for Robustness Analysis

■ Sequential metamodel-based Monte Carlo Analysis

- 5 simulations per iteration, 10 iterations

➔ Improvement of metamodel and classifier approximation in each iteration

➔ Improvement of estimation of probability of failure, mean value, standard deviation, ...



Case Study – Setup for Robustness Analysis

■ Definition of classifiers

Classifier

Name for classifier: FI_thickness_red_cls

Classifier system type: Series

Entity	Label Type	Lower Bound	Upper Bound	Feasible Cluster
* FI	Threshold	Set lower bound	*	1
* thickness_reduction	Threshold	Set lower bound	*	35

Classifier type:

Simulation designator only

SVC (support vector classification)

Set advanced SCV options

Add new

- Responses
- Results
- Composites
- Variables
 - [HR](#)
 - [ag](#)
 - [e0_Gosh](#)
 - [n_Gosh](#)
 - [rm](#)
 - [rp02](#)
- Classifiers
 - [FI_cls](#)
 - [thickness_reduction_cls](#)

Case Study – Setup for Robustness Analysis

■ Adaptive Sampling – using classifiers!

- 3 points adaptive (near classifier boundary) using classifier with components
 - $\max_{EL}[\min_{IP}(FI)] < 1$
 - $\max_{EL}(\mathbf{thickness\ reduction}) < 35$
- 2 space filling points

Classifier	Lower Bound	Upper Bound	First	Gap	Last	Random
* FI_thickness_red_cls	-1	1	1 (default)	2 (default is 1)	5 (default)	<input checked="" type="checkbox"/>

Note: EDSD Sampling constraints are only considered for pointselection Space Filling

Case Study – Setup for Robustness Analysis

■ Noise variables

- Scatter constituted by means of statistical distribution
- Correlation between variables

Parameter Setup | Stage Matrix | Sampling Matrix | Resources | Features

Show advanced options

Noise Variable Subregion Size (in Standard Deviations)

Enforce Variable Bounds

Type	Name	Starting	Minimum	Maximum	Distribution	Delete
Constant	HR	5				🔒
Constant	ag	0.24				🔒
Constant	e0_Gosh	0.0325023				🔒
Constant	n_Gosh	-0.137766				🔒
Noise	rm				rm_dist	🔒
Noise	rp02				rp02_dist	🔒

Variable Correlation

First Variable	Correlation	Second Variable	Delete
rm	0.004	rp02	*

Add...

Statistical Distribution

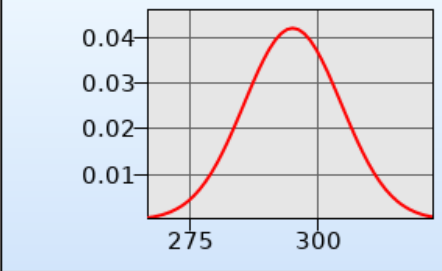
Distribution Name: rm_dist

Type: Normal

Mean: 295

Standard Dev: 9.5

Preview: Mean = 295; Std Dev = 9.5

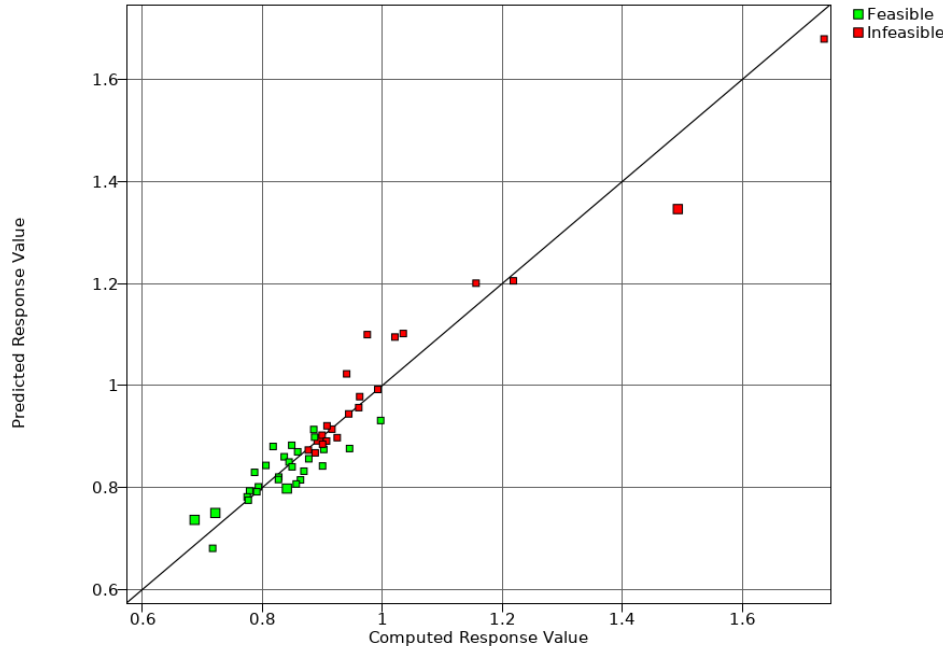


Cancel OK

Case Study – Metamodel Quality and Convergence

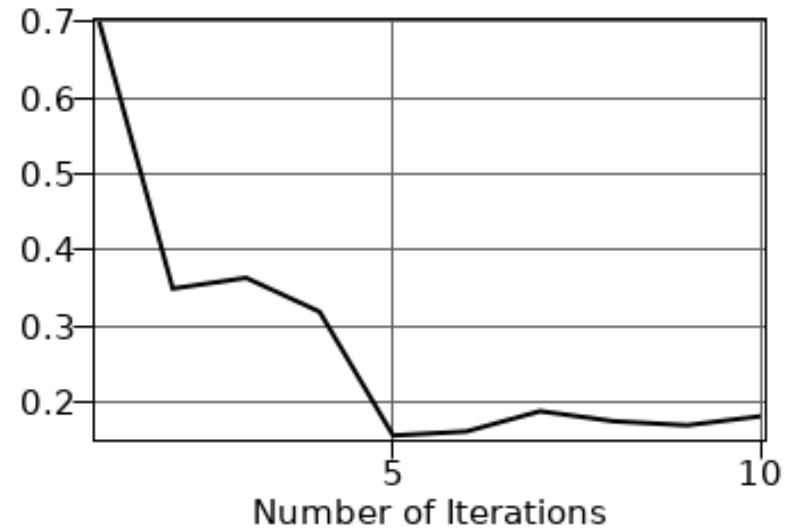
Metamodel quality

Metamodeling Accuracy
For Response Function "FI"
RBF Net: RMS Err = 0.0443 (4.84 %), Sqrt PRESS = 0.0615 (6.72 %), R-sq = 0.898



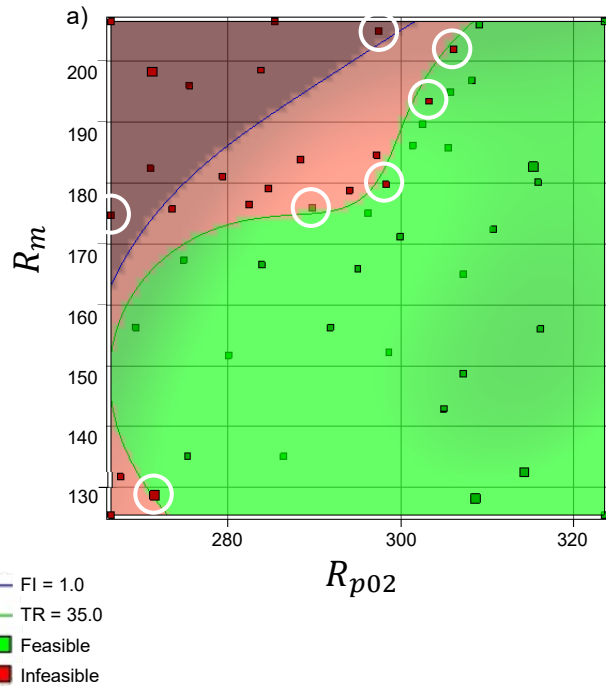
Convergence

Convergence Statistics
Probability of failure

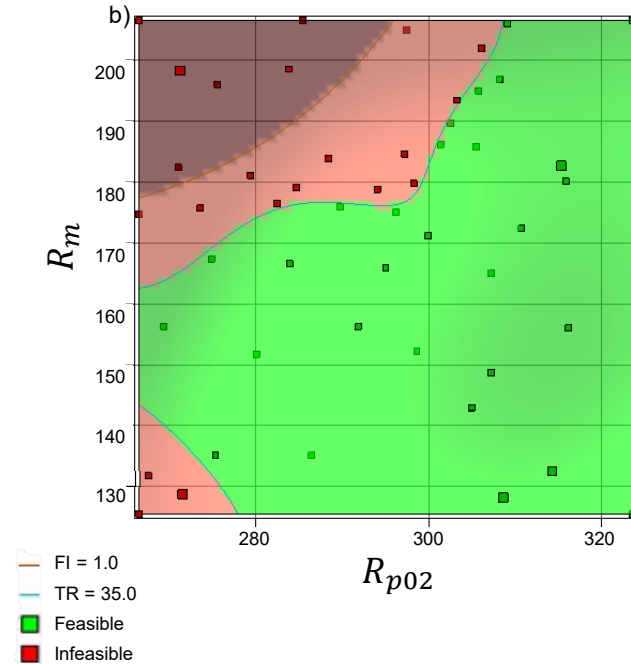


Case Study – Comparison of Failure Boundaries

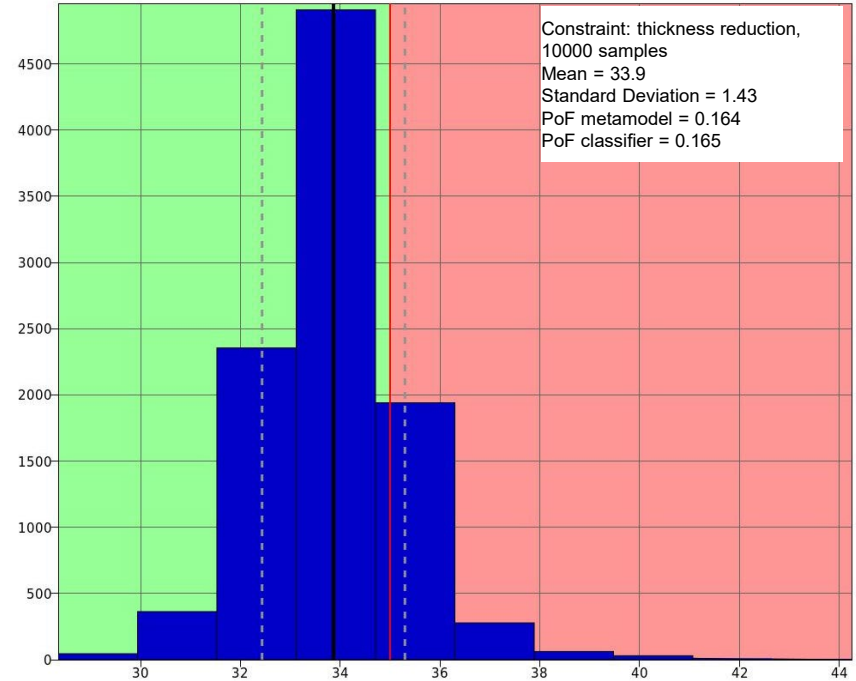
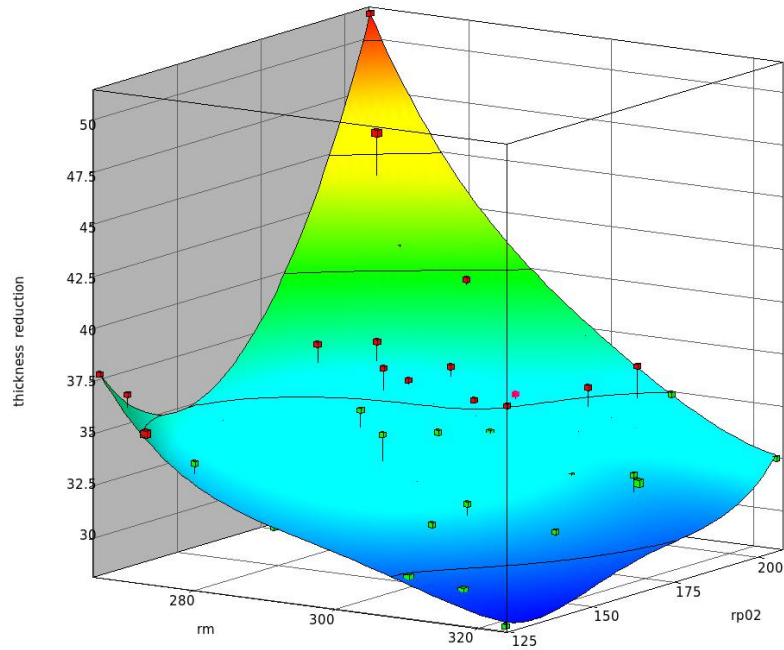
Metamodel



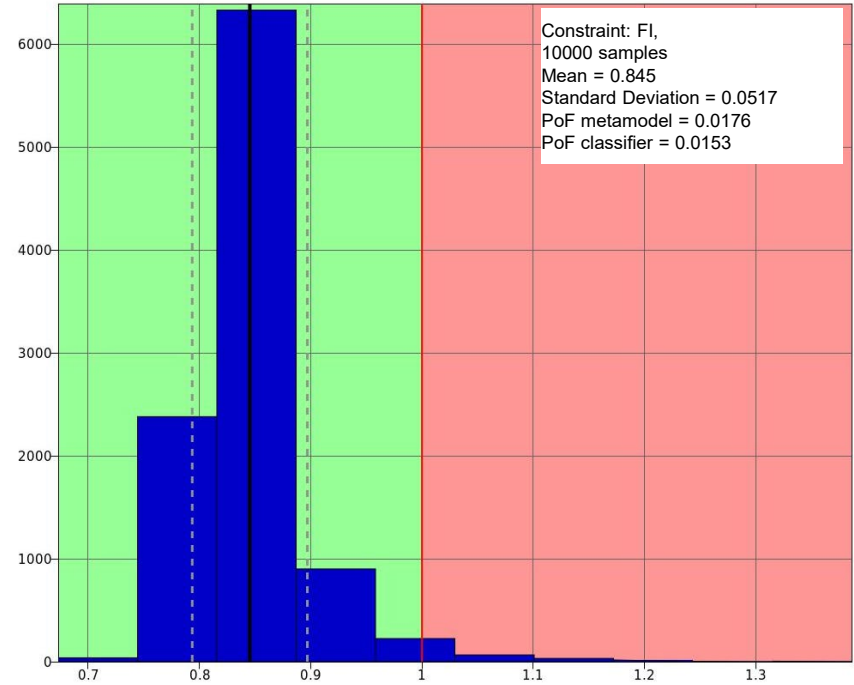
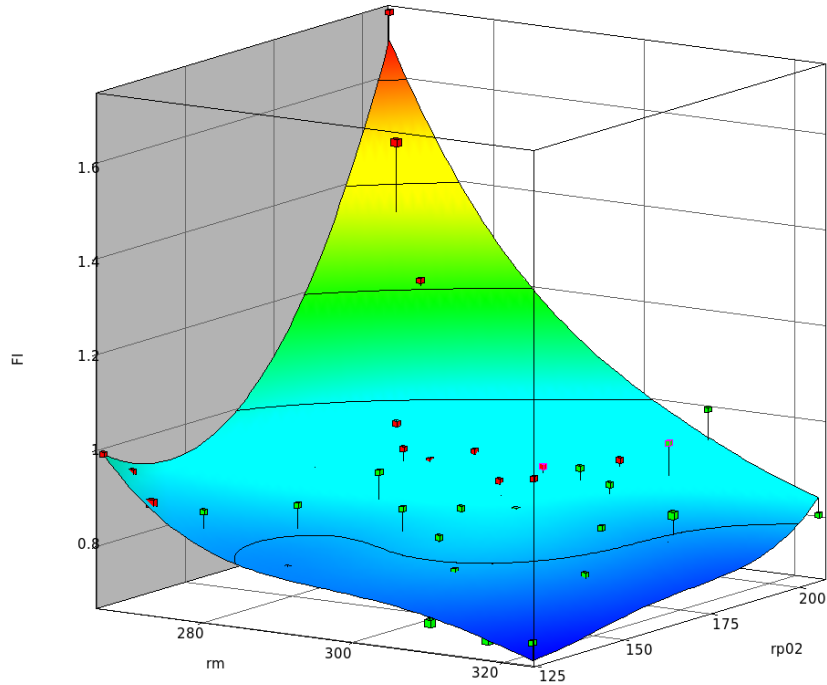
Classifier



Case Study – Thickness Reduction

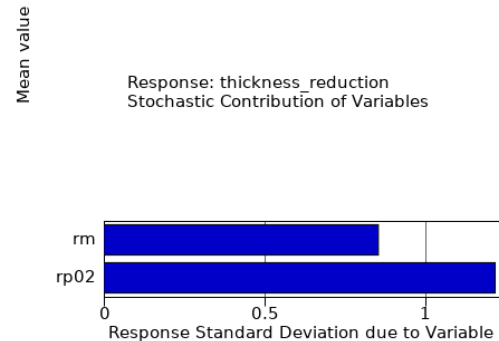
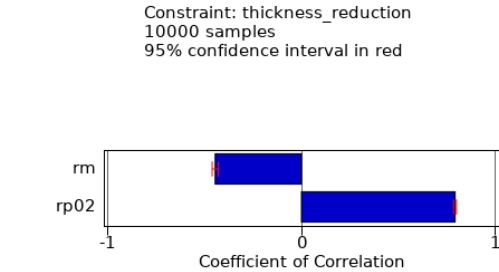
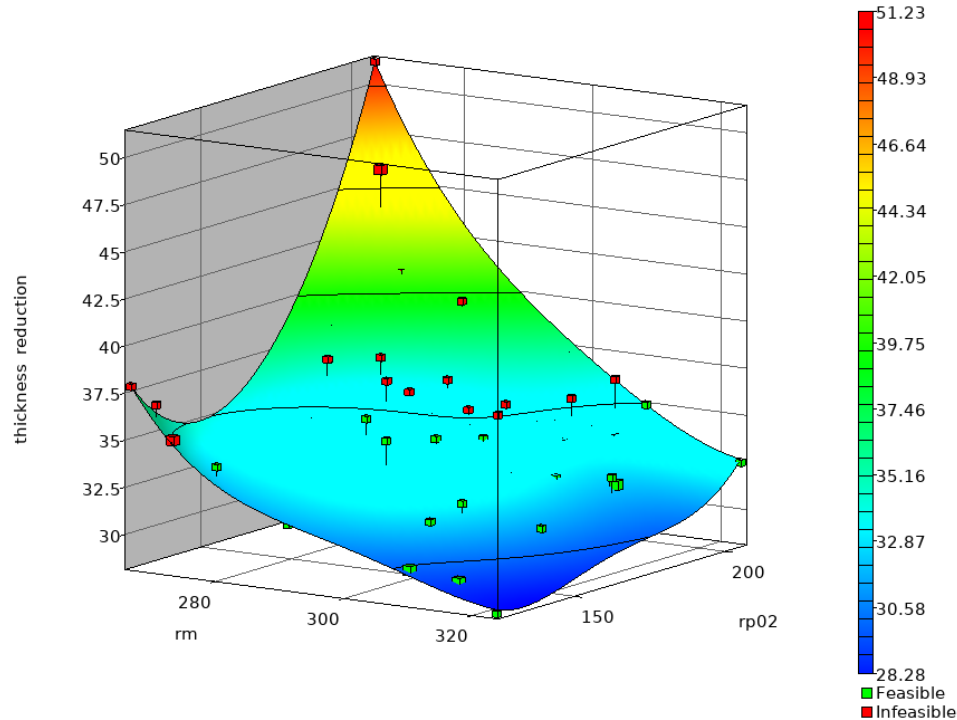


Case Study – Formability Index



Case Study – Sensitivities

■ Which parameter influences the responses?



Case Study - DYNAStats

■ Statistical values as fringe component in LS-PrePost

The screenshot displays the LS-PrePost interface with the DYNASTats module. The main window shows a list of D3Plot components, with **%_thickness_reduction** selected. A dialog box titled "Step 2 of 4" is open, allowing the user to configure the plot. The dialog includes options for selecting the component, stage, and statistical method. Annotations 1, 2, and 3 highlight specific parts of the interface.

1 Fringe plot - display contour plot of D3Plot data upon the active response. The D3Plot data can also be displayed as a history plot. The history plot displays the response over time, and statistical calculations are performed on the contribution analysis.

2 Select D3Plot component to plot

- ▼ D3Plot Components
 - ▶ Ndv
 - ▶ Stress
 - ▶ Strain
 - ▶ Infn
 - ▶ Green
 - ▶ Result
 - ▼ Misc
 - pressure
 - user
 - temperature
 - internal_energy
 - shell_thickness
 - %_thickness_reduction**
 - history_var#1
 - history_var#2
 - history_var#3
 - history_var#4
 - history_var#5
 - history_var#6
 - history_var#7
 - history_var#8
 - ▶ FLD
 - ▶ Beam

Follow coordinates instead of nodes
for part: 1027

3 Select what to plot

- Statistic of D3Plot data
- Statistic of residuals (errors) in a metamodel of the D3Plot data
- Safety Margin
- A single variable's contribution to the D3Plot data
- Which variable contributes the most to the D3Plot data

Select statistic to plot

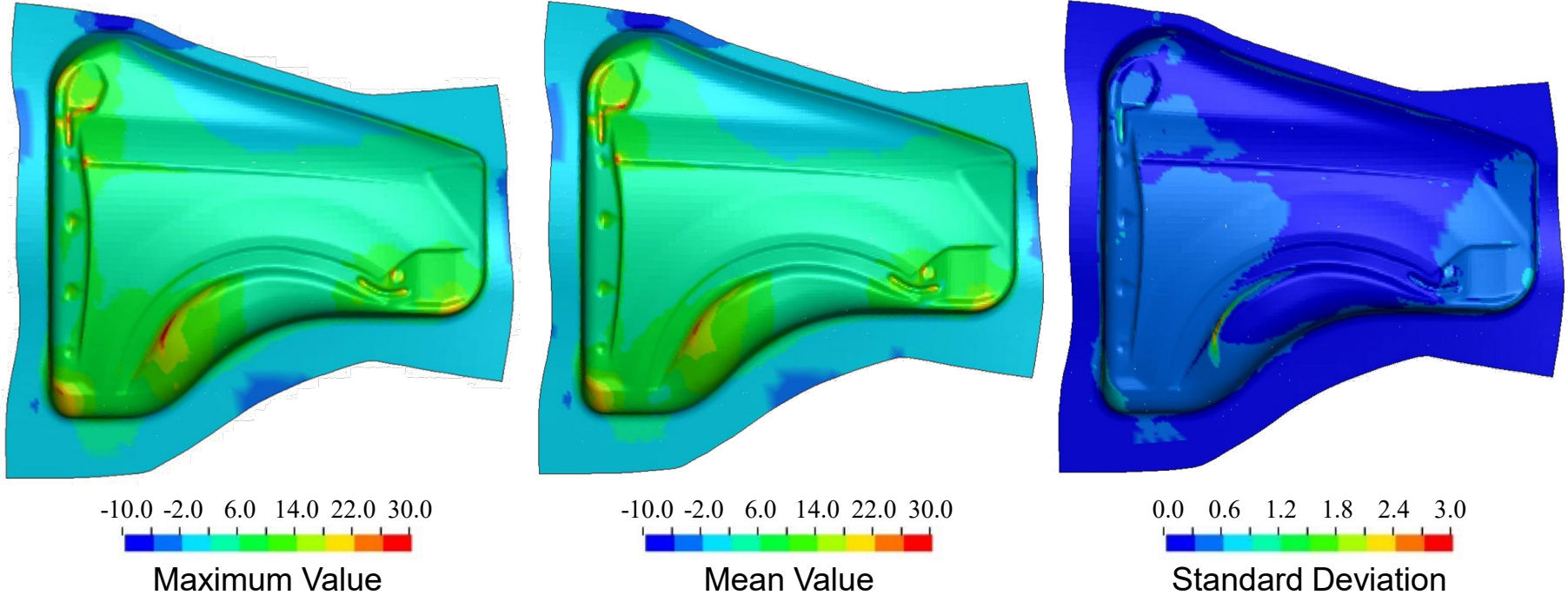
- Mean
- Std Dev
- Max Value
- Min Value
- Range
- Max Job ID
- Min Job ID

Select analysis method

- Use actual FEA results (Monte Carlo)
- Build linear metamodel from FEA Results
- Build quadratic metamodel from FEA results

Case Study – Identification of critical zones

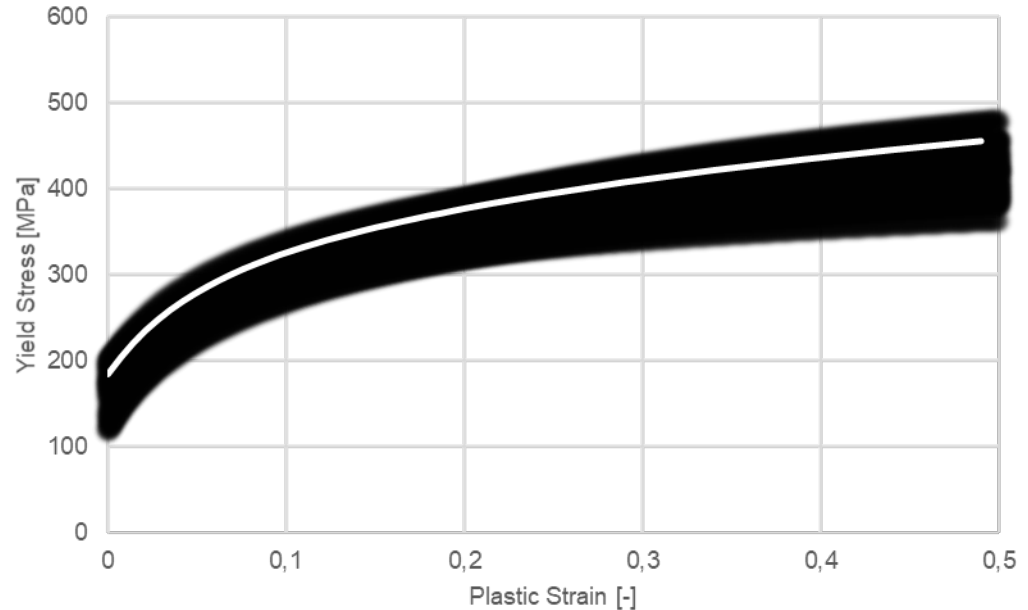
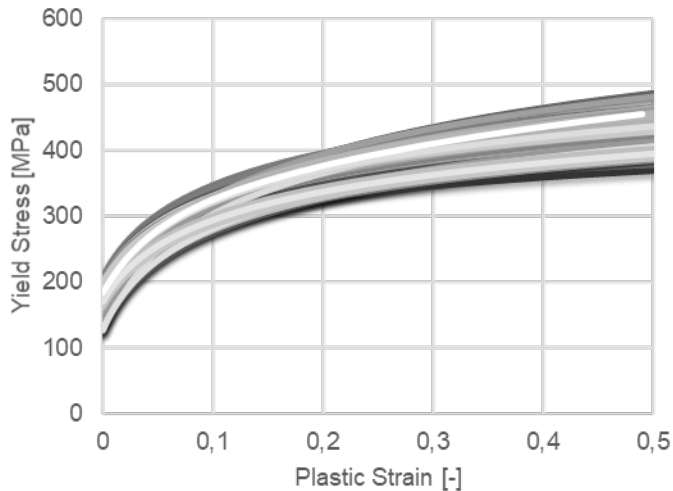
- Based on calculated simulations to generate the metamodels



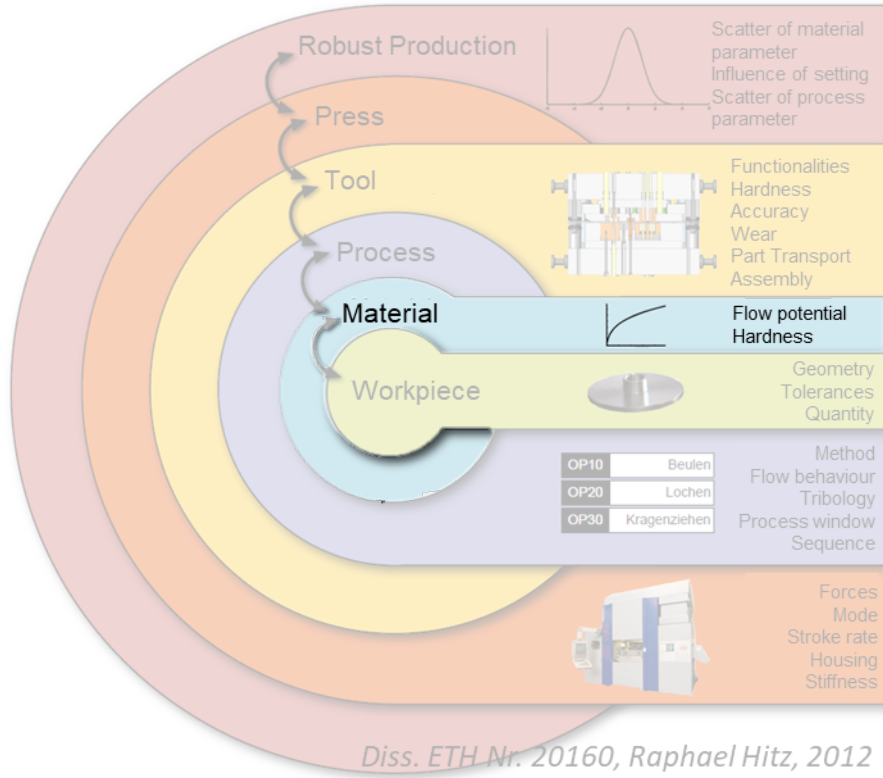
Summary

■ Comparison of initial yield curve to the yield curves of the 50 simulations

- NOT a scaling
- Shape and slope changes



Summary



■ Workpiece

- CAD discretization during meshing

■ Material

- One material card (one part of it)

■ Process

- Operation sequences / method
- Boundary Conditions

■ Tool

- Working surface

■ Press

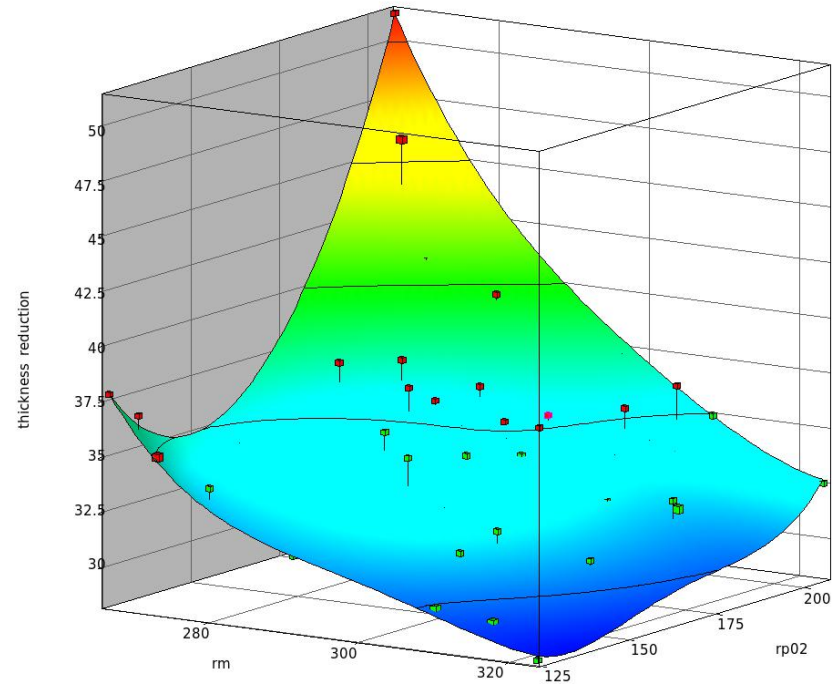
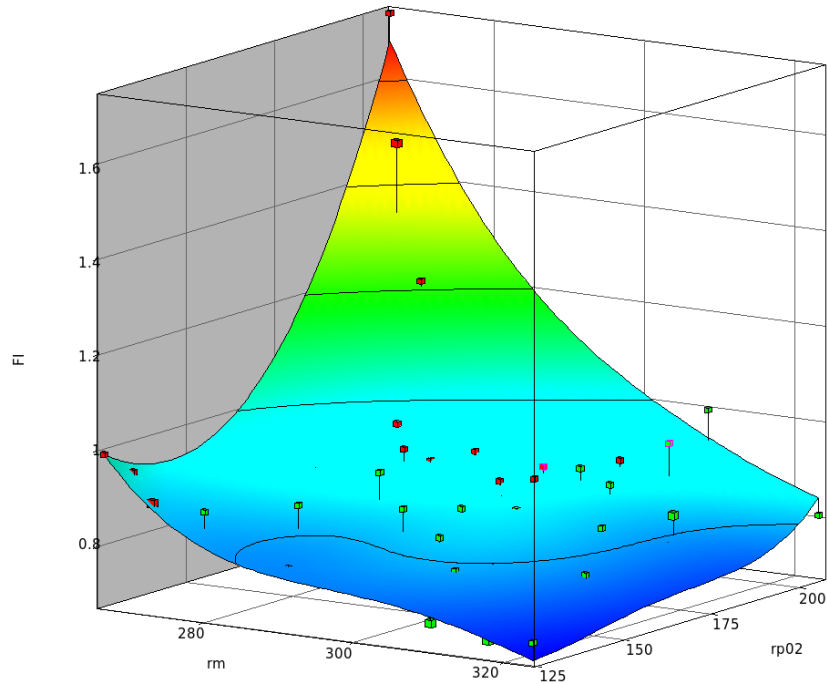
- Not in general accounted for

■ Scatter of all parameters

- Not in general accounted for

Summary

- The metamodels in this case are quite similar, due to assumptions.



Outlook

■ LS-Dyna inputs can be easily parametrized

- *PARAMETER(_EXPRESSION)
- *PART_MOVE
- *CONTROL_FORMING_INITIAL_THICKNESS
- *CONTACT ... (FS, FD, ...)
- *DEFINE_CURVE (SFA, SFO, OFFA, OFFO, ...)
- ...

■ Challenges:

1. Having a suitable simulation model of your process
2. Finding the right parameters for your case
3. Getting a reliable range of data for your parameters

