Which discretization level for uncertainties do we need for reliable robustness evaluations in forming application?

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Task description

Often simplified scatter definitions (like truncated normal distribution and idealized correlation between selected scattering material parameter) are used to investigate Robustness of forming simulation. Using an example where significant robustness problems where seen in reality, we compare the results by using “simplified” and “best as possible” translation of material input scatter.

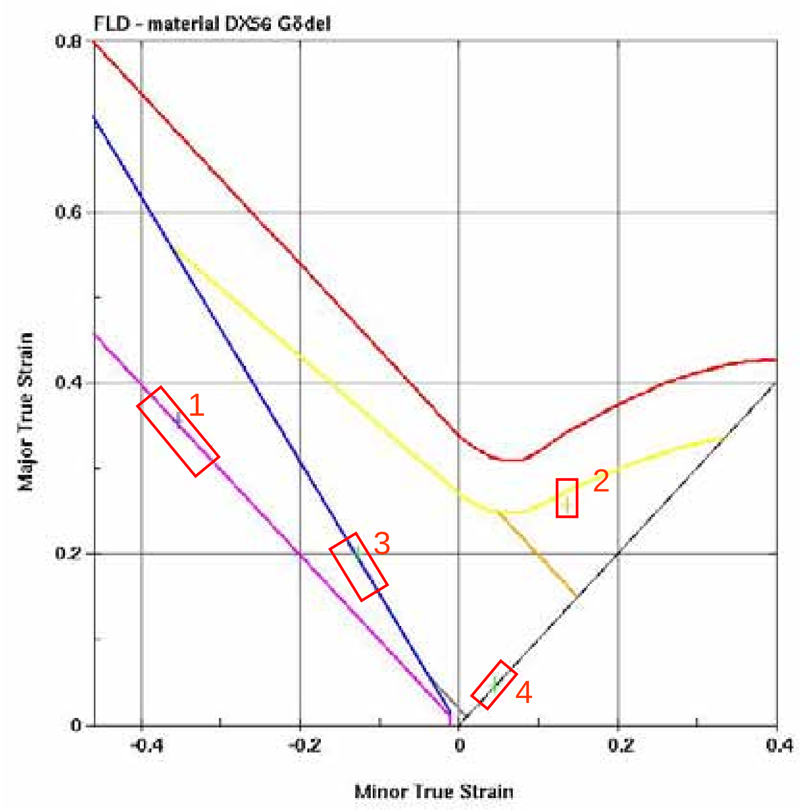
Thyssen provides scatter of material data. AUDI did perform reference simulation and robustness evaluation with current AUDI robustness evaluation tool chain.

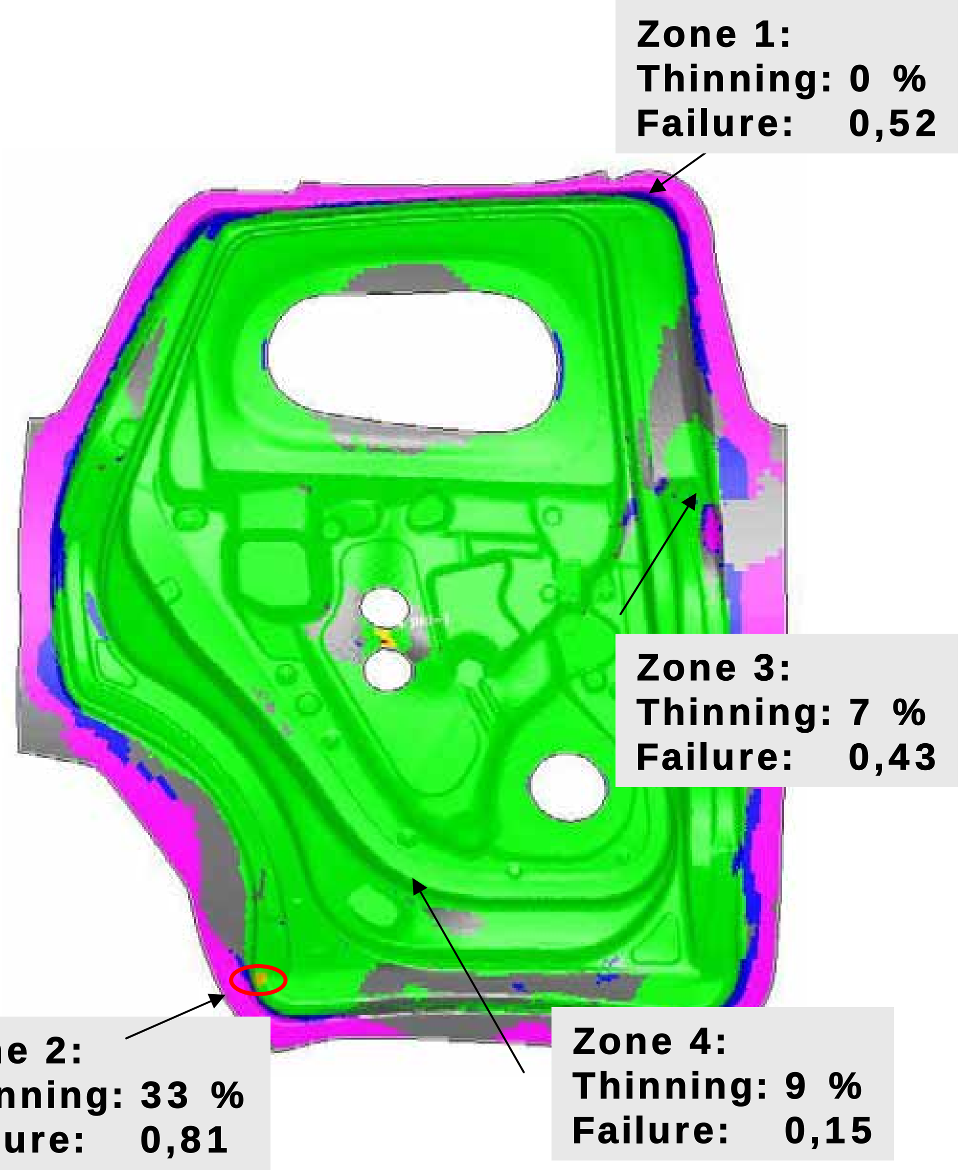
DYNARDO was setting up the robustness evaluation using LS-DYNA and optiSLang/SoS. To verify that differences are not resulting from using different forming solver, Dynardo repeated the AUDI Robustness Evaluation with the new process chain LS-DYNA/optiSLang.

Step A: Robustness Evaluation of forming process using simplified input material scatter definition.

Step B: Robustness Evaluation using „best as possible“ input scatter definition

Base simulation LS-DYNA

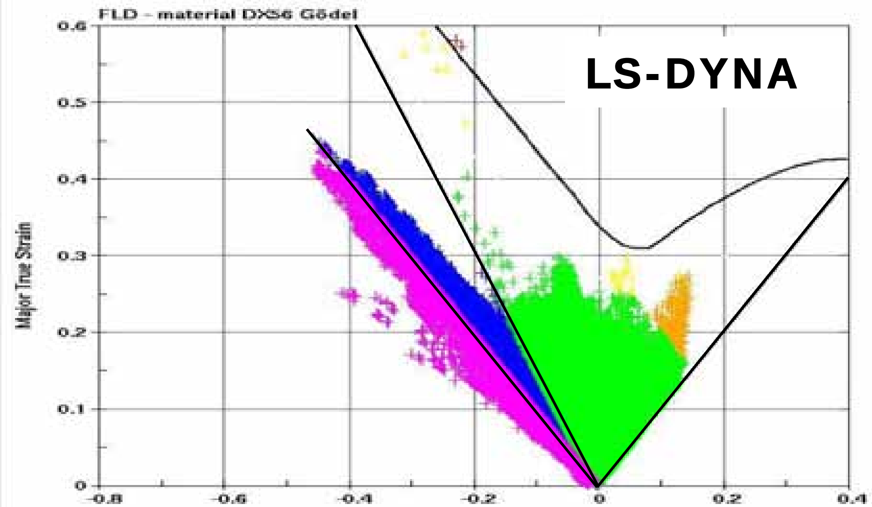


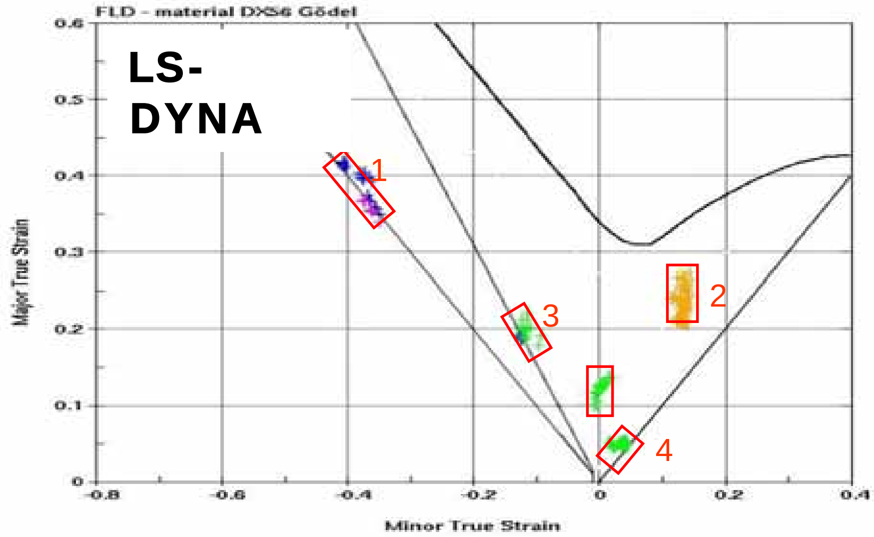


The LS-DYNA forming simulation of TIT Q5 door was prepared by AUDI and Thyssen, the Robustness Evaluation was performed by dynardo.

Comparison base simulation Audi tool – LS-DYNA

The result of the base simulation for the Robustness evaluation show very good agreement overall and in the hot spots. Therefore it is proven, that differences in the two different forming solver are very small.





THINNING

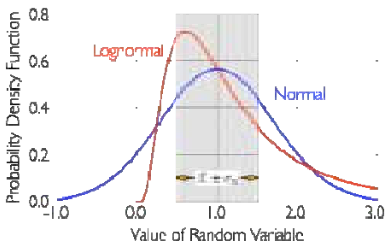
	AUDI forming tool		LS-DYNA
	Maximum	Averaged	
zone 1	2%	0%	0%
zone 2	27%	25%	33%
zone 3	12%	9%	7%
zone 4	12%	8%	9%

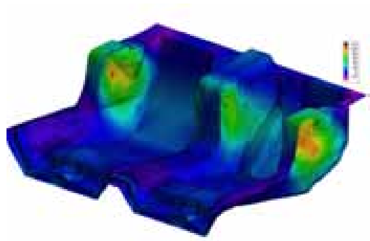
FAILURE

	AUDI forming tool		LS-DYNA
	Maximum	Averaged	
zone 1	0.54	0.52	0.52
zone 2	0.88	0.83	0.81
zone 3	0.57	0.50	0.43
zone 4	0.32	0.18	0.15

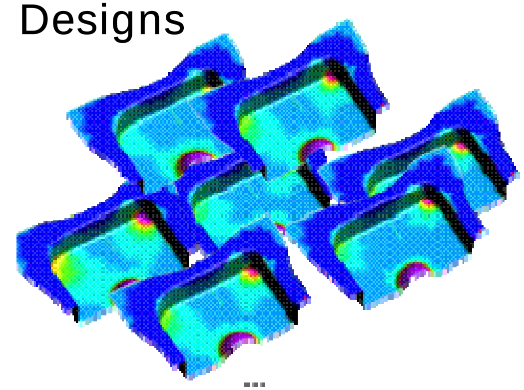
Robustness evaluation using optiSLang

1) Define the robustness space using scatter range, distribution and correlation

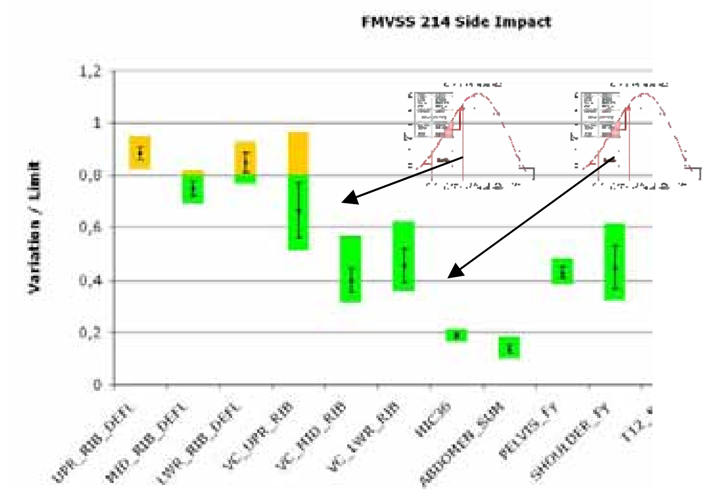




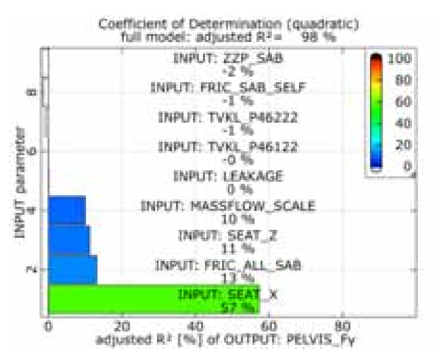
2) Scan the robustness space by producing and evaluating n (100) Designs



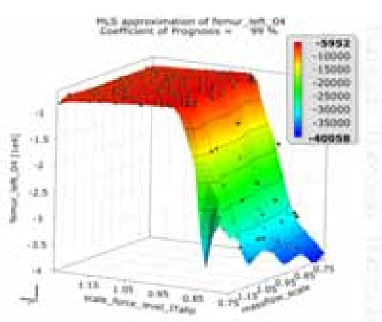
3) Check the variation interval



4) Check the CoP

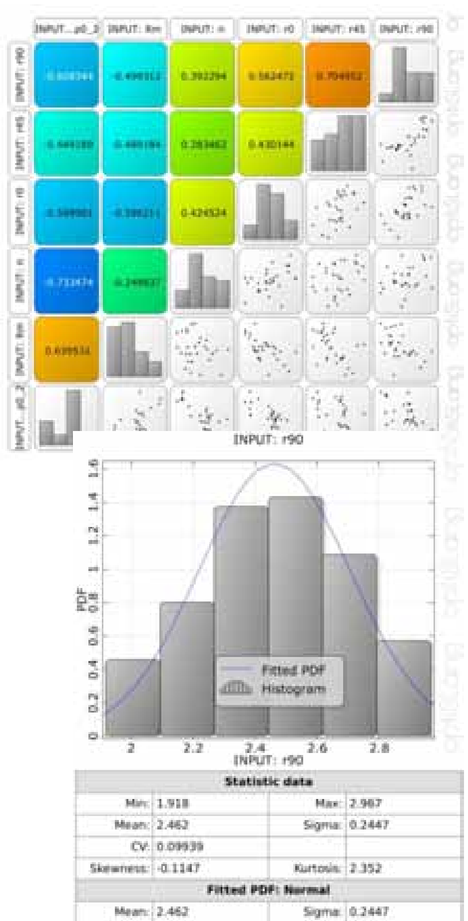


5) Identify the most important scattering variables

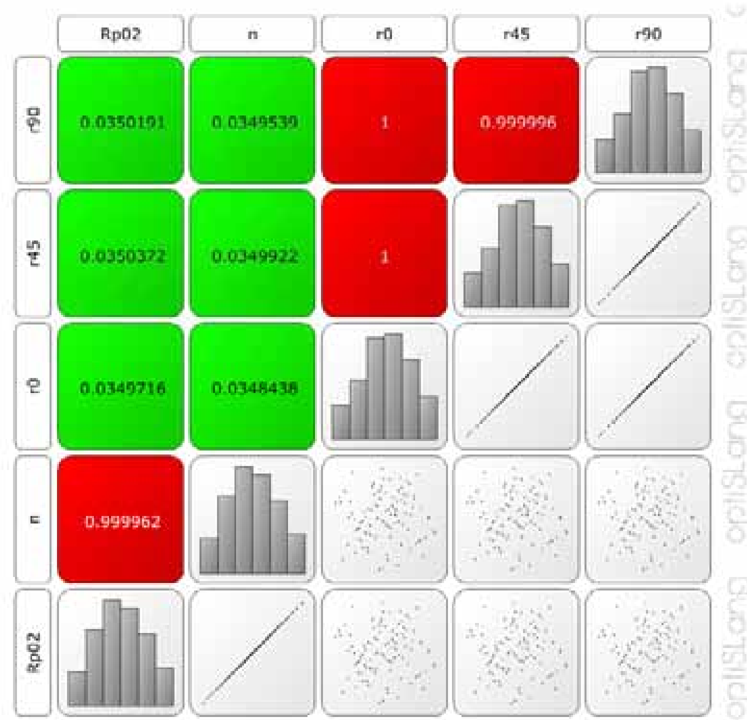


Step A: Recalculation of AUDI Robustness with LS-DYNA using simplified scatter definition

The material scatter were derived from 39 experiments. All variables are defined using truncated normal distribution. For large correlation values (r0,r45,r90 and rp02, n-value) a linear correlation is used. In addition scatter of thickness, positioning, stamping force and friction is taken into account.



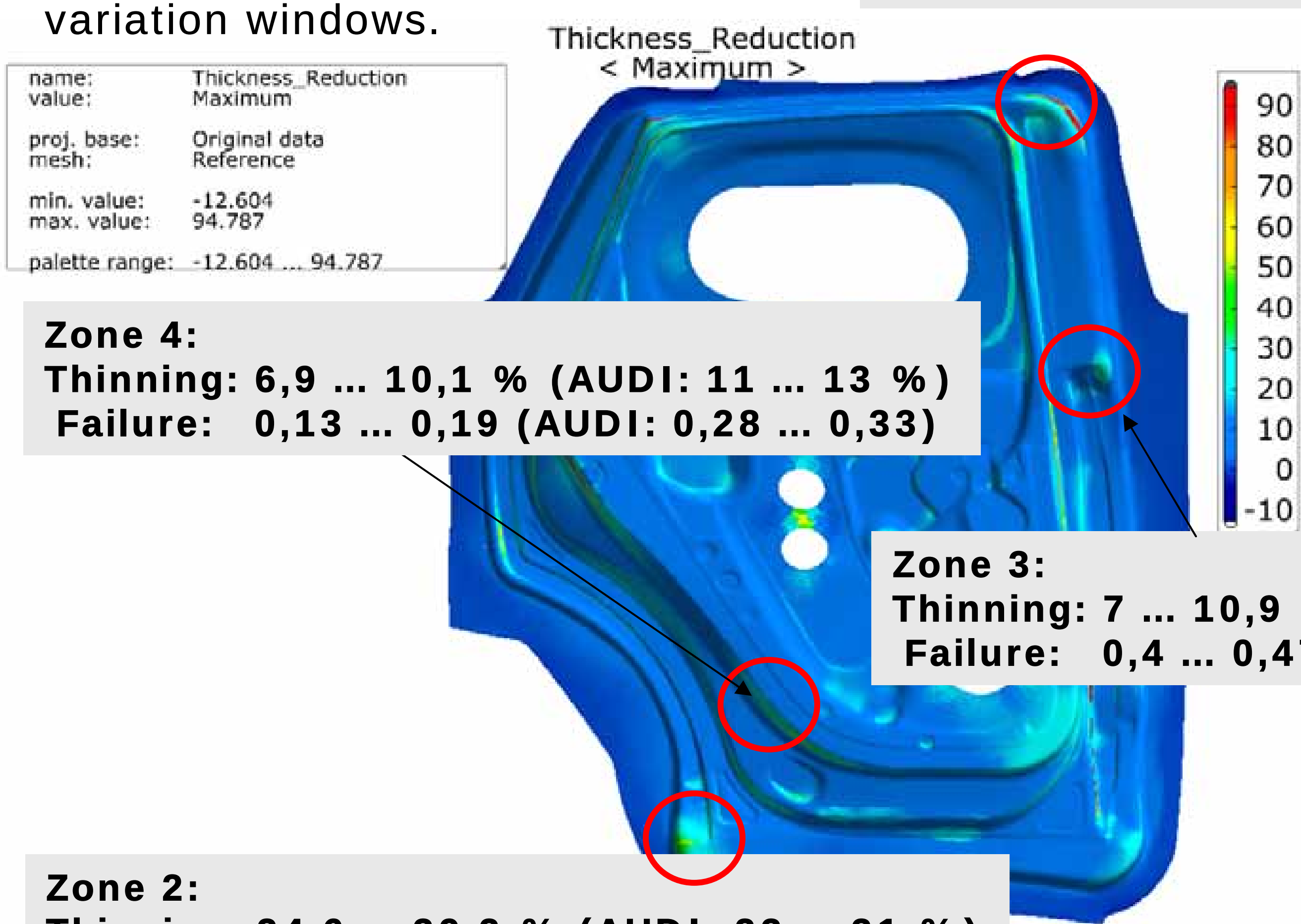
Idealized distribution function



Step A: Variation Windows

All the hot spots show very similar variation windows.

Zone 1:
Thinning: 0,5 … 3,7 % (AUDI: 0 … 4 %)
Failure: 0,51 … 0,59 (AUDI: 0,50 … 0,56)



Zone 4:
Thinning: 6,9 … 10,1 % (AUDI: 11 … 13 %)
Failure: 0,13 … 0,19 (AUDI: 0,28 … 0,33)

Zone 3:
Thinning: 7 … 10,9 % (AUDI: 11 … 15 %)
Failure: 0,4 … 0,47 (AUDI: 0,54 … 0,62)

Zone 2:
Thinning: 24,6 … 39,2 % (AUDI: 23 … 31 %)
Failure: 0,63 … 1,04 (AUDI: 0,76 … 1,0)

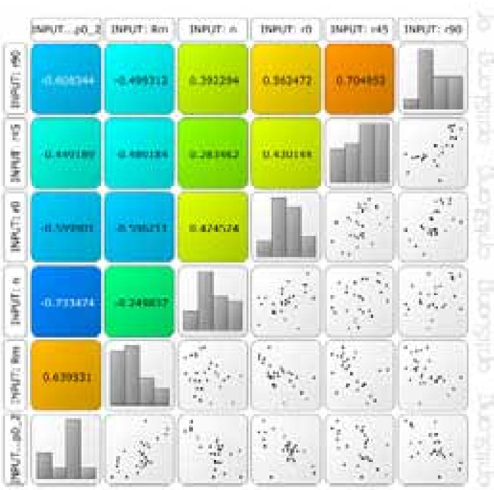
Summary

1. Critical location is hot spot 2
2. Maximum failure values of 1.04 (1.00 AUDI)

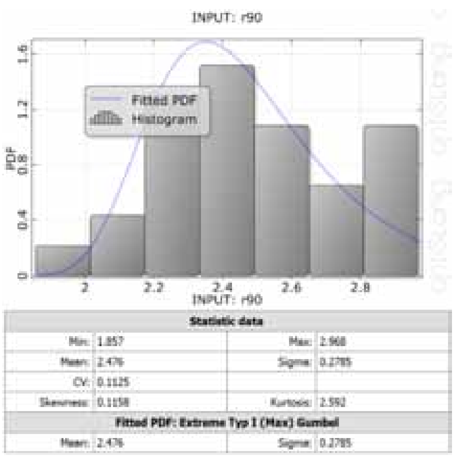
Having a maximal values of 1.00 the process does not violate Robustness Criteria.

Note: Of course using different forming solvers will result in small differences in hot spot values of reference designs as well as hot spot variation windows of robustness evaluation. We prove that this differences are small, therefore we can now go on to investigate the differences in scatter definition.

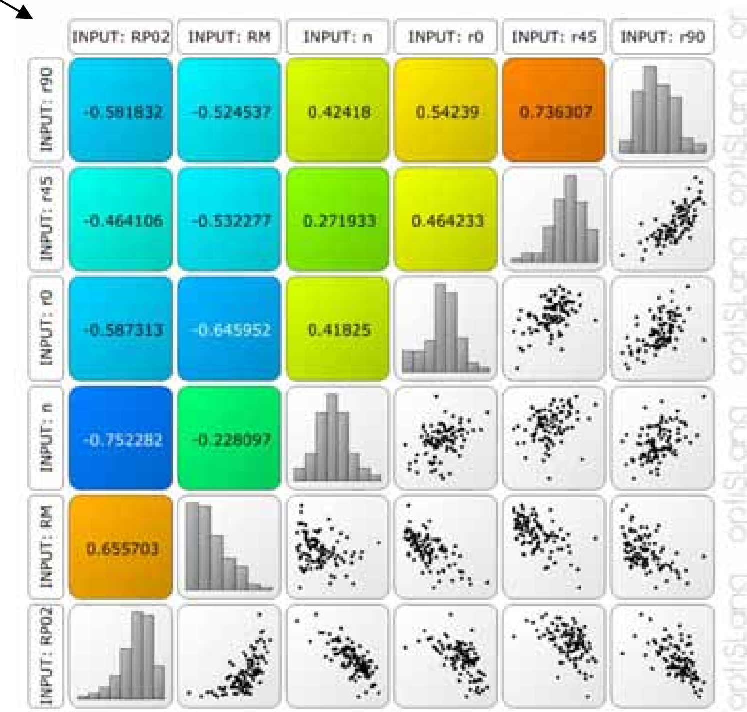
Step B: “best as possible” scatter definition



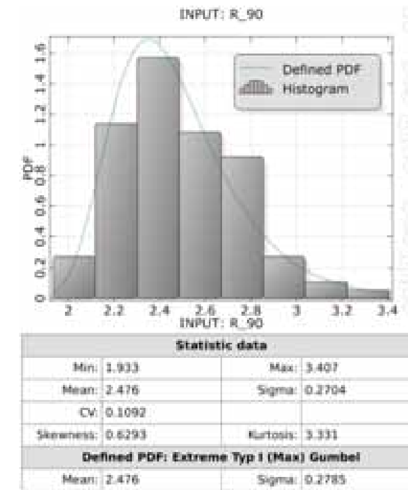
The scatter and correlations of input variables Rp02, Rm, n, r0, r45 and r90 were derived from 39 experiments. The fitted distribution functions and the identified correlation coefficients are used for optiSLang scatter definition.



Fitted distribution function in optiSLang



Generated correlation structure in optiSLang



Defined distribution function in optiSLang

Step B: Variation Windows

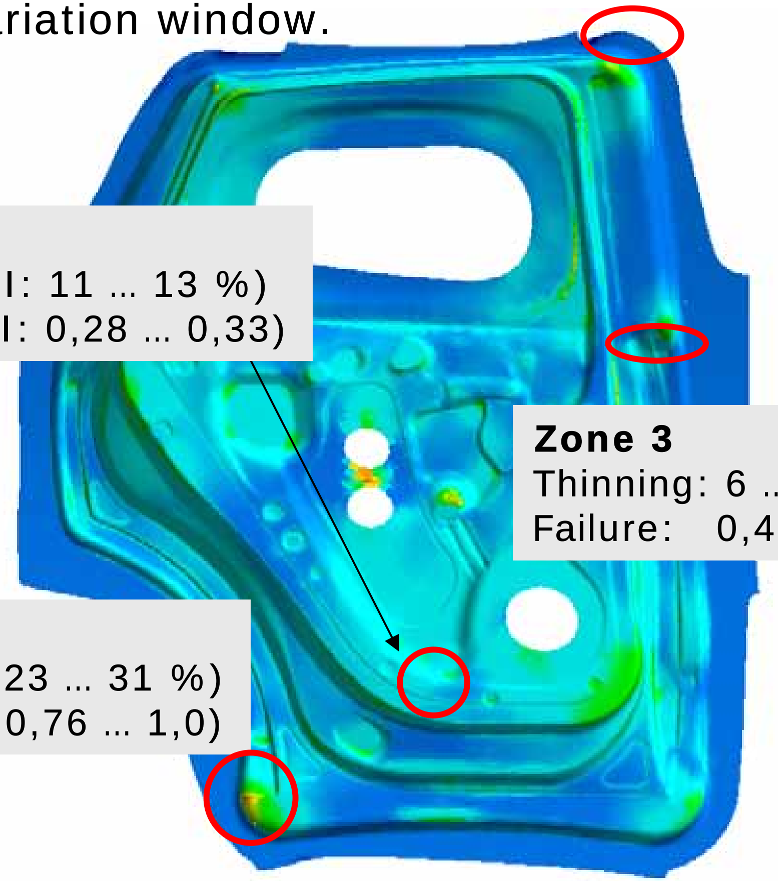
We see much more differences in variation windows of hot spots. Especially the critical hot spot 2 shows much larger variation window.

Zone 1
Thinning: -1 ... 3 % (AUDI: 0 ... 4 %)
Failure: 0,48 ... 0,59 (AUDI: 0,50 ... 0,56)

Zone 4
Thinning: 7 ... 10 % (AUDI: 11 ... 13 %)
Failure: 0,13 ... 0,19 (AUDI: 0,28 ... 0,33)

Zone 3
Thinning: 6 ... 9 % (AUDI: 11 ... 15 %)
Failure: 0,4 ... 0,47 (AUDI: 0,54 ... 0,62)

Zone 2
Thinning: 23 ... 45 % (AUDI: 23 ... 31 %)
Failure: 0,57 ... 1,3 (AUDI: 0,76 ... 1,0)



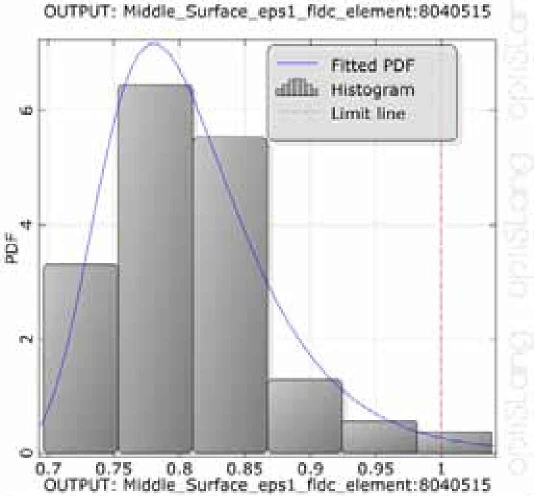
Probability of violating limits

Robustness usually is measured with violation of limits. Here the limit of flc-values is 1.00.

When calculating the probability of failure at hot spot 2 the difference between the two different scatter definitions becomes dramatic.

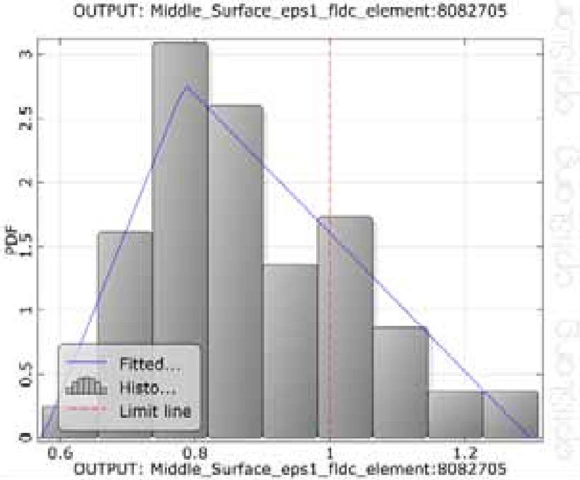
Probability of failure using simplified scatter definitions of **1%** is not critical.

Probability of failure using detailed scatter definition of **25%** correlates much better to the observations of the real world.



Statistic data			
Min:	0.6962	Max:	1.038
Mean:	0.81	Sigma:	0.06575
CV:	0.08117		
Skewness:	0.9223	Kurtosis:	4.421
Fitted PDF: Extreme Typ I (Max) Gumbel			
Mean:	0.81	Sigma:	0.06575
Limit x = 1			
P_rel:	0.989474	1 - P_rel:	0.0105263
P_fit:	0.986307	1 - P_fit:	0.0136933
Sigma-Level:	2.89014		
Probability P(X<x) = 0.9973			
x_rel =	1.03845	x_fit =	1.08352

Simplified scatter definition
Probability of failure=1 ..1.3%
3Sigma Value= 1.04..1.08
2.9 Sigma level



Statistic data			
Min:	0.5739	Max:	1.300
Mean:	0.8851	Sigma:	0.1517
CV:	0.1714		
Skewness:	0.5547	Kurtosis:	2.736
Fitted PDF: Triangular			
Mean:	0.8851	Sigma:	0.1517
Lower cut:	0.5739		
Limit x = 1			
P_rel:	0.737374	1 - P_rel:	0.262626
P_fit:	0.762163	1 - P_fit:	0.237837
Sigma-Level:	0.757313		
Probability P(X<x) = 0.9973			
x_rel =	1.30007	x_fit =	1.26503

Detailed scatter definition
Probability of failure=24..26%
3Sigma Value=1.26..1.31
0.75 Sigma Level

Summary

1. Critical location is hot spot 2
2. Maximum failure values of **1.30** (1.00 AUDI). The probability of failure is app. 25%.

Detailed scatter definition: Having a maximal values of 1.30 and a failure Probability of 25% the process does clearly violate Robustness Criteria.

Simplified scatter definition: Having a maximal values of 1.0 and a failure probability of 1% the robustness evaluation may end with the wrong statement of Robustness.

Note: Because of conservative character of FEA analysis calculated violation of limits of 0..1..2% indicate that process windows is close to the limit. That is expected in forming simulation. With validation to experience and real world measurements we usually state designs „close to limits (robust)“ if we can see failure probability of 1..2% only.

Is it really a surprise?

Only with suitable discretization of input scatter, which is the most important input to any case of robustness/reliability analysis, the robustness problem could be identified!

Summary

Using the Post Processor SoS different hot spots of critical variation of thickness reduction can be identified.

Of course in case of violation we would like to know which input scatter is responsible.

Because local correlation analysis checking single node/element values has there boundaries in case of non-linear problems, Dynardo developed global correlation analysis using Random Field theory.

With the help of Random Field and the scatter can be decomposed into the mechanisms (scatter shapes).

Background correlation analysis

Local correlation analysis

Dynardo extend the local (element wise) correlation to multi dimensional nonlinear correlation analysis combined with automatic reduction to the most important parameters and search for optimal meta model (MoP Metamodel of optimal Prognosis) regarding optimal forecast quality (CoP - Coefficient of Prognosis) of variation.

- unique optiSLang functionality

Global correlation analysis

If scatter of response values result from different mechanisms we may need to decompose the different mechanisms and their sources. Like modal analysis which decompose the vibration behavior, DYNARDO has developed decomposition of response scatter into **scatter shapes**.

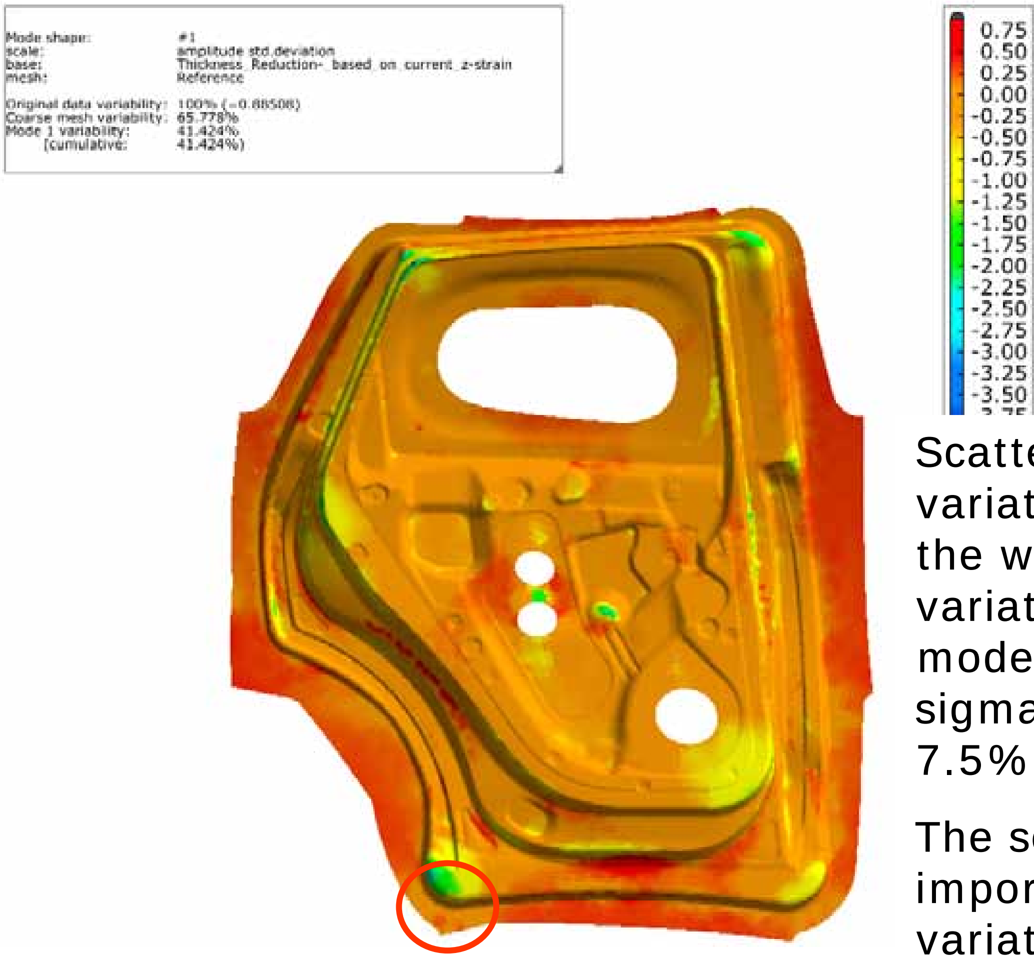
Amplitudes of scatter shapes are calculated as sigma values of variation.

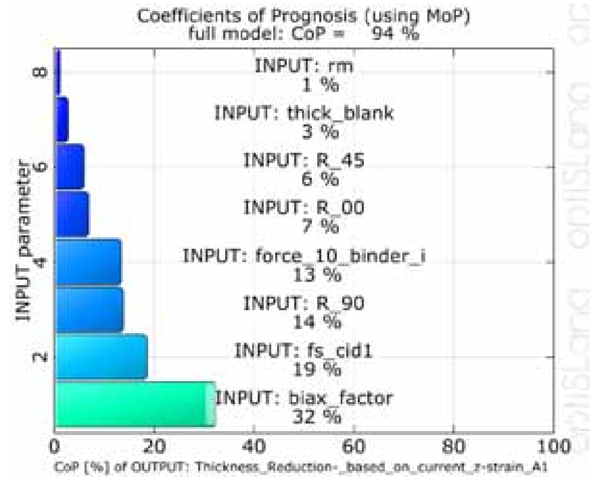
Correlation between amplitude and input scatter identifies the sources of scatter of every mechanism separately.

- unique optiSLang functionality

Verification of global and local correlation analysis result in reliable results about variable importance and explainability/uniquness of response values.

Thickness reduction - mode 1

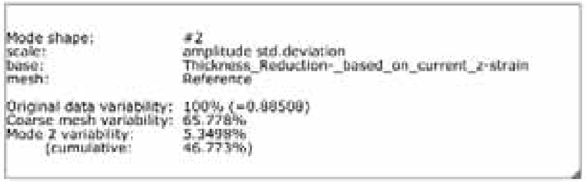


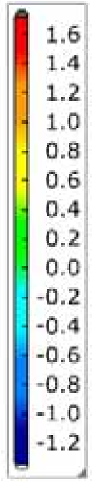


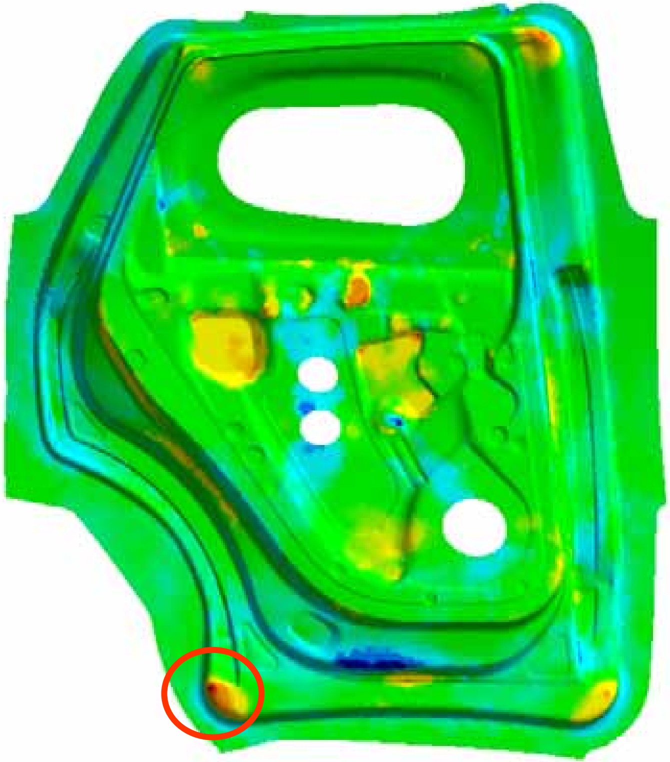
Scatter mode 1 explains 41% of the variation of the Thickness reduction across the whole structure. In zone 2, the variation is significantly influenced by mode 1. The amplitude in zone 2 reach a sigma value of 2.5, which explains up to 7.5% of scatter at 3-Sigma probability.

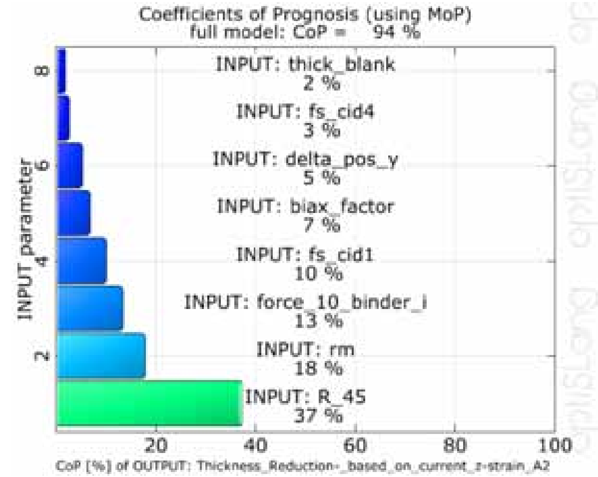
The scatter of biax_factor has the most important influence on the overall total variation of thickness reduction, represented at scatter shape 1.

Thickness reduction - mode 2





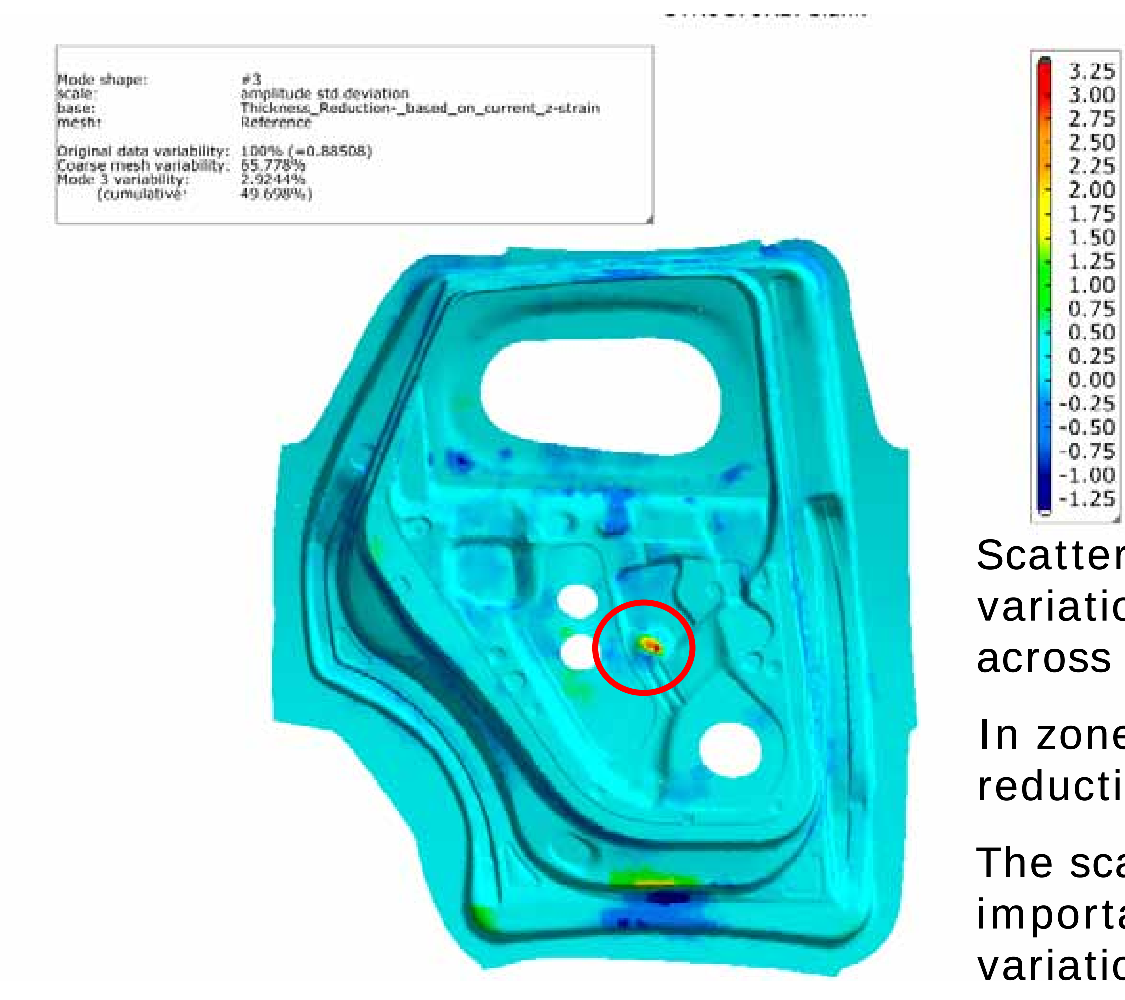


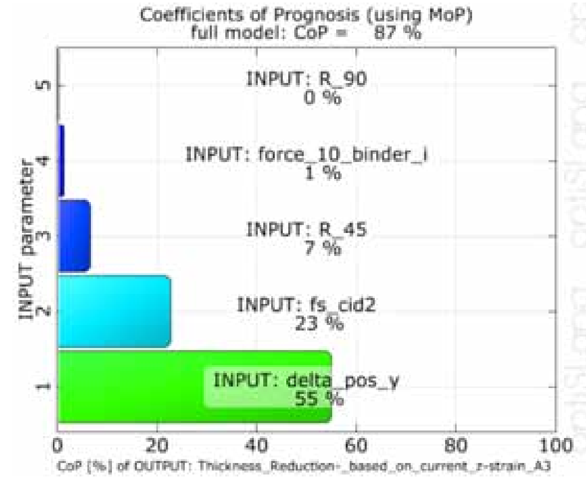


Scatter mode 2 explains 5% of the variation. In zone 2, the variation of thickness reduction is significantly influenced by mode 2. The amplitude in zone 2 reach a sigma value of 1.5, which explains up to 4.5% of scatter at 3-Sigma probability.

The scatter of R_45 has the most important influence on the overall total variation of thickness reduction, represented at scatter shape 2.

Thickness reduction - mode 3





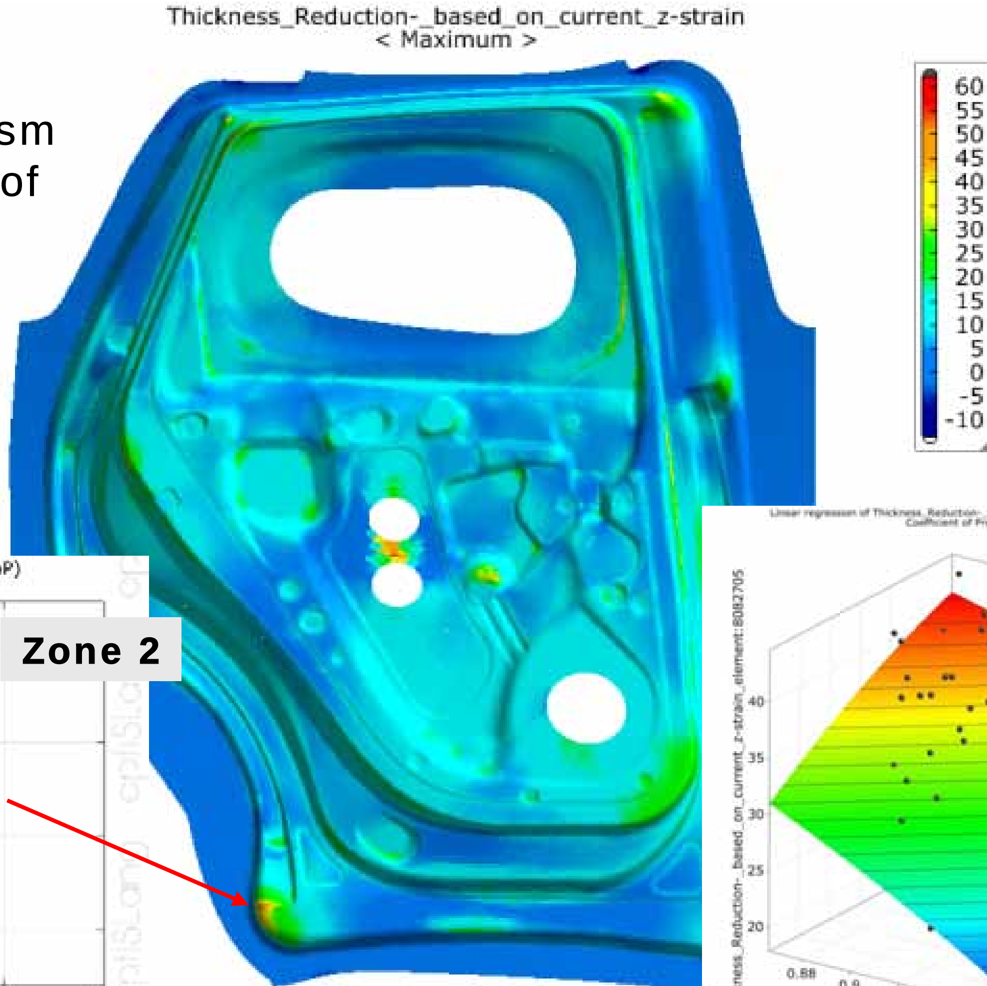
Scatter mode 3 explains 3% of the variation of the Thickness reduction across the whole structure.

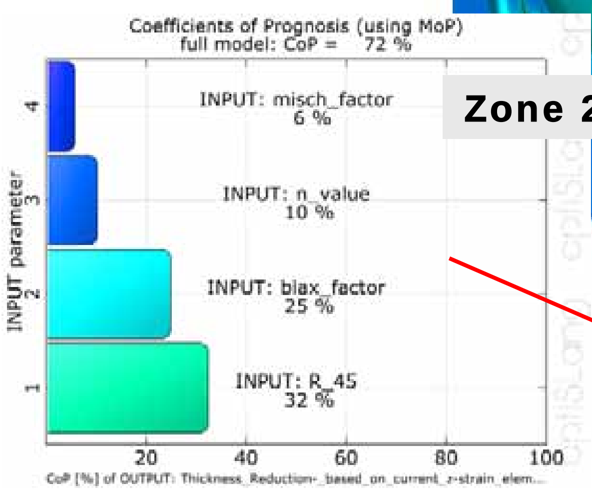
In zone 2, the variation of thickness reduction is not influenced by mode 3.

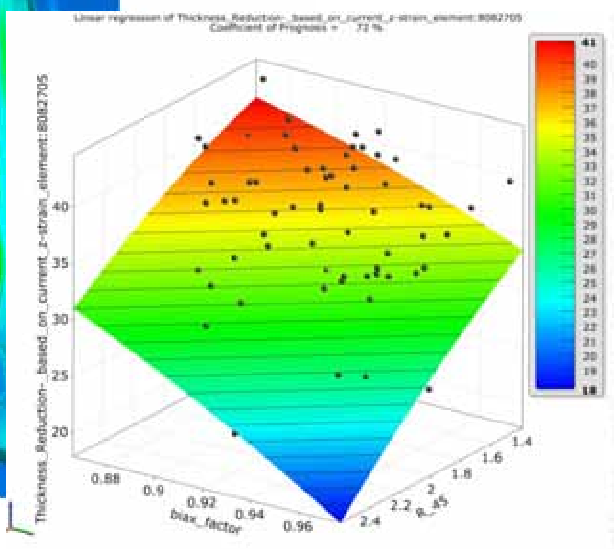
The scatter of delta_pos_y has the most important influence on the overall total variation of thickness reduction, represented at scatter shape 3.

Thickness reduction – local correlation analysis

Note: Because of different mechanism the explainability of local correlation analysis drops down.

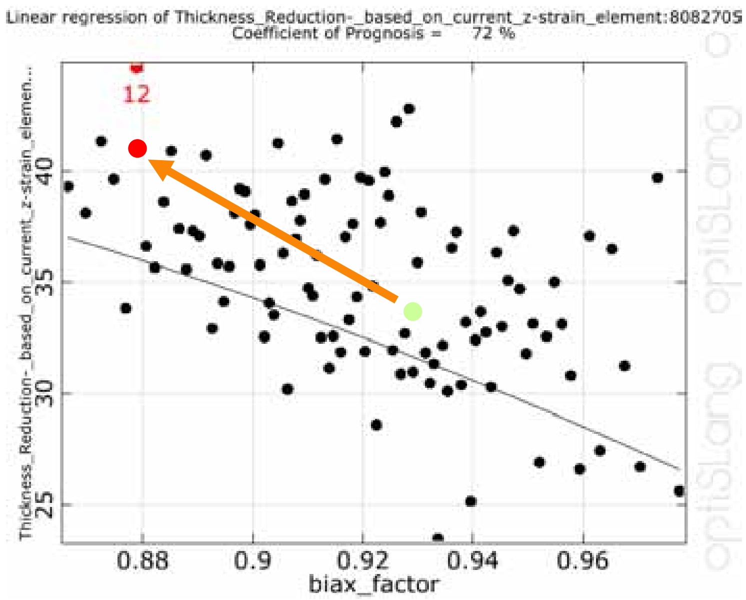


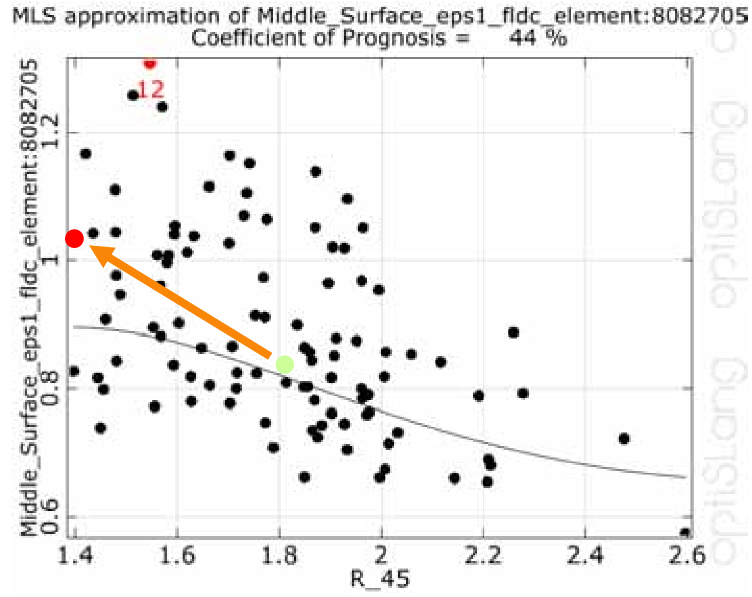




Verification – design „worst case“ data set for zone 2

In zone 2, the most important input variation regarding thickness reduction and failure variation result from R_45 and biax_factor. Design 12 shows the highest failure in zone 2. For the reference the failure is < 1.0.





We choose (yield curve, M-value) with low biax_factor and combine with lower limit for R_45 (=1.345). Other inputs are unchanged compared to reference.

Reference Zone 2:
Thinning: 33 %
Failure: 0,81

„Worst case“ Zone 2:
Thinning: 41 %
Failure: 1,05

Summary

1. Critical location is hot spot 2
2. Maximum failure values of **1.30** (1.00 AUDI). The probability of failure is app. 25%.
3. Global scatter shape analysis indicates that the important source of the total variation of thickness reduction and failure for zone 2 is the scatter of anisotropy R45 (R90, R0) and biax-factor.
4. The local analysis for zone 2 indicate, that scatter of R45, biax-factor and misch-factor is the most important scatter source for thickness reduction scatter and failure at hot spot 2.
5. The correlation analysis is confirmed with an created „worst case". Low biax values in combination with low R_45 values result in high thinning and high failure rates. That „worst case" should be used in virtual prototyping to evaluate any design modification to improve design robustness.

Outlook

Numerical Robustness Evaluations are the key for robust design in virtual prototyping.

With realistic definitions of input scatter reliable Robustness analysis is possible.

By using global scatter shape analysis and a local element based correlation analysis the correlation structure (Who is responsible for the result scatter) can be identified as well as the explainability of the measures can be evaluated (which mechanisms/how much numerical noise/effects).

With optimized Latin Hypercube Samplings the number of samples of the stochastic analysis to identify the responsable scattering input variables can be minimized.