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Optimization and Robustness Evaluation of the Force-Stroke-Characteristic of a Solenoid Actuator for Hydraulic Proportional Valves

Weimar, 2020-06-25

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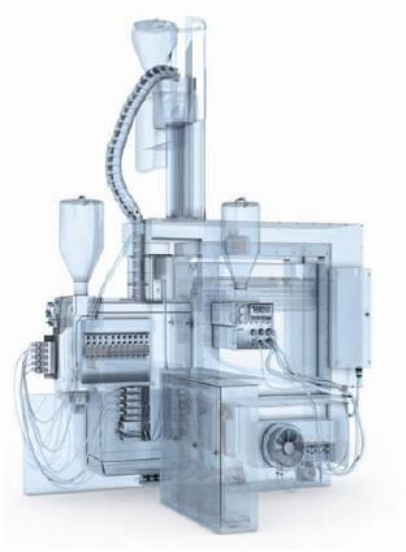

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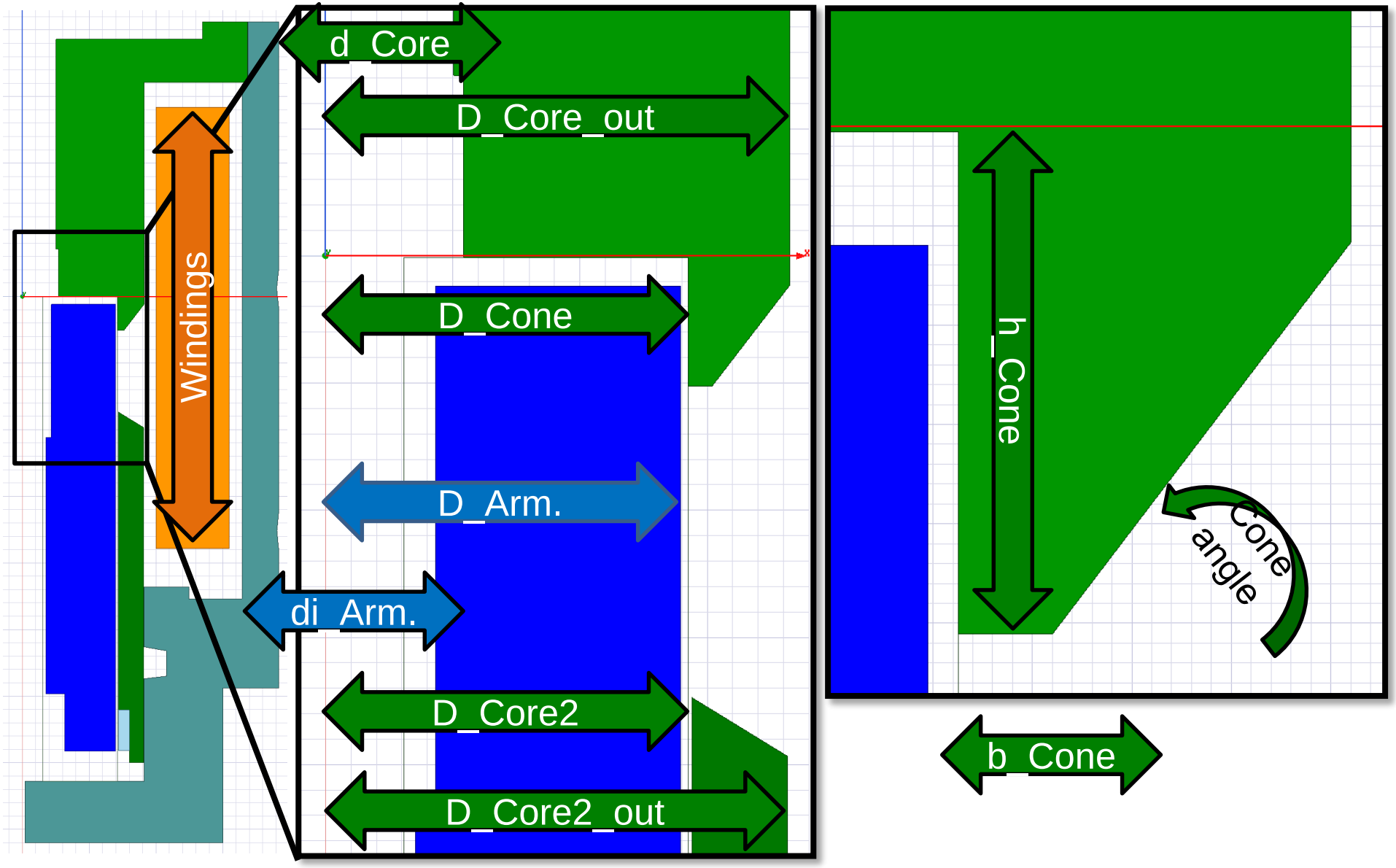
Parameter - Geometry

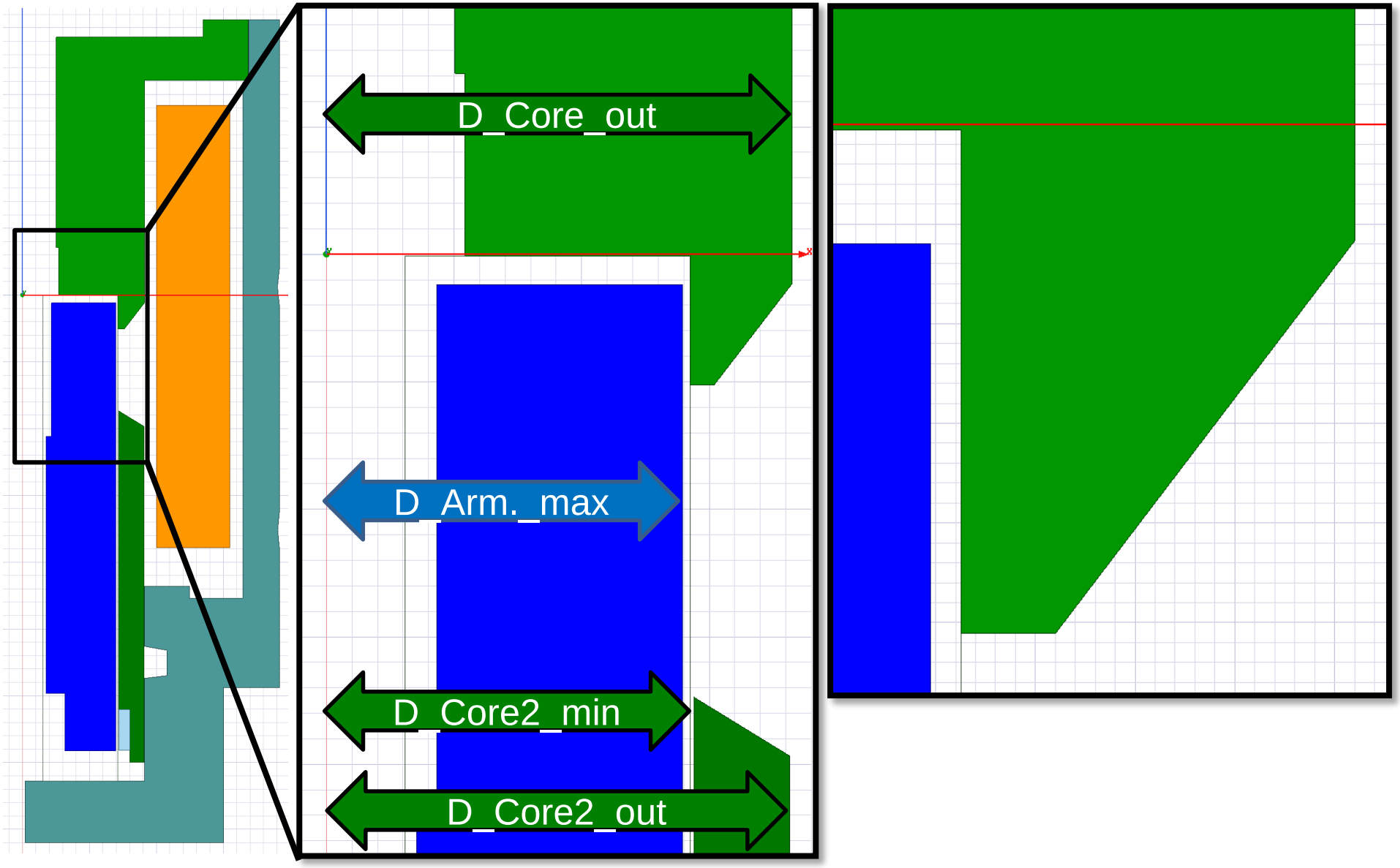
For Robustness Evaluation



:

Parameter - Geometry

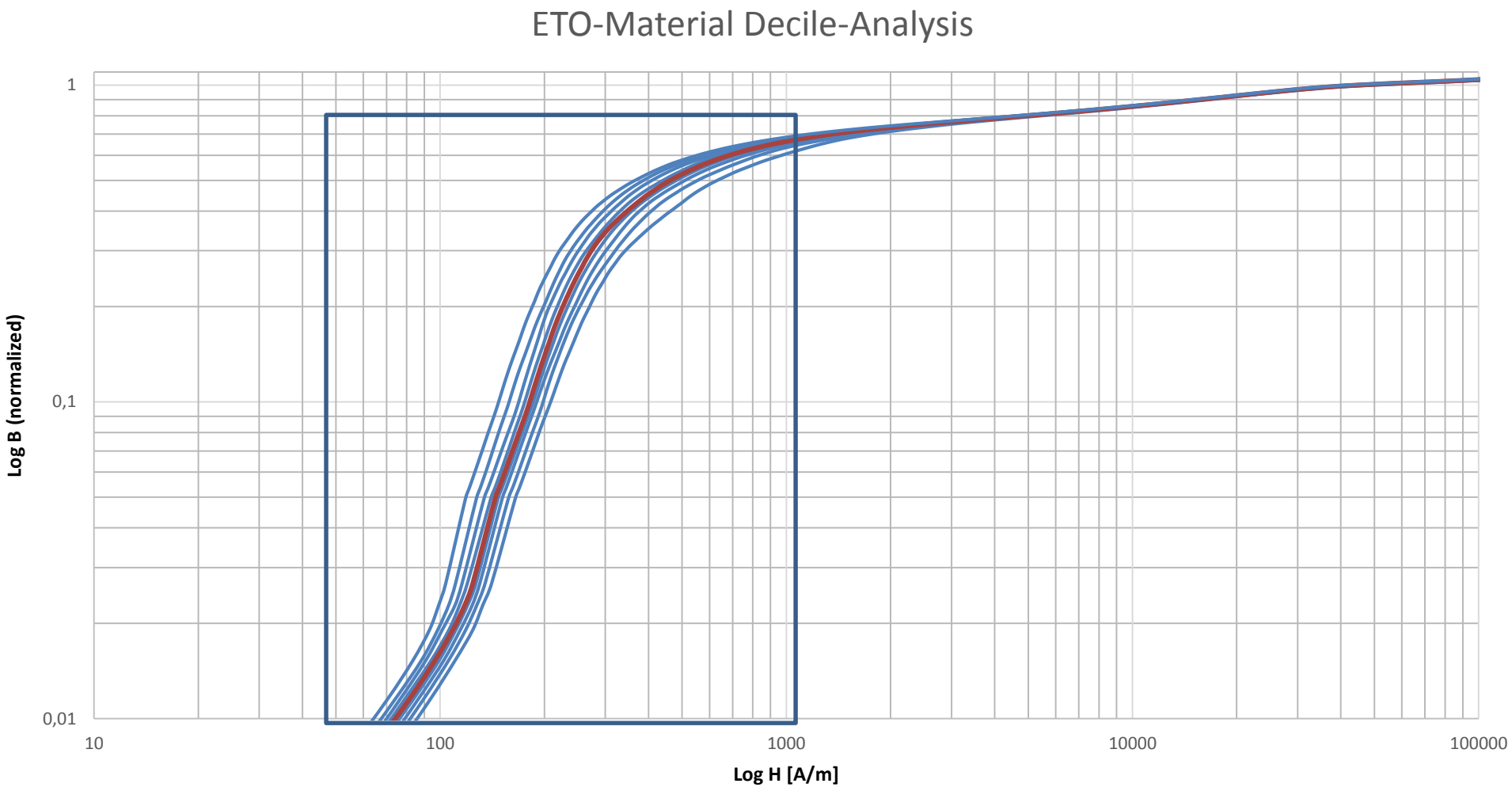
Constant Values for Optimization



:

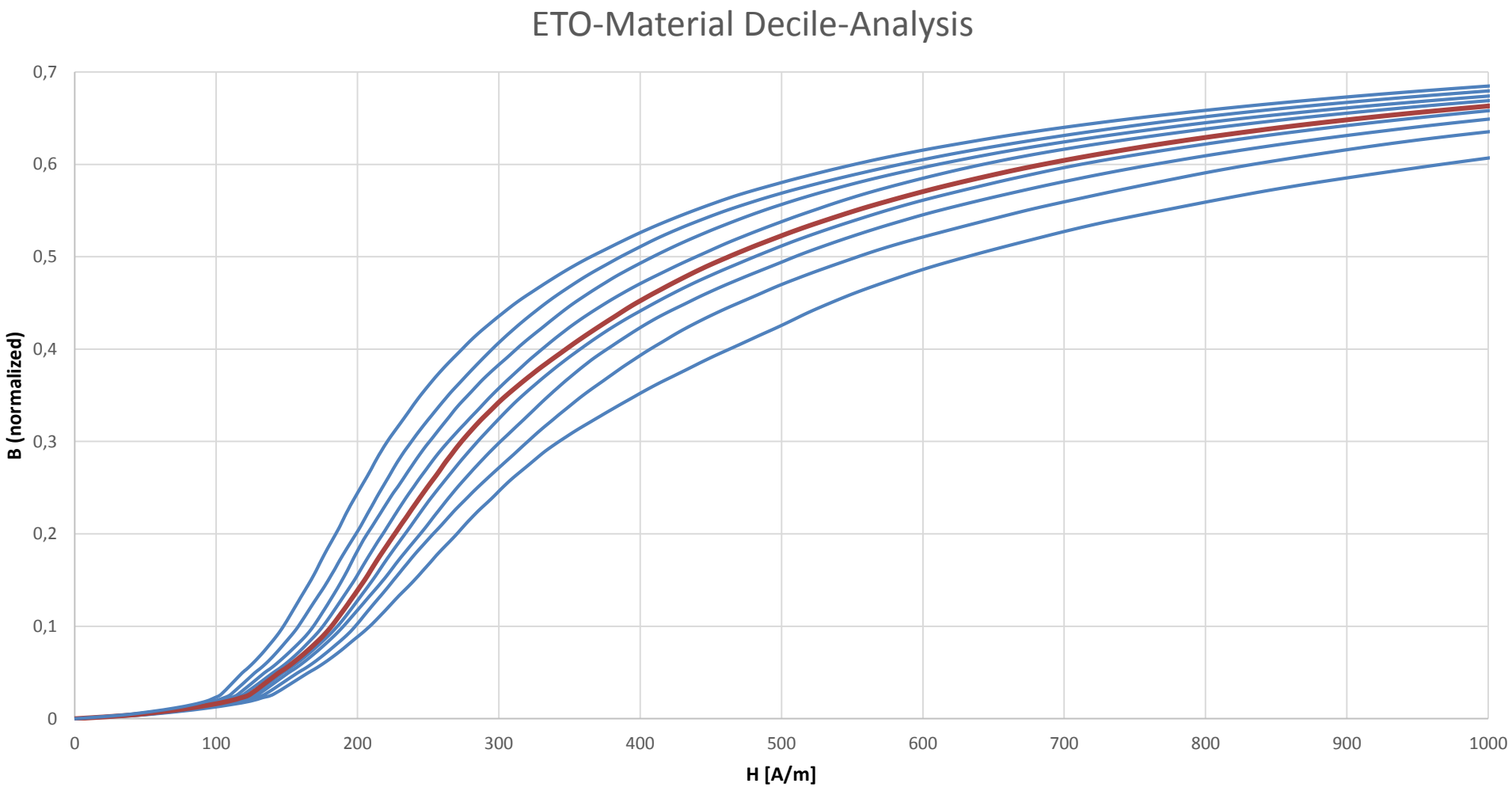
Parameter - Material

ETO-Material BH-Characteristic



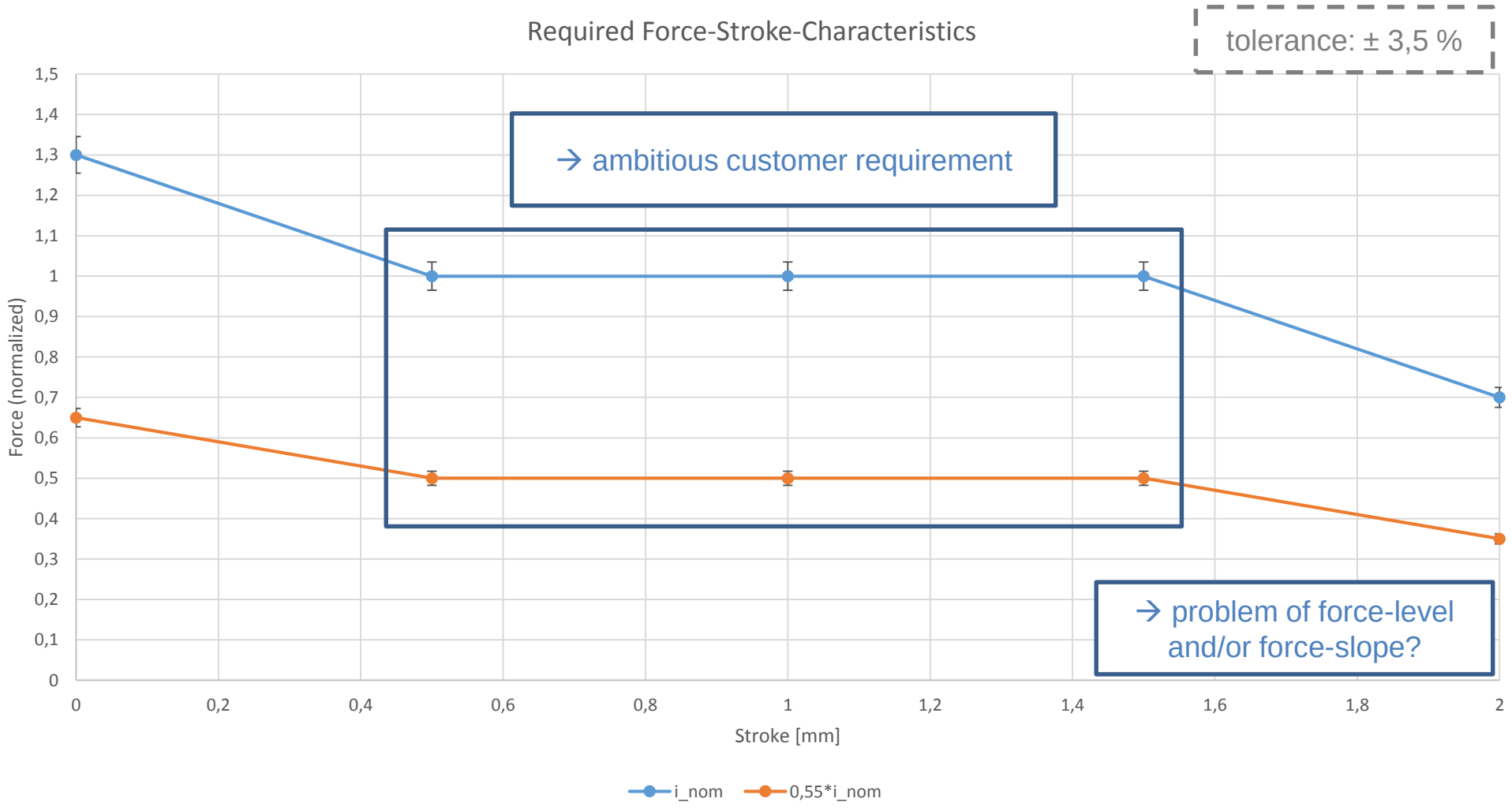
Parameter - Material

Problem: High Material Influence



Motivation

2 Force-Stroke-Characteristics (FSC) @ 2 Actuation Currents



Goals

1. **Increase robustness of Force-Stroke-Characteristics (FSC) on 2 ways:**

   a. **Cone optimization**

      → **Perfect straight-lined FSC**

      → **Perfect tolerance-centered FSC**

   b. **Working area shift**

      → **Material influence reduction**

2. **Quantify material influence**
3. **Get design ideas**

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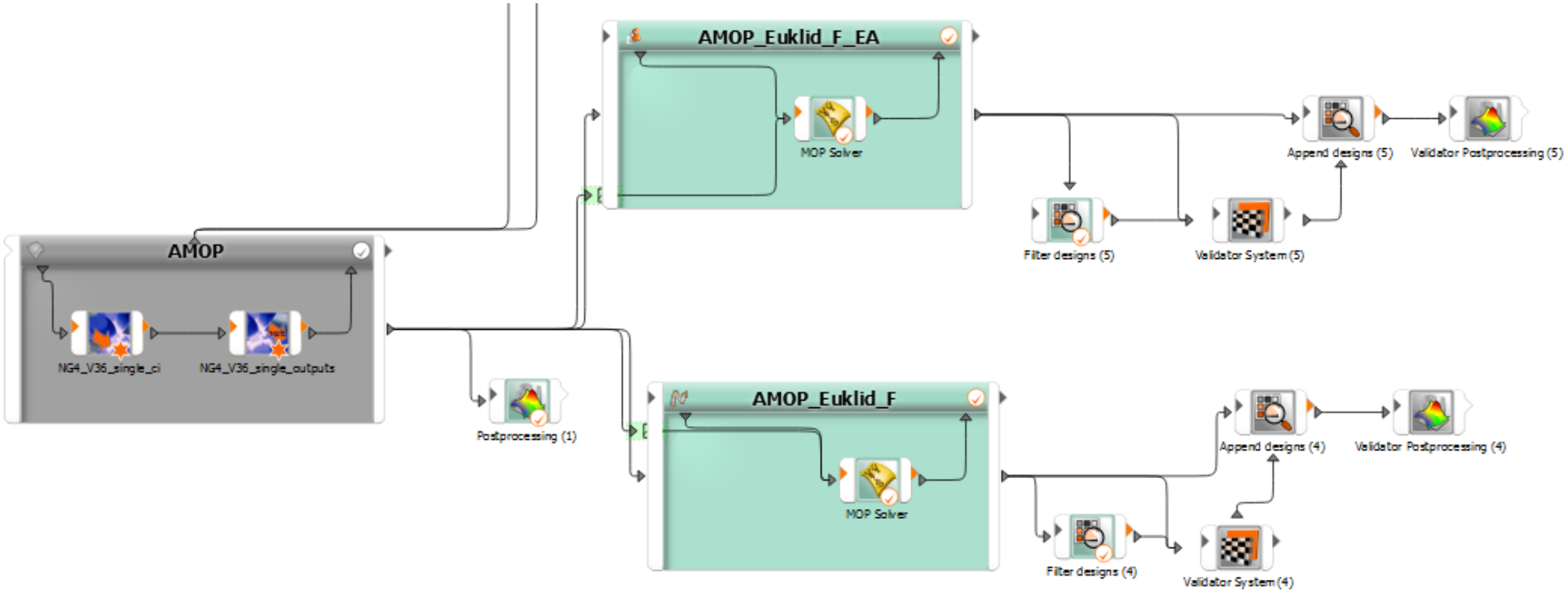
Workflow


AMOP_Euklid_F_EA
MOP Solver
Append designs (5)
Validator Postprocessing (5)
Filter designs (5)
Validator System (5)
AMOP
NG4_V36_single_ci
NG4_V36_single_outputs
Postprocessing (1)
AMOP_Euklid_F
MOP Solver
Append designs (4)
Validator Postprocessing (4)
Filter designs (4)
Validator System (4)

Sensitivity Analysis

CoP Matrix

Total effects

Models	b_Konus	Konus_Winkel	w	h_Konus	D_Kern2	D_Konus	di_Anker	Total
Fds_vec_1p3[4]	11.1 %	1.6 %	21.3 %	79.3 %		11.8 %	1.0 %	98.3 %
Fds_vec_1p3[3]	15.6 %	2.4 %	23.4 %	58.7 %		17.5 %	1.9 %	98.8 %
Fds_vec_1p3[2]	22.6 %	5.8 %	27.9 %	25.9 %		35.8 %	3.2 %	99.0 %
Fds_vec_1p3[1]	20.7 %	7.4 %	27.7 %	14.5 %		52.3 %	3.6 %	99.2 %
Fds_vec_1p3[0]	19.6 %	7.5 %	28.5 %	11.0 %		60.2 %	3.6 %	99.3 %
Fds_vec_0p72[4]	7.5 %		13.0 %	96.0 %		16.8 %		96.7 %
Fds_vec_0p72[3]	11.8 %		15.7 %	76.9 %		20.1 %	3.9 %	94.5 %
Fds_vec_0p72[2]	24.4 %	5.2 %	28.7 %	35.2 %		45.3 %	4.2 %	96.9 %
Fds_vec_0p72[1]	0.0 %	0.0 %	17.5 %	12.6 %		39.6 %		59.7 %
Fds_vec_0p72[0]	0.0 %	0.0 %	8.5 %	8.2 %		25.1 %		37.0 %
F_vec_1p3[4]	6.2 %		76.1 %	6.9 %		56.9 %		97.3 %
F_vec_1p3[3]	7.6 %		73.1 %	4.9 %		56.0 %	0.4 %	98.0 %
F_vec_1p3[2]	9.9 %		68.2 %	6.0 %		49.7 %	0.7 %	97.6 %
F_vec_1p3[1]	14.1 %		61.6 %	9.8 %	2.0 %	39.7 %	1.9 %	98.8 %
F_vec_1p3[0]	19.9 %	8.7 %	49.0 %	15.7 %	1.9 %	24.8 %	3.8 %	99.4 %
F_vec_0p72[4]	4.3 %		71.8 %	8.3 %		63.6 %		97.8 %
F_vec_0p72[3]	5.1 %	5.4 %	69.8 %	2.8 %	1.2 %	65.1 %		99.3 %
F_vec_0p72[2]	4.4 %		72.0 %	3.2 %	1.8 %	61.9 %		98.5 %
F_vec_0p72[1]			73.4 %	2.5 %	2.3 %	52.7 %		97.1 %
F_vec_0p72[0]			71.4 %	6.4 %	4.1 %	43.3 %		89.9 %

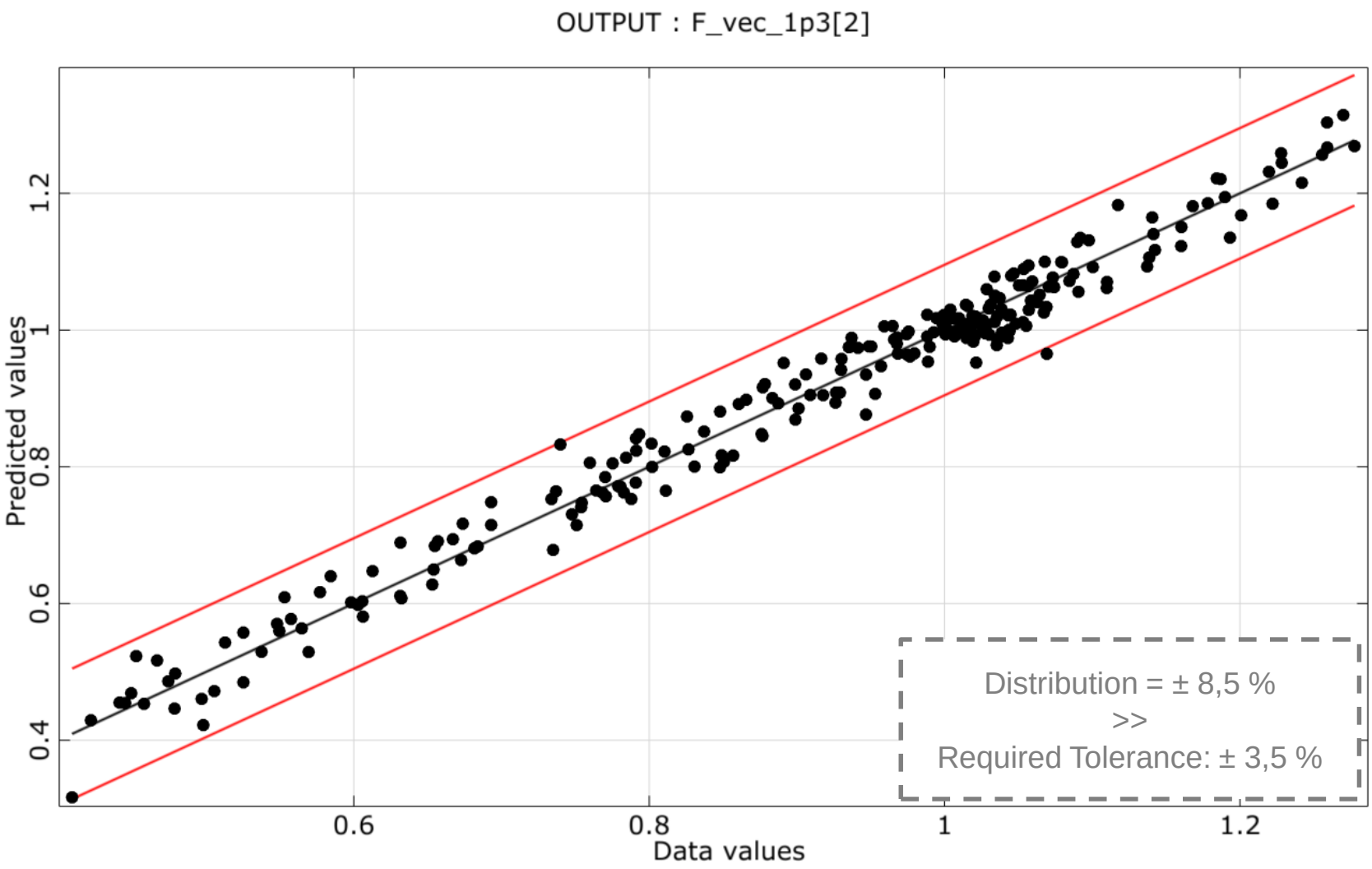
Parameter

→ no significant influence of cone angle?

→ problem of force-level and/or force-slope?

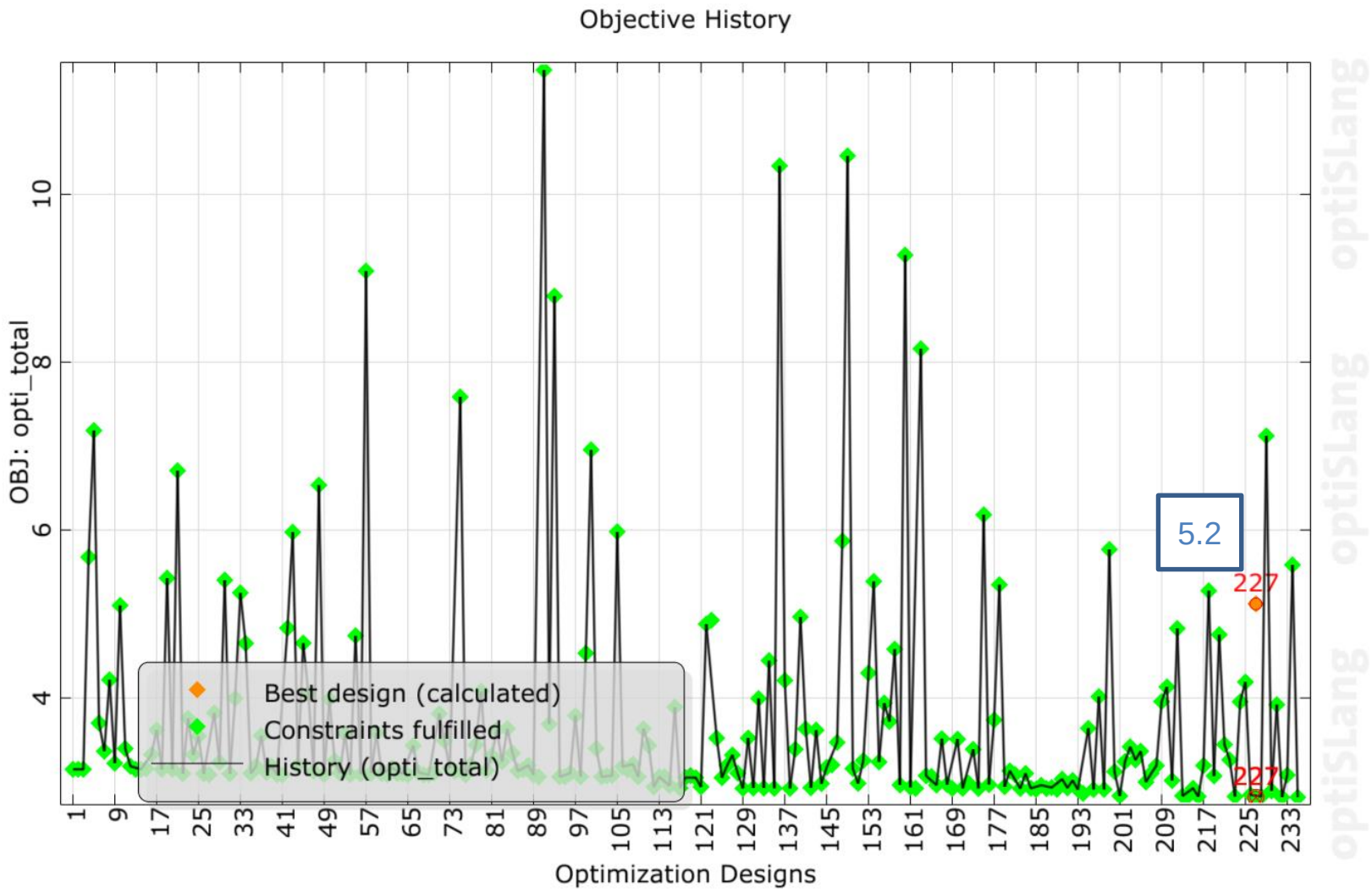
Sensitivity Analysis

Residual Plot



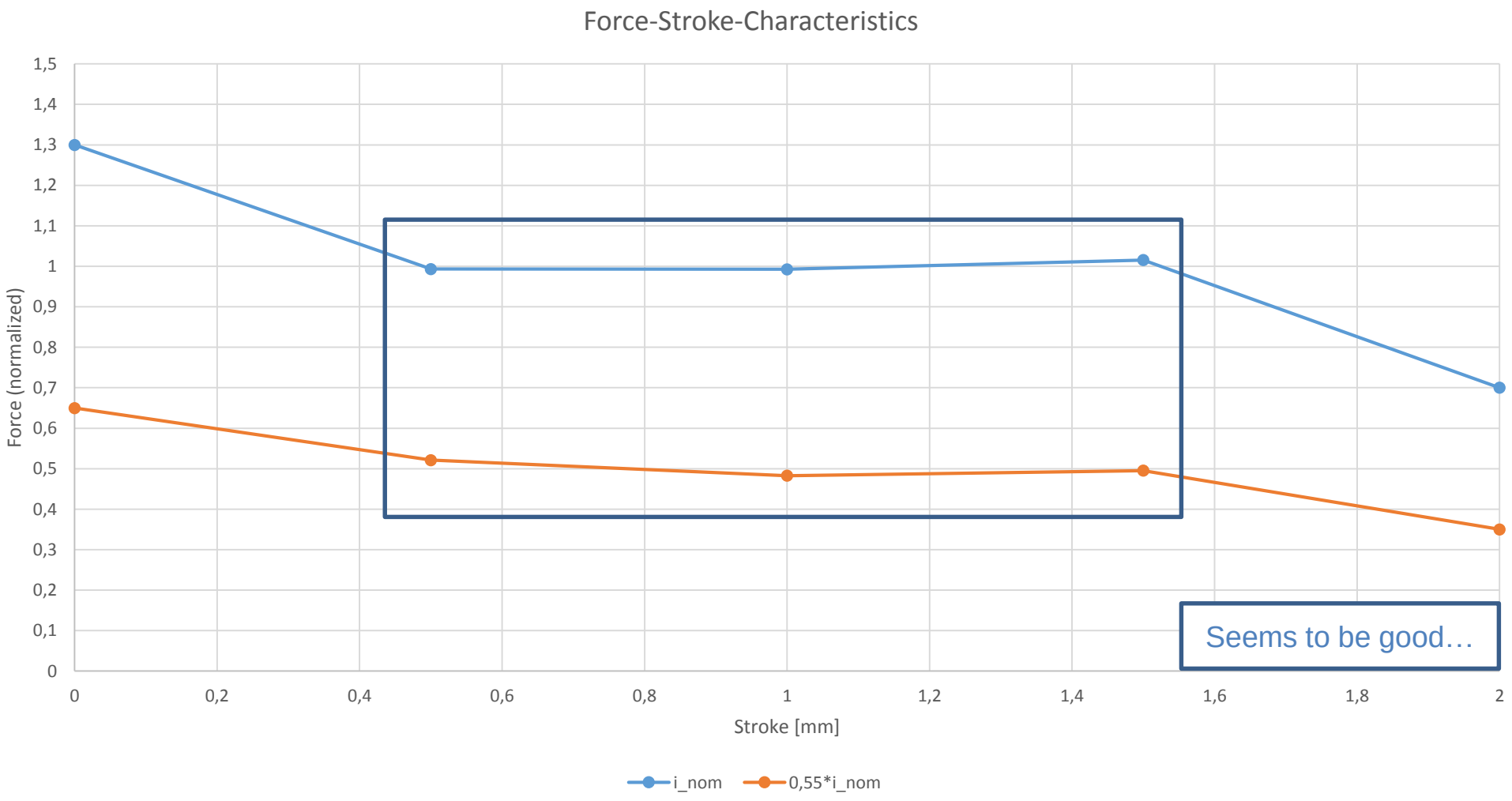
Optimization on the MOP

Convergency of EA



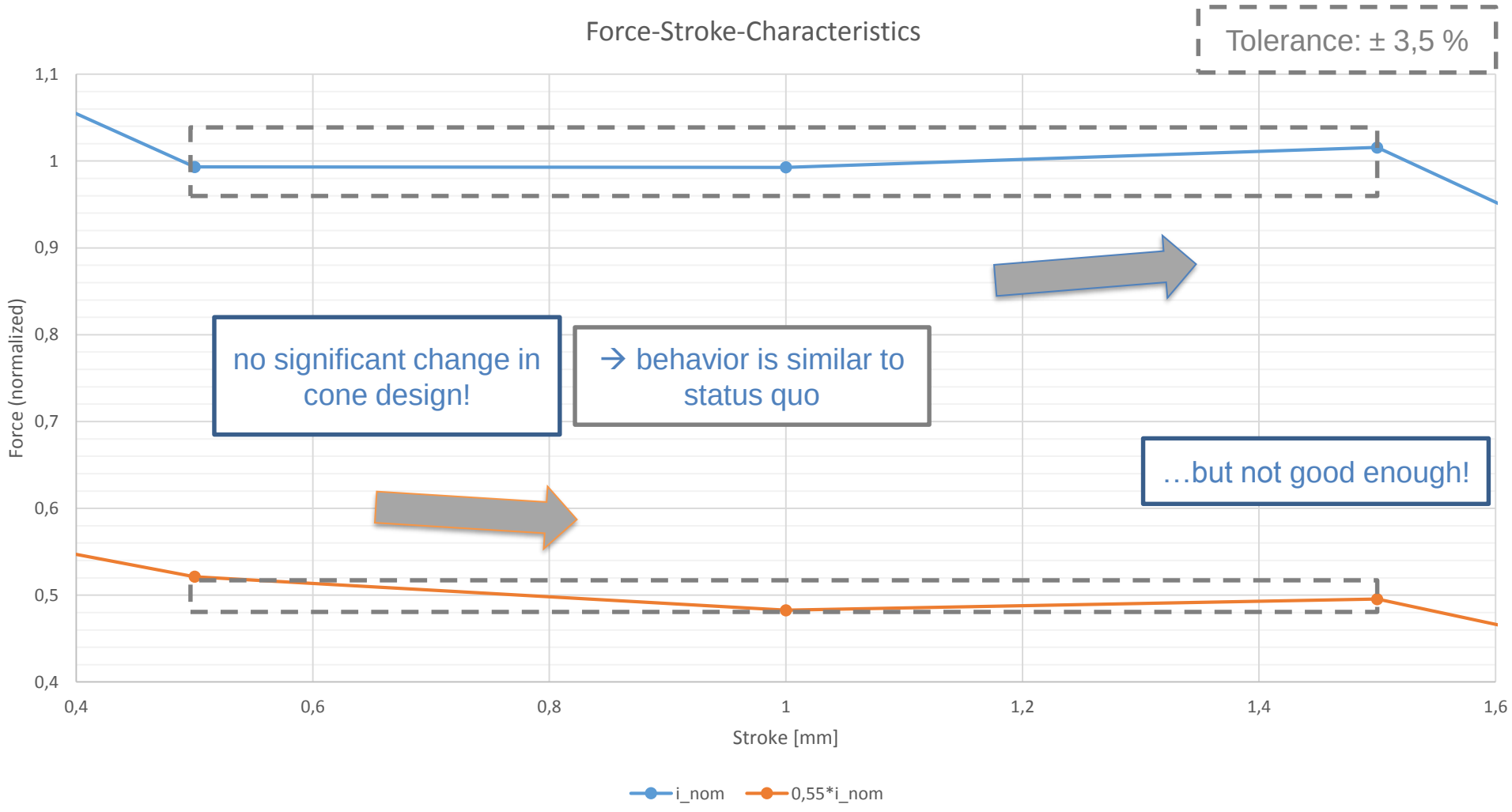
Optimization on the MOP

Best Result



Optimization on the MOP

Best Result



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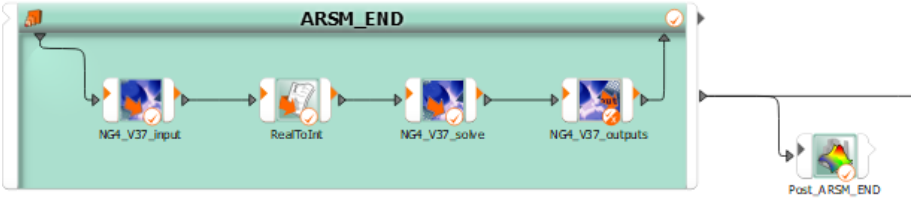
Optimization on the Model

Setup



	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range		Range plot
1	Abbrand	Opt.+Stoch.	0.2	☑	REAL	Continuous	0	0.3	
2	Anker_index	Opt.+Stoch.	4	☑	REAL	Discrete by value	0; 1; 2; 3; 4; 5; 6; 7; 8		
3	b_Konus	Opt.+Stoch.	0.5	☐	REAL	Continuous	0.3	1.5	
4	D_Anker	Opt.+Stoch.	13.97	☐	REAL	Continuous	13	13.97	
5	d_Kern	Opt.+Stoch.	5	☐	REAL	Continuous	5	7	
6	D_Kern2	Opt.+Stoch.	14.37	☐	REAL	Continuous	14.37	15.37	
7	D_Kern2_aussen	Opt.+Stoch.	18.19	☑	REAL	Continuous	16.371	20.009	
8	D_Kern_aussen	Opt.+Stoch.	18.19	☑	REAL	Continuous	16.371	20.009	
9	D_Konus	Opt.+Stoch.	14.24	☐	REAL	Continuous	14.24	15.24	
10	di_Anker	Opt.+Stoch.	4.33	☐	REAL	Continuous	4.33	6.33	
11	Gehaeuse_index	Opt.+Stoch.	1	☑	REAL	Discrete by value	0; 1; 2		
12	h_Konus	Opt.+Stoch.	2.55	☐	REAL	Continuous	2	3	
13	h_Konus_Boden	Opt.+Stoch.	0	☑	REAL	Continuous	-1	1	
14	Kern_index	Opt.+Stoch.	4	☑	REAL	Discrete by value	0; 1; 2; 3; 4; 5; 6; 7; 8		
15	Konus_Winkel	Opt.+Stoch.	52.7	☐	REAL	Continuous	42	70	
16	w	Opt.+Stoch.	700	☐	REAL	Continuous	600	800	

Optimization on the Model

Optimization Goals and Constraints

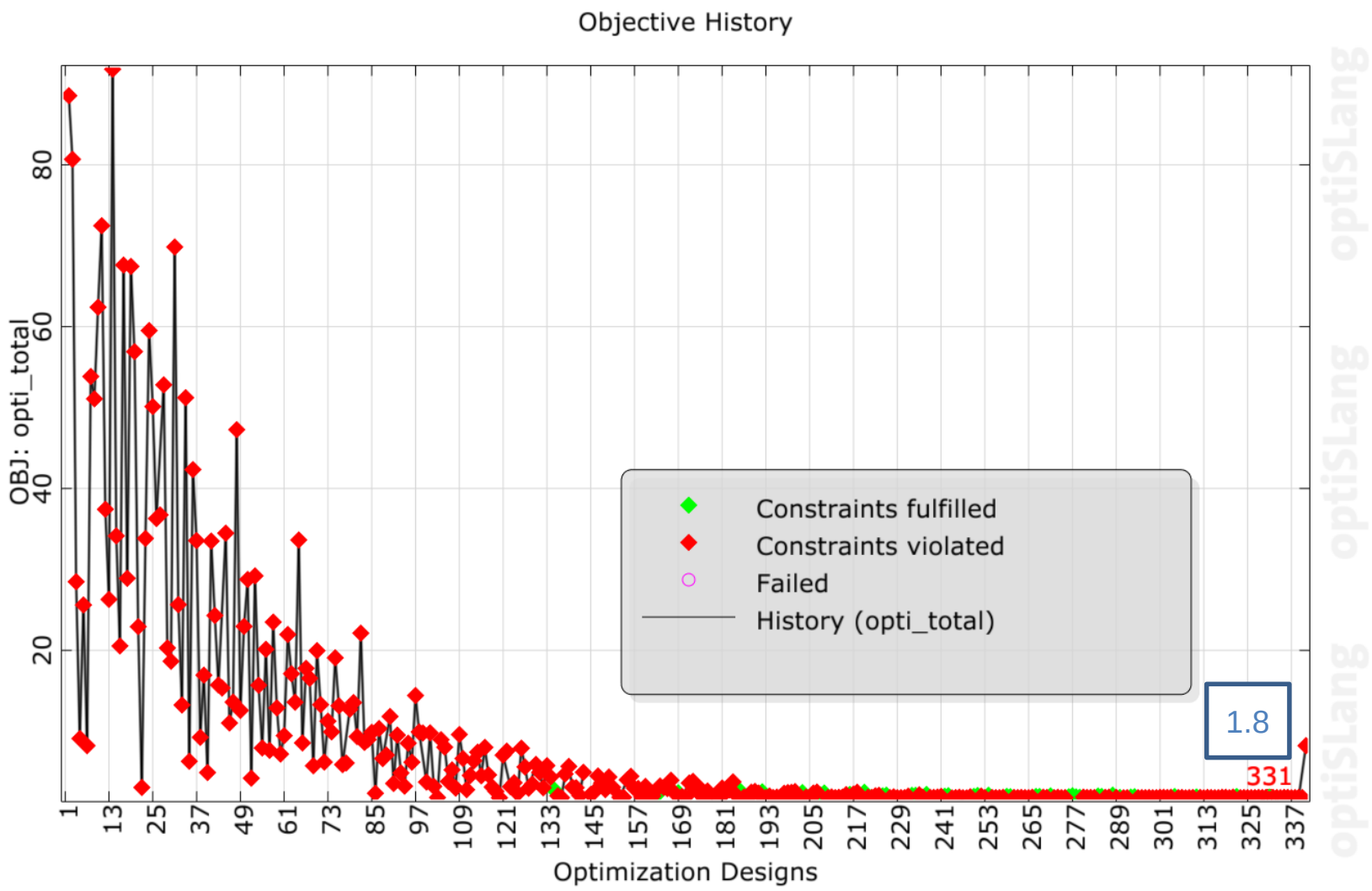
Name	Type	Expression	Criterion	Limit
Ziel_1	Variable	[1,1,1,1,1]		
Ziel_0p55	Variable	[0.5,0.5,0.5,0.5,0.5]		
err_0p55	Variable	euklidnorm(Ziel_0p55-F_vec_0p55)		
err_1	Variable	euklidnorm(Ziel_1-F_vec_1)		
opti_total	Objective	err_0p55+err_1	MIN	
constr_F_vec_1	Constraint	abs(1-F_vec_1[2])	≤	0.01
LS_rad_Konus	Constraint	D_Konus-D_Anker	≥	0.35
constr_0p55	Constraint	F_vec_0p55[2]	≤	0.51
constr2_0p55	Constraint	F_vec_0p55[2]	≥	0.5

Goals
→ force-level

Constraints
→ force-level
@ stroke = 1 mm

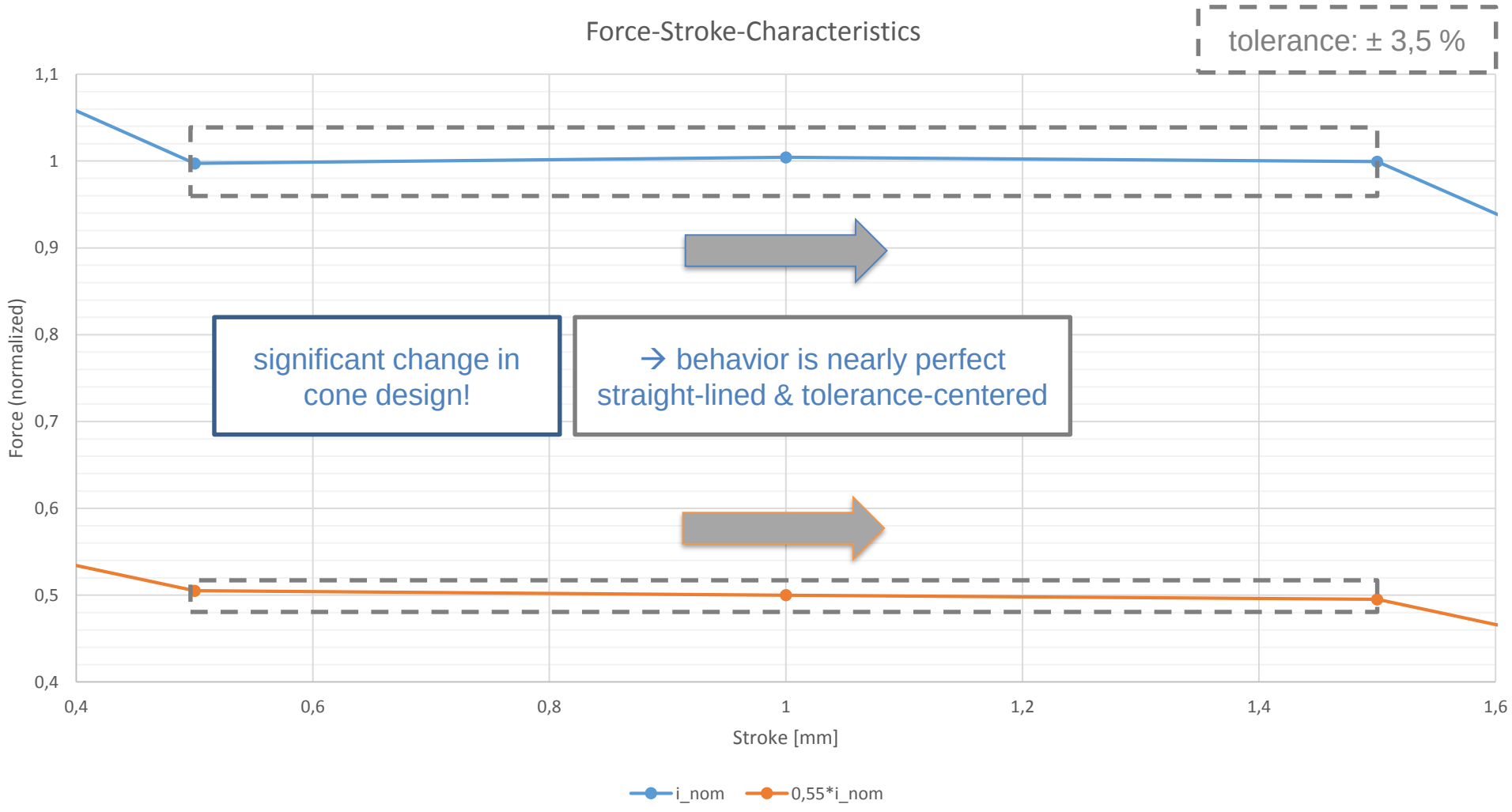
Optimization on the Model

Convergency



Optimization on the Model

Best Result



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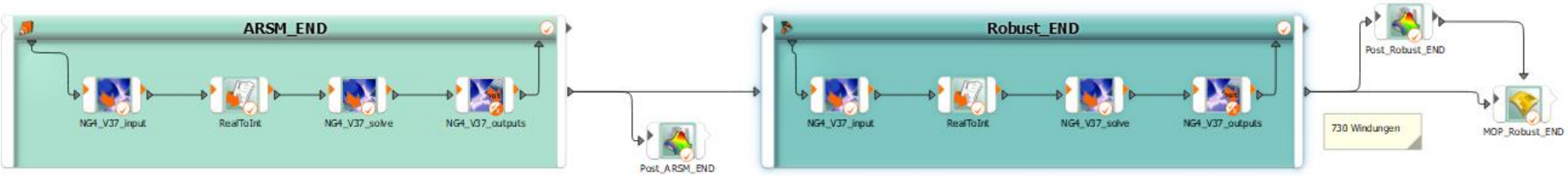
1. Robustness Evaluation

Standard Deviation according to Quality Management



	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range		Range plot	PDF	Type
1	Abbrand	Opt.+Stoch.	0.2	☑	REAL	Continuous	0	0.3			NORMAL
2	Anker_index	Opt.+Stoch.	4	☑	REAL	Discrete by value	0; 1; 2; 3; 4; 5; 6; 7; 8				DISCRETE
3	b_Konus	Opt.+Stoch.	0.5	☐	REAL	Continuous	0.3	1.5			NORMAL
4	D_Anker	Opt.+Stoch.	13.97	☐	REAL	Continuous	13	13.97			NORMAL
5	d_Kern	Opt.+Stoch.	5	☐	REAL	Continuous	5	7			NORMAL
6	D_Kern2	Opt.+Stoch.	14.37	☐	REAL	Continuous	14.37	15.37			NORMAL
7	D_Kern2_aussen	Opt.+Stoch.	18.19	☑	REAL	Continuous	16.371	20.009			NORMAL
8	D_Kern_aussen	Opt.+Stoch.	18.19	☑	REAL	Continuous	16.371	20.009			
9	D_Konus	Opt.+Stoch.	14.24	☐	REAL	Continuous	14.24	15.24			NORMAL
10	di_Anker	Opt.+Stoch.	4.33	☐	REAL	Continuous	4.33	6.33			NORMAL
11	Gehaeuse_index	Opt.+Stoch.	1	☑	REAL	Discrete by value	0; 1; 2				DISCRETE
12	h_Konus	Opt.+Stoch.	2.55	☐	REAL	Continuous	2	3			NORMAL
13	h_Konus_Boden	Opt.+Stoch.	0	☑	REAL	Continuous	-1	1			NORMAL
14	Kern_index	Opt.+Stoch.	4	☑	REAL	Discrete by value	0; 1; 2; 3; 4; 5; 6; 7; 8				DISCRETE
15	Konus_Winkel	Opt.+Stoch.	52.7	☐	REAL	Continuous	42	70			NORMAL
16	w	Opt.+Stoch.	700	☐	REAL	Continuous	600	800			

1. Robustness Evaluation - Results

CoP Matrix for Forces & Force Slopes

Total effects

Models	Anker_index	Gehaeuse_index	Kern_index	b_Konus	h_Konus	D_Anker	D_Kern2	D_Konus	dl_Anker	Total
Fds_vec_1p3[4]				4.3 %	83.2 %	6.8 %		4.0 %		98 %
Fds_vec_1p3[3]	2.0 %			14.8 %	62.7 %	11.9 %		7.2 %		97.4 %
Fds_vec_1p3[2]	7.0 %		4.1 %	55.1 %	9.1 %	11.7 %		9.2 %	1.1 %	98.3 %
Fds_vec_1p3[1]	7.2 %		6.4 %	70.7 %	1.4 %	5.8 %		6.0 %	1.2 %	99.1 %
Fds_vec_1p3[0]	7.7 %		6.8 %	72.5 %	0.8 %	4.5 %		5.1 %	1.2 %	98.1 %
Fds_vec_0p72[4]			1.0 %	12.2 %	78.1 %	5.5 %		3.2 %		98.8 %
Fds_vec_0p72[3]			1.1 %	18.5 %	55.4 %	15.9 %		8.1 %		98.9 %
Fds_vec_0p72[2]	4.3 %		1.5 %	3.8 %	9.6 %	52.9 %		25.2 %		96.9 %
Fds_vec_0p72[1]	7.7 %	1.1 %		45.9 %	1.5 %	22.9 %		17.4 %		97 %
Fds_vec_0p72[0]	4.4 %			64.9 %		15.4 %		11.8 %		95.2 %
F_vec_1p3[4]	10.2 %	0.8 %	21.9 %	16.4 %		40.7 %		8.0 %		99 %
F_vec_1p3[3]	12.7 %	1.1 %	23.9 %	14.6 %	7.6 %	34.5 %		6.2 %		98.9 %
F_vec_1p3[2]	17.6 %	1.1 %	22.2 %	7.7 %	15.5 %	30.3 %		3.0 %		98.4 %
F_vec_1p3[1]	25.4 %	1.7 %	20.4 %	1.0 %	22.2 %	26.4 %		1.7 %		97.8 %
F_vec_1p3[0]	35.0 %	1.7 %	14.8 %	1.9 %	24.0 %	21.2 %			1.2 %	98.4 %
F_vec_0p72[4]	5.1 %	0.8 %	9.7 %	1.3 %	3.9 %	63.8 %		15.7 %		99.4 %
F_vec_0p72[3]	6.2 %	1.1 %	13.4 %	7.5 %	1.8 %	54.2 %		14.1 %		99.1 %
F_vec_0p72[2]	8.7 %	1.6 %	16.7 %	17.2 %	8.4 %	37.0 %		7.8 %		98.9 %
F_vec_0p72[1]	14.9 %	2.8 %	23.1 %	14.1 %	7.9 %	29.9 %		4.9 %		98.3 %
F_vec_0p72[0]	22.9 %	4.8 %	28.5 %	3.3 %	10.2 %	24.5 %	1.1 %	2.1 %		98.5 %

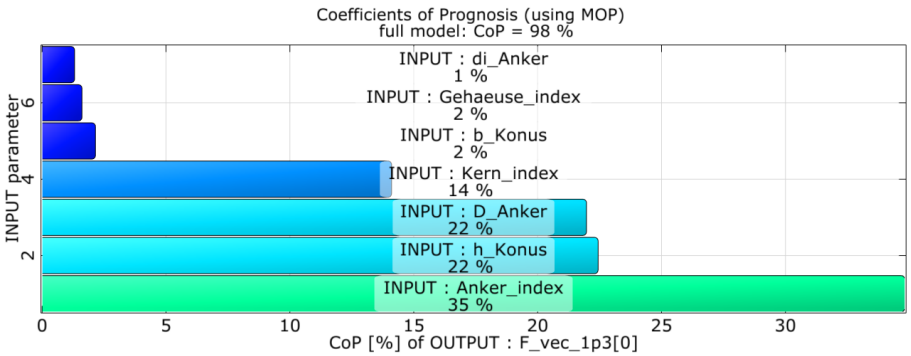
Parameter

really no influence of cone angle?

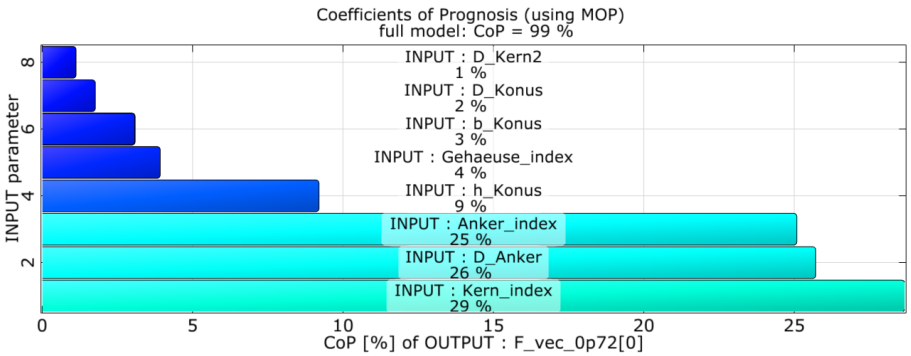
1. Robustness Evaluation - Results

CoP for 2 Forces at different Strokes @ i_nom and 0.55*i_nom

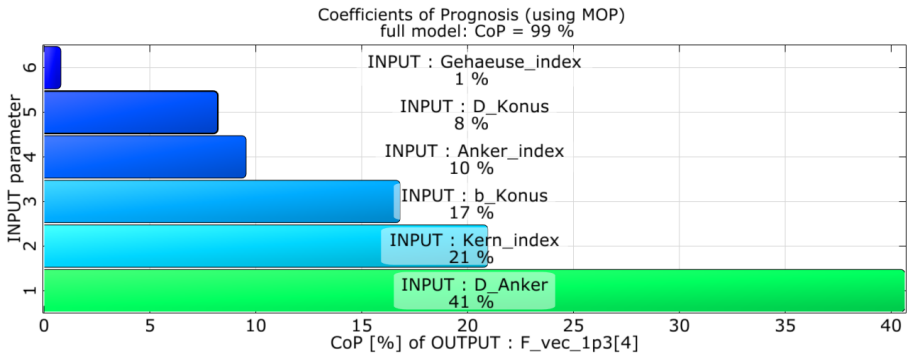
Stroke = 0,5 mm



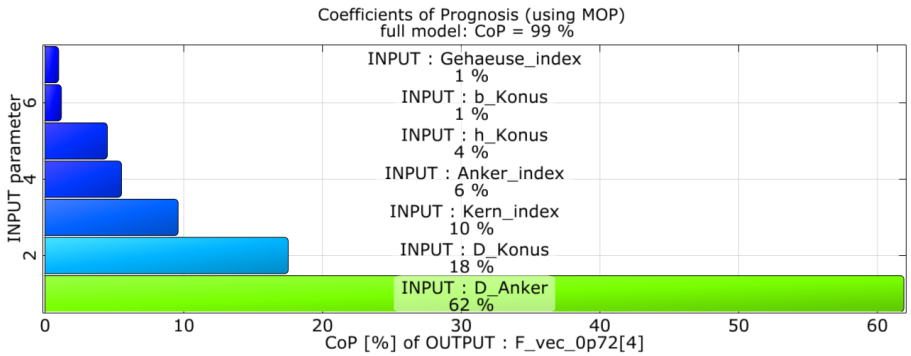
→ 51…58 % material influence!



Stroke = 1,5 mm

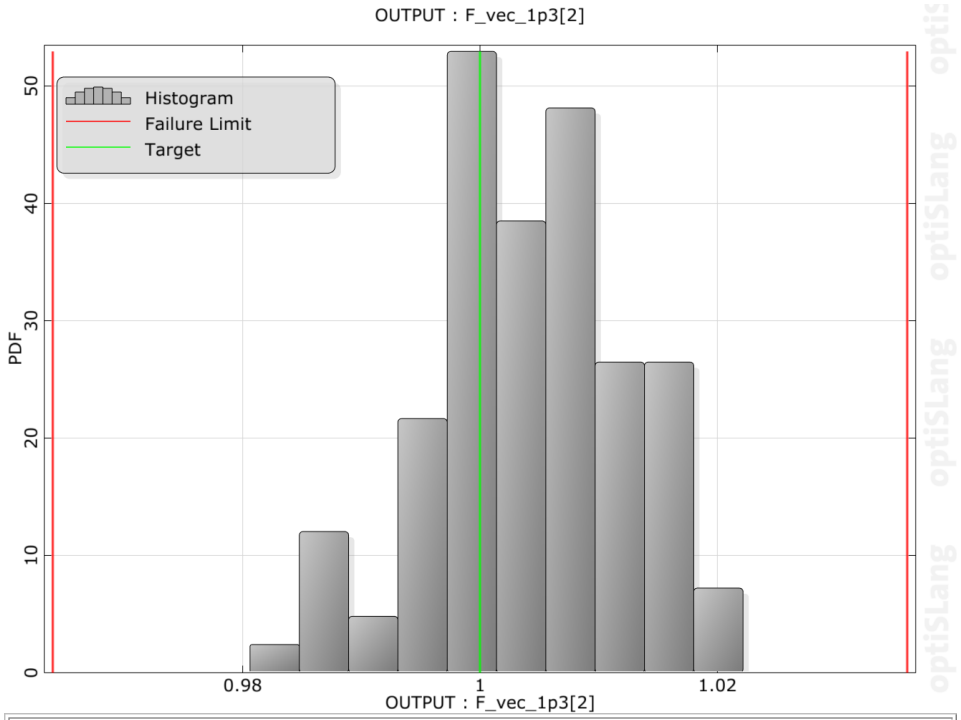


→ 17…32 % material influence!

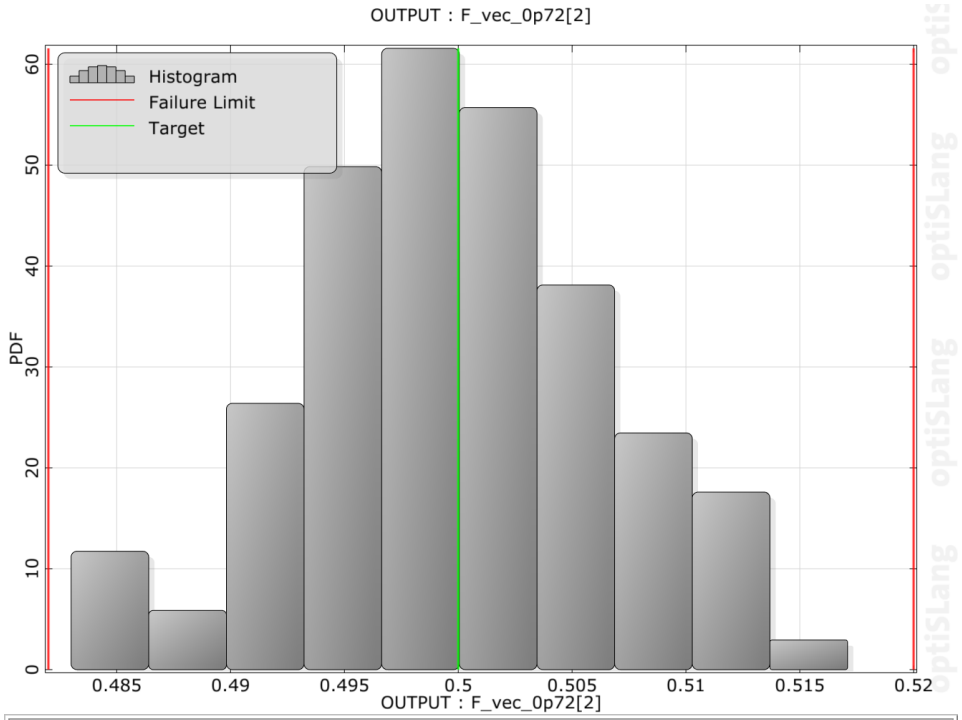


1. Robustness Evaluation - Results

Statistical Analysis @ 1 mm @ i_nom and 0.55*i_nom



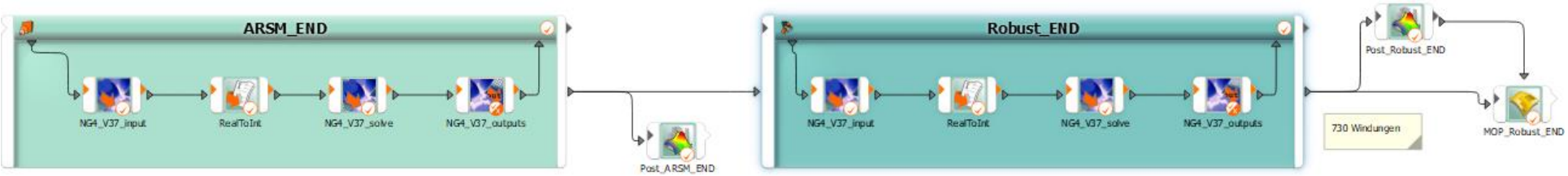
Statistical data			
Min:	0.980616	Max:	1.02216
Mean value:	1.00408	Standard deviation:	0.00830761
CoV:	0.00827387		
Skewness:	-0.229957	Excess kurtosis:	0.0181647
Limit : Failure Limit			
	Lower value = 0.964	Upper value = 1.036	Total
P_rel:	0	0	0
Sigma-Level:	4.82429	3.84246	



Statistical data			
Min:	0.482996	Max:	0.517099
Mean value:	0.499589	Standard deviation:	0.00667016
CoV:	0.0133513		
Skewness:	-0.0553872	Excess kurtosis:	0.00438716
Limit : Failure Limit			
	Lower value = 0.482	Upper value = 0.52	Total
P_rel:	0	0	0
Sigma-Level:	2.63696	3.06005	

2. Robustness Evaluation

Standard Deviation according to Drawing



	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range		Range plot	PDF	Type
1	Abbrand	Opt.+Stoch.	0.2	☑	REAL	Continuous	0	0.3			NORMAL
2	Anker_index	Opt.+Stoch.	4	☑	REAL	Discrete by value	0; 1; 2; 3; 4; 5; 6; 7; 8				DISCRETE
3	b_Konus	Opt.+Stoch.	0.5	☐	REAL	Continuous	0.3	1.5			NORMAL
4	D_Anker	Opt.+Stoch.	13.97	☐	REAL	Continuous	13	13.97			NORMAL
5	d_Kern	Opt.+Stoch.	5	☐	REAL	Continuous	5	7			NORMAL
6	D_Kern2	Opt.+Stoch.	14.37	☐	REAL	Continuous	14.37	15.37			NORMAL
7	D_Kern2_aussen	Opt.+Stoch.	18.19	☑	REAL	Continuous	16.371	20.009			NORMAL
8	D_Kern_aussen	Opt.+Stoch.	18.19	☑	REAL	Continuous	16.371	20.009			NORMAL
9	D_Konus	Opt.+Stoch.	14.24	☐	REAL	Continuous	14.24	15.24			NORMAL
10	di_Anker	Opt.+Stoch.	4.33	☐	REAL	Continuous	4.33	6.33			NORMAL
11	Gehaeuse_index	Opt.+Stoch.	1	☑	REAL	Discrete by value	0; 1; 2				DISCRETE
12	h_Konus	Opt.+Stoch.	2.55	☐	REAL	Continuous	2	3			NORMAL
13	h_Konus_Boden	Opt.+Stoch.	0	☑	REAL	Continuous	-1	1			NORMAL
14	Kern_index	Opt.+Stoch.	4	☑	REAL	Discrete by value	0; 1; 2; 3; 4; 5; 6; 7; 8				DISCRETE
15	Konus_Winkel	Opt.+Stoch.	52.7	☐	REAL	Continuous	42	70			NORMAL
16	w	Opt.+Stoch.	700	☐	REAL	Continuous	600	800			

2. Robustness Evaluation - Results

CoP Matrix for Forces & Force Slopes

Total effects

Models	Anker_index	Gehaeuse_index	Kern_index	b_Konus	Konus_Winkel	h_Konus	Abbrand	D_Anker	D_Kern2	D_Kern2_aussen	D_Kern_aussen	D_Konus	di_Anker	Total
Fds_vec_1p3[4]						97.2 %								97.2 %
Fds_vec_1p3[3]				0.7 %		94.2 %						1.5 %	1.0 %	97.5 %
Fds_vec_1p3[2]	7.1 %		3.0 %	12.1 %	2.6 %	49.0 %		2.5 %				7.4 %	10.8 %	95.5 %
Fds_vec_1p3[1]	9.1 %		7.8 %	27.8 %	13.7 %	14.7 %	2.4 %	2.7 %				8.3 %	10.7 %	98.2 %
Fds_vec_1p3[0]	6.6 %		7.3 %	27.0 %	19.5 %	10.0 %	3.5 %	2.1 %				7.2 %	11.8 %	95.5 %
Fds_vec_0p72[4]						97.3 %								97.3 %
Fds_vec_0p72[3]				1.9 %		94.0 %		0.8 %				1.4 %		97.7 %
Fds_vec_0p72[2]	3.6 %		2.0 %	1.4 %	3.3 %	55.2 %		9.4 %			1.0 %	18.4 %		94.5 %
Fds_vec_0p72[1]	13.6 %	1.1 %		23.1 %	1.1 %	12.8 %	0.3 %	10.7 %		1.3 %		27.1 %	5.1 %	95.9 %
Fds_vec_0p72[0]	5.0 %			30.9 %	8.9 %	9.8 %	0.4 %	6.4 %				22.0 %	7.4 %	92.1 %
F_vec_1p3[4]	15.1 %	1.7 %	32.5 %	8.4 %	5.8 %	0.0 %		15.7 %		4.1 %		14.5 %		96.7 %
F_vec_1p3[3]	10.9 %	1.3 %	16.2 %	4.4 %	3.3 %	45.2 %		7.3 %		2.9 %		5.4 %		97.1 %
F_vec_1p3[2]	11.2 %	0.9 %	12.2 %	1.9 %	2.2 %	60.6 %		4.4 %		1.7 %		2.5 %	1.9 %	98.3 %
F_vec_1p3[1]	13.4 %	0.9 %	8.5 %		1.2 %	66.6 %		3.2 %		1.8 %			3.3 %	97.5 %
F_vec_1p3[0]	15.8 %		6.8 %			66.1 %		2.6 %		1.5 %			5.1 %	97.6 %
F_vec_0p72[4]	5.3 %	1.2 %	11.3 %			35.7 %		17.8 %		3.3 %		21.1 %		97.4 %
F_vec_0p72[3]	9.8 %	2.2 %	17.9 %	3.3 %	1.6 %	18.8 %		17.9 %		4.2 %		21.0 %		97.7 %
F_vec_0p72[2]	8.1 %	1.8 %	12.9 %	5.7 %	2.6 %	50.5 %		7.8 %		2.9 %		7.6 %		98.4 %
F_vec_0p72[1]	12.1 %	1.8 %	15.8 %	4.1 %	3.5 %	45.6 %		6.3 %		4.1 %		4.1 %		97.6 %
F_vec_0p72[0]	17.9 %	2.8 %	18.5 %		1.9 %	44.1 %		4.6 %	1.4 %	4.6 %		1.6 %	1.0 %	98.2 %

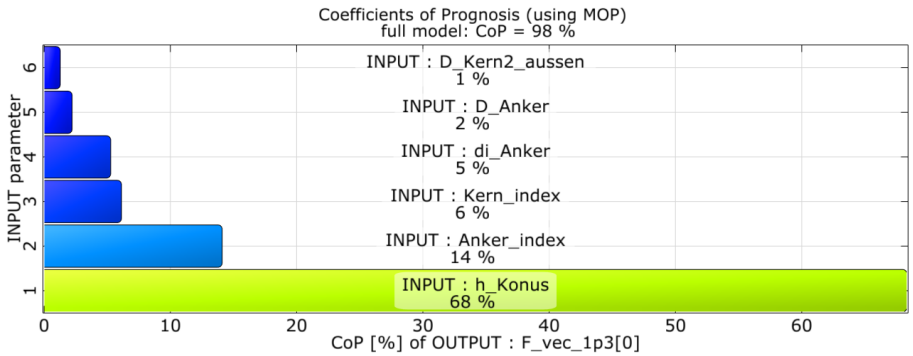
Parameter

→ desired influence of cone design!

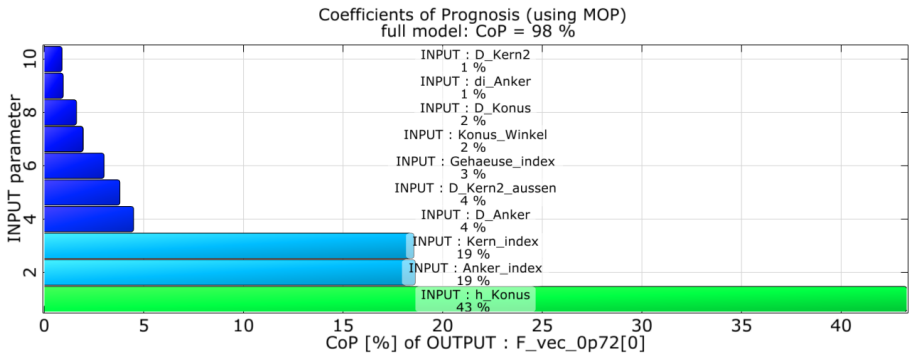
2. Robustness Evaluation - Results

CoP for 2 Forces at different Strokes @ i_nom and 0.55*i_nom

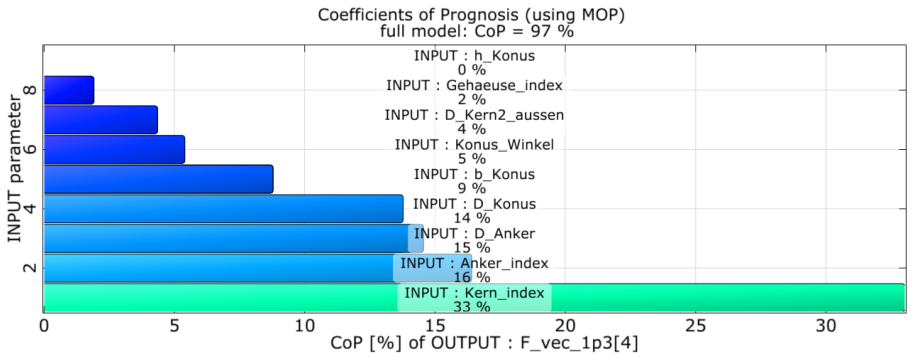
Stroke = 0.5 mm



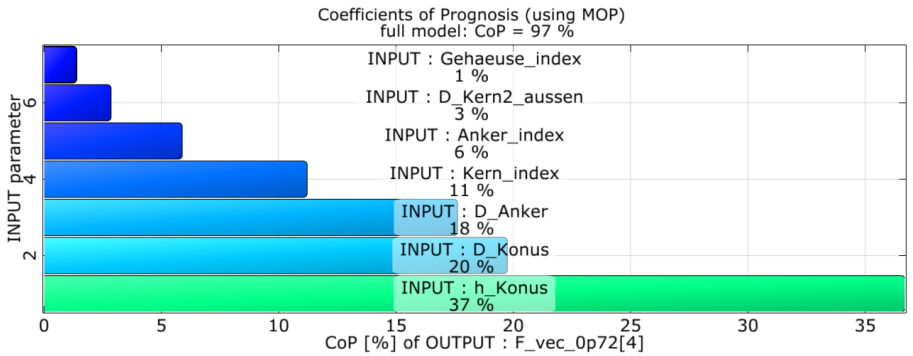
→ 20…41 % material influence!



Stroke = 1.5 mm

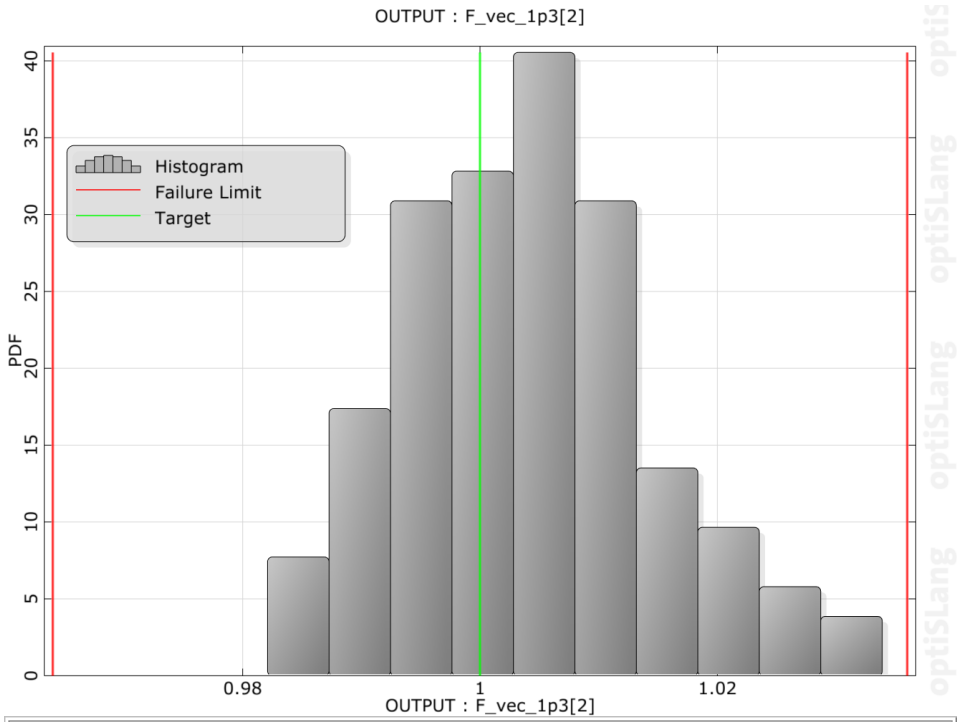


→ 18…51 % material influence!

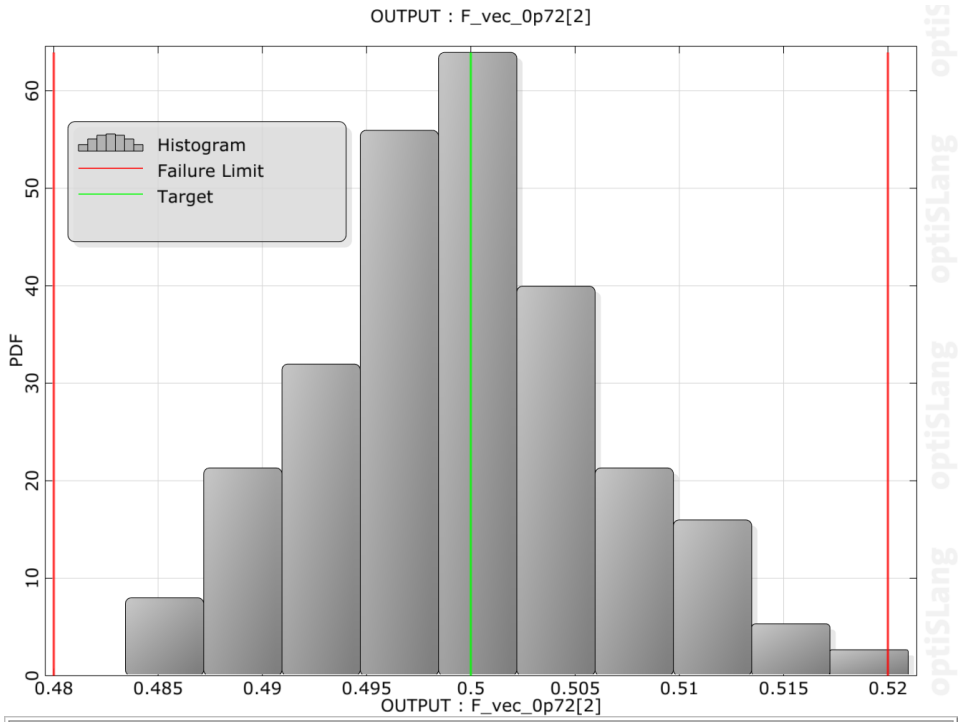


2. Robustness Evaluation - Results

Statistical Analysis @ 1 mm @ i_nom and 0.55*i_nom



Statistical data			
Min:	0.982098	Max:	1.03389
Mean value:	1.00415	Standard deviation:	0.0106705
CoV:	0.0106265		
Skewness:	0.338894	Excess kurtosis:	-0.0137455
Limit : Failure Limit			
	Lower value = 0.964	Upper value = 1.036	Total
P_rel:	0	0	0
Sigma-Level:	3.76227	2.98528	

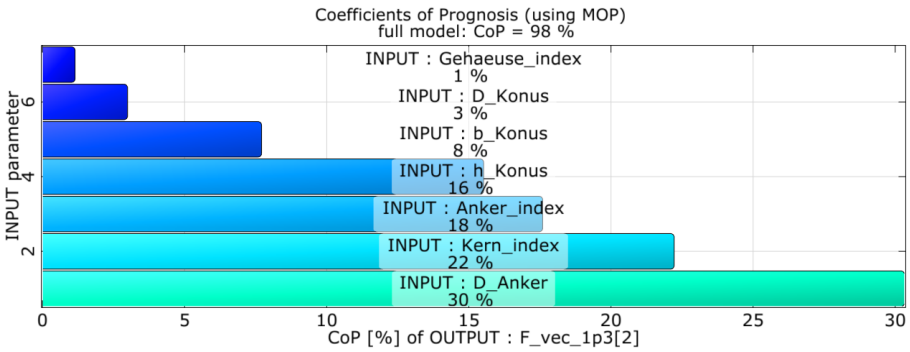


Statistical data			
Min:	0.483434	Max:	0.520975
Mean value:	0.4997	Standard deviation:	0.00698864
CoV:	0.0139857		
Skewness:	0.365423	Excess kurtosis:	0.333559
Limit : Failure Limit			
	Lower value = 0.48	Upper value = 0.52	Total
P_rel:	0	0.01	0.01
Sigma-Level:	2.8189	2.90467	

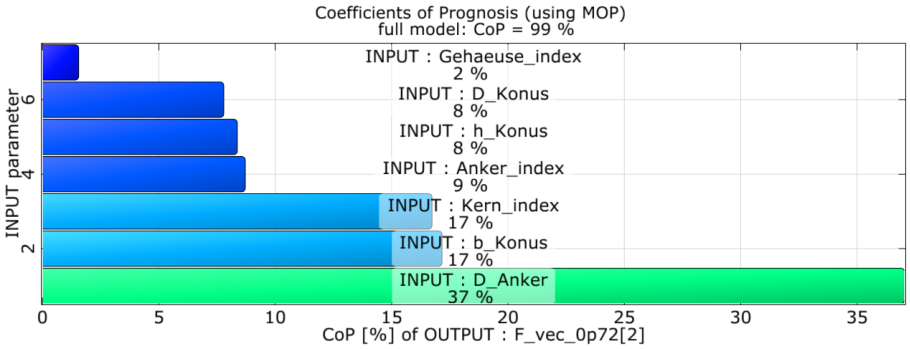
Robustness Evaluations - Results

Comparison: CoP for Force @ 1mm @ i_nom and 0.55*i_nom

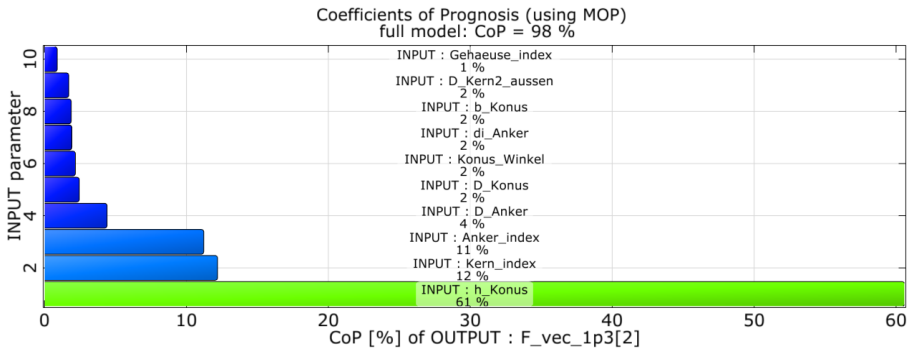
1. Robustness Evaluation



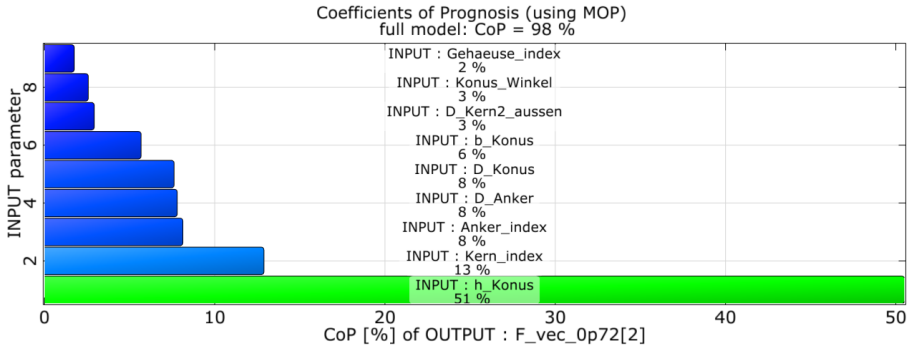
→ 28…41 % material influence!



2. Robustness Evaluation



→ 23…24 % material influence!



Contents

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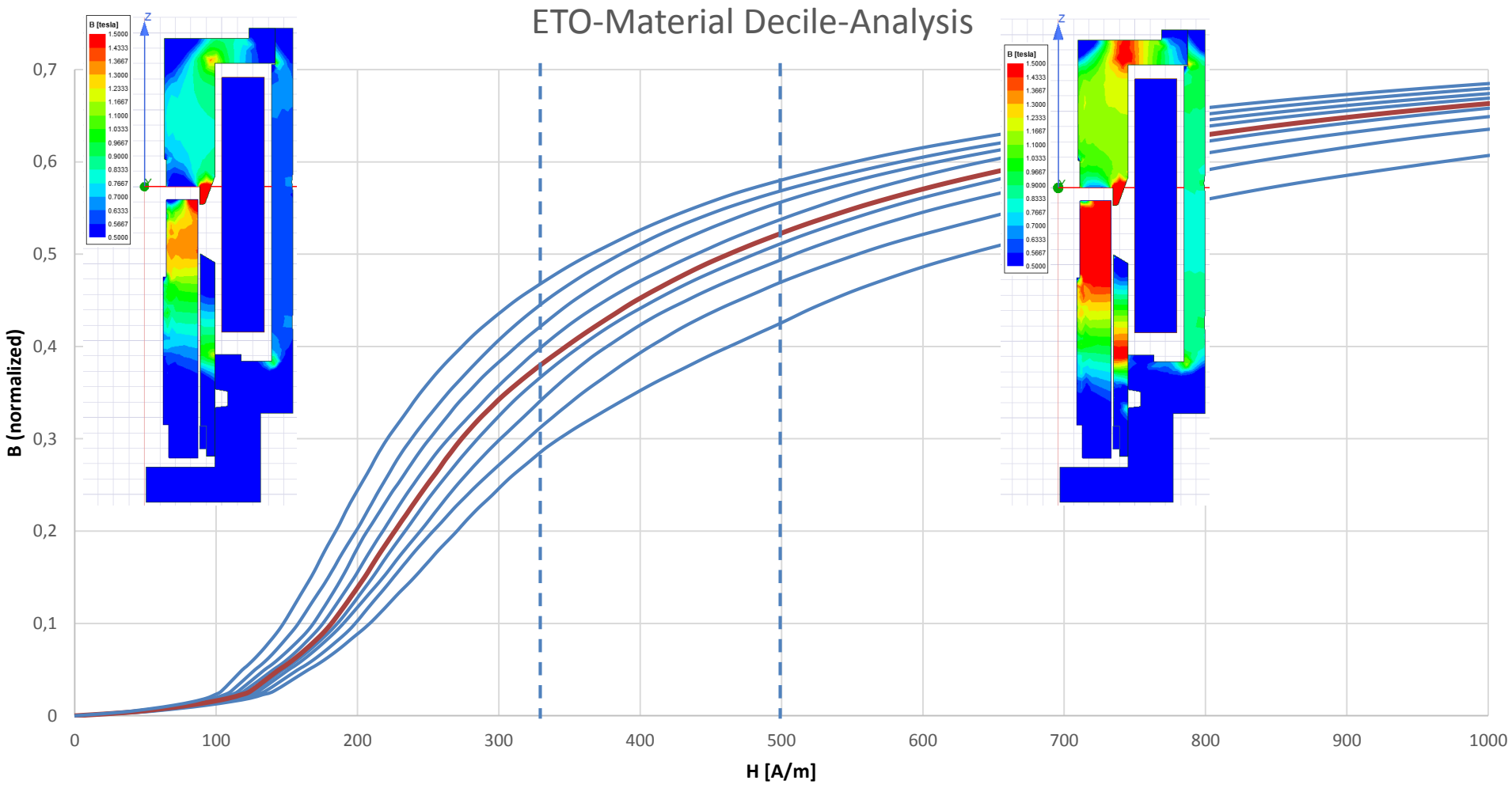
2. Motivation
3. Goals
4. Solution approach
   a. Optimization on the MOP
   b. Optimization on the model
   c. Robustness evaluation
   d. **Robustness improvement**
5. Conclusion & Outlook

Robustness Improvement

Problem: High Material Influence at the Working Points (WP)

WP Core @ 1mm @ 0.55*i_nom

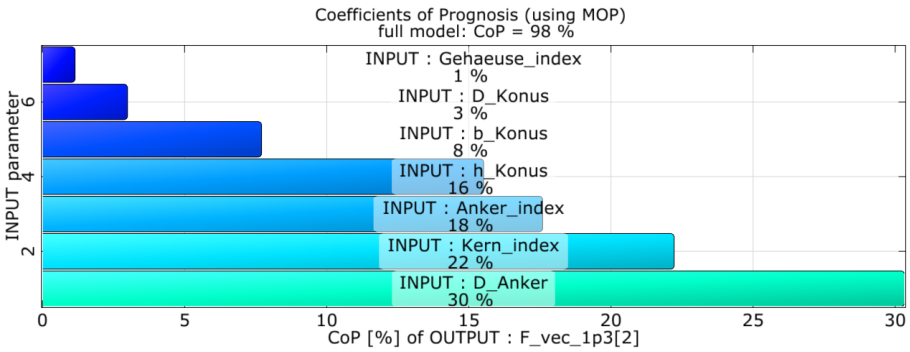
WP Core @ 1mm @ i_nom



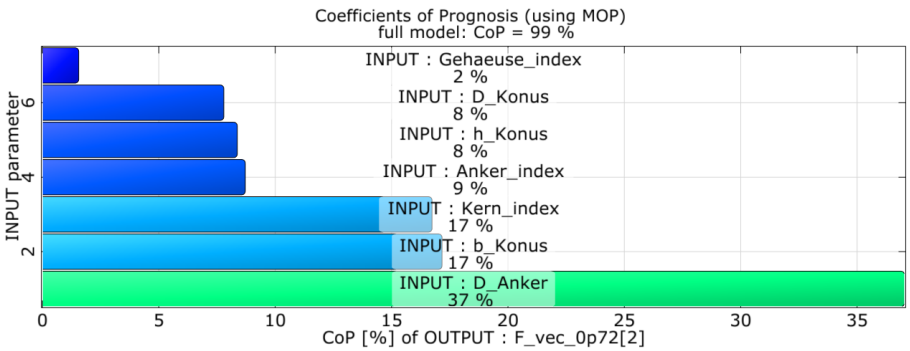
Robustness Improvement - Results

CoP for Force @ 1mm @ i_nom and 0.55*i_nom

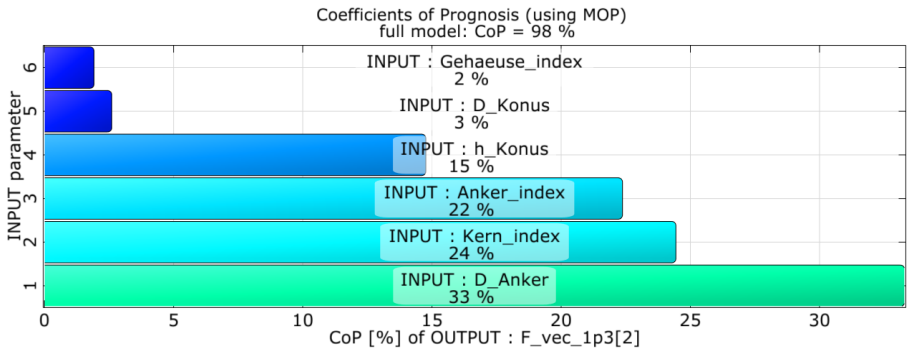
Nom. windings



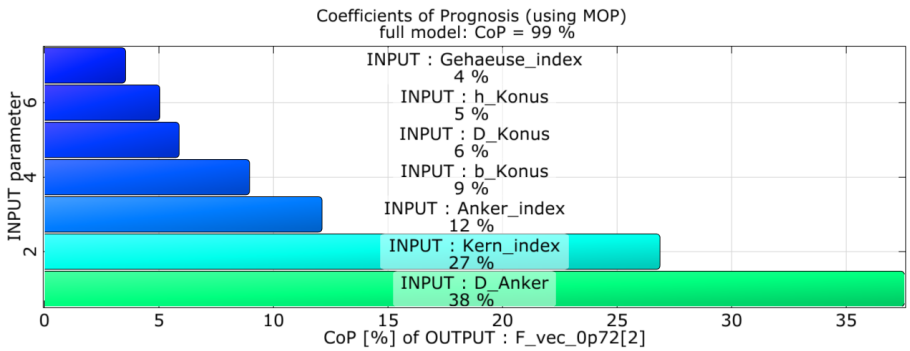
→ 28…41 % material influence!



Max. windings



→ 43…48 % material influence!



Conclusion & Outlook

Conclusion

- **Robustness of FSC is increased**
- **Optimization on the MOP is not precise enough (@ ambitious requirements)**
- **Optimization on the model leads to very good results**
  → Nearly perfect straight-lined & tolerance-centered FSC
- **Working area shift is ineffective (under given design space restrictions)**
  → No reduction of material influence (up to 58 %)
- **Statistical values have to be reliable**
- **Best cone has an unusual design**

Outlook

- **Better dimensioning of cone length on the drawing**
- **Better material quality?**
- **Test series for evaluation of “real” standard deviation**
- **Real RDO?**