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Robustness analysis in the modeFrontier environment applied to the development of hydraulic pump components using CAE tools

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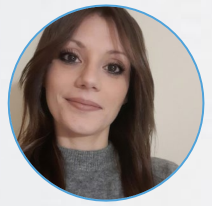


Agenda

Introduction

First case study – compression spring

Second case study – balancing plate

Third case study – valve plate

Conclusions

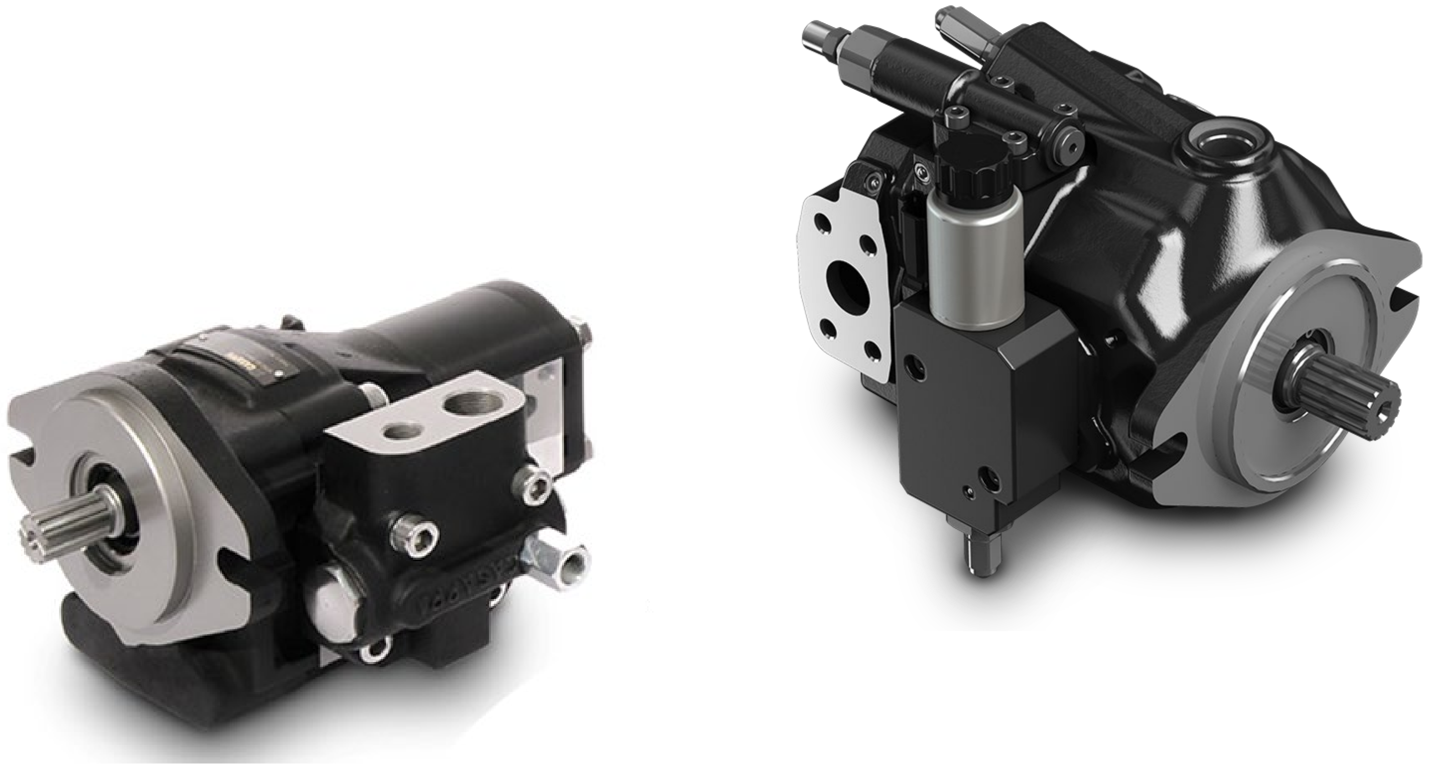
Introduction

Introduction

In modern hydraulic pumps, internal components are optimized through traditional calculations and CAE simulations integrated into multi-objective optimization workflows. At Casappa, these processes have been structured for years using modeFRONTIER software and continue to be refined and further evolved.

The aim of this work is to evaluate the effects of integrating robustness analysis into three of the most common case studies used at Casappa, with increasing levels of complexity:

- Compression spring (piston pump)
- Balancing plate (external gear pump)
- Valve plate (piston pump)



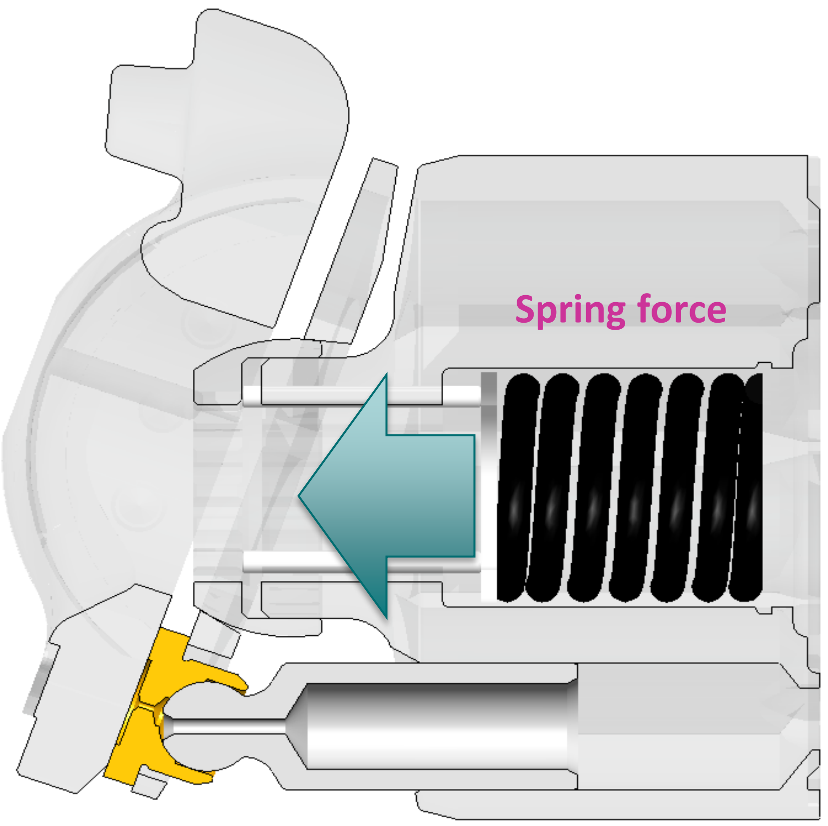
First case study – compression spring

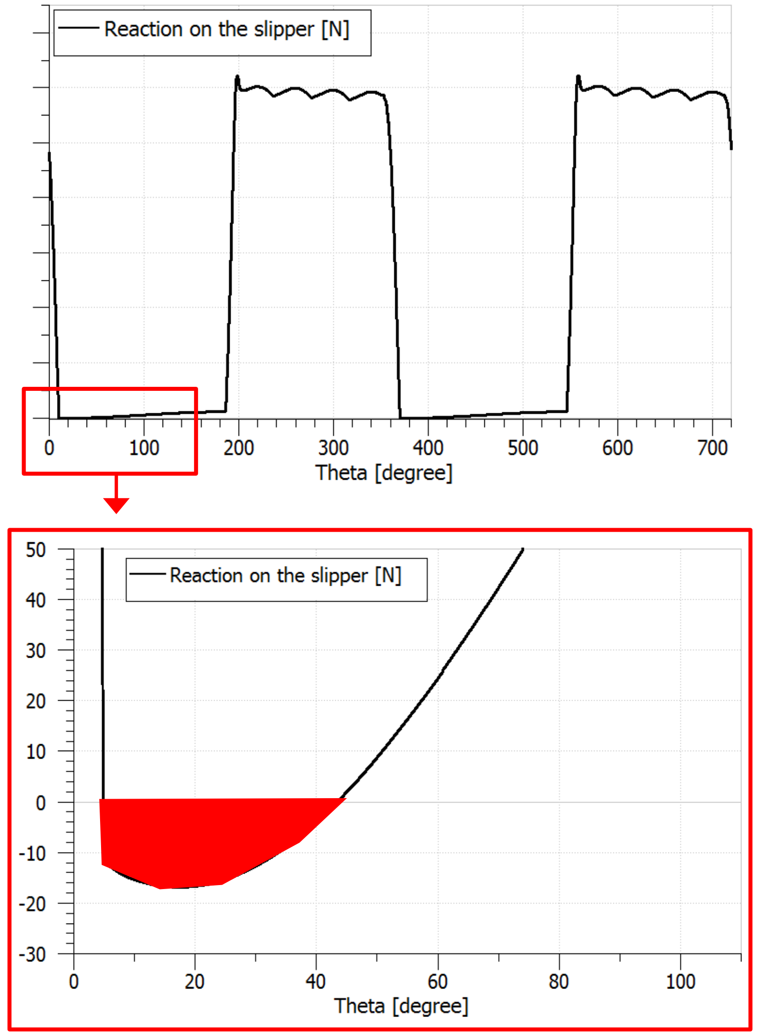
- Working principle
- Casappa optimization method
- Robust analysis setup
- Result analysis

Compression spring – working principle

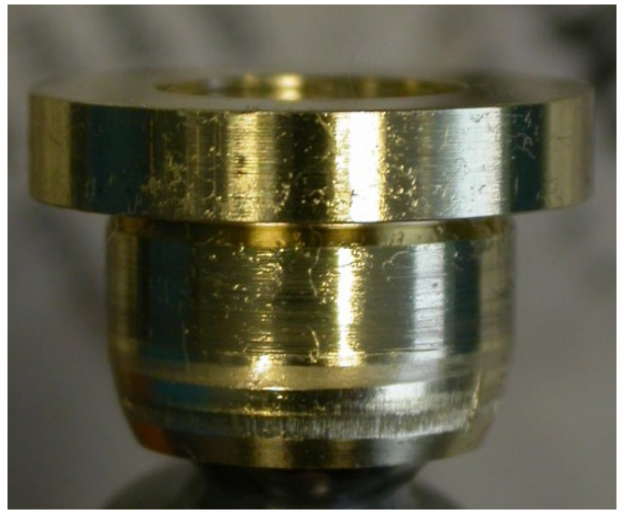
The first case study concerns the optimization of the piston support spring, a component used in a swashplate axial piston pump. The function of the spring is to exert an adequate compressive force on the slippers, especially during the suction phase, when inertial forces tend to detach them from the swashplate.

Proper spring sizing (preload, minimum and maximum compression force) ensures that the reaction force between the slippers and the swashplate is always positive, meaning that the slippers stay in contact with the swashplate at all times.





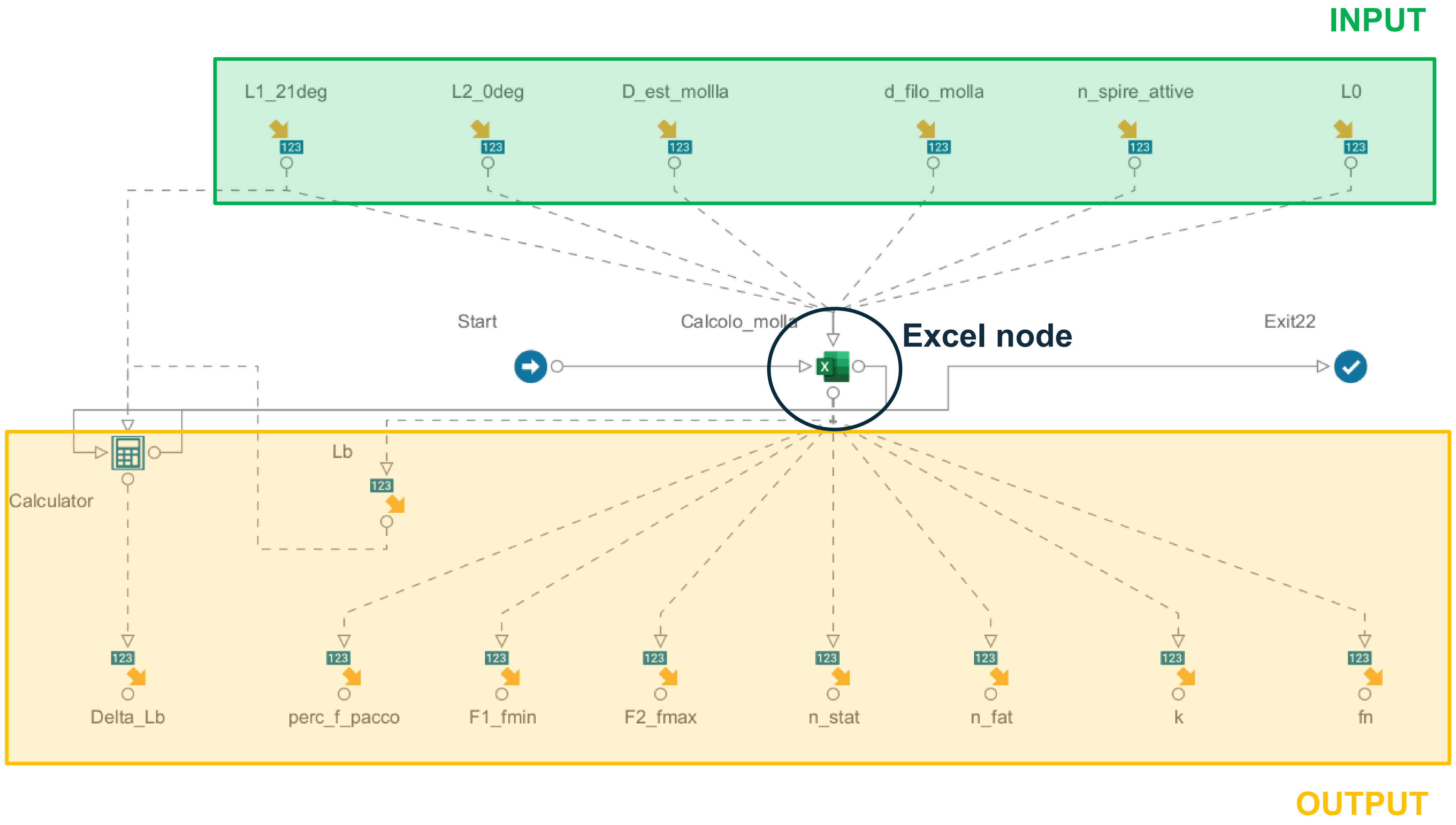
Fmin > 0



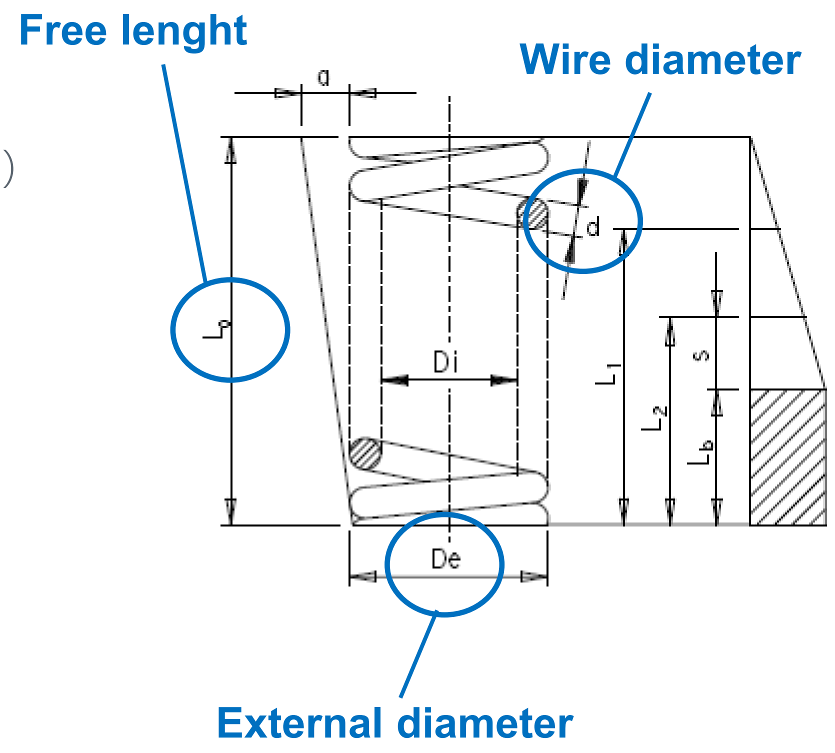
Fmin < 0

Compression spring – Casappa optimization method

The standard Casappa method for spring optimization is based on an Excel calculation tool integrated into the modeFRONTIER workflow shown below.



Main input variables:
- External diameter (Dext)
- Wire diameter (d_filo)
- Number of coils (n)
- Spring free length (Lo)
- First working length (L1)
- Second working length (L2)



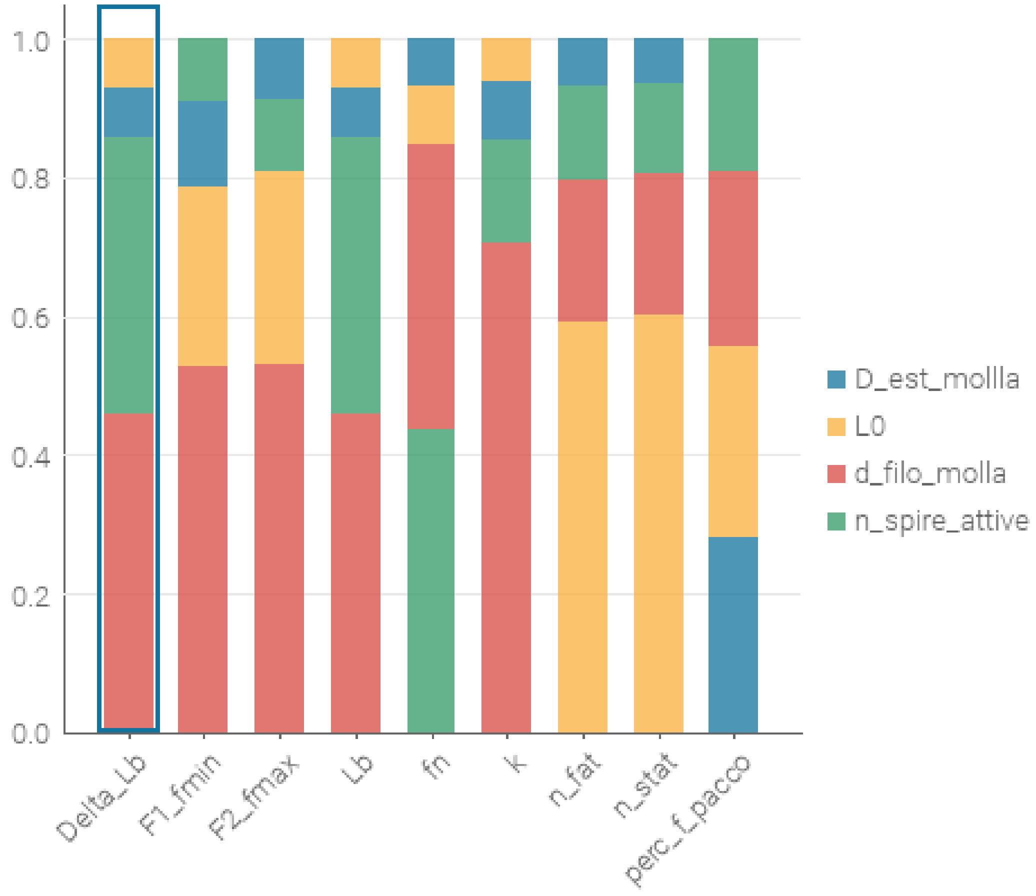
Main output variables:
- Spring solid length (Lb)
- First working load (F1)
- Second working load (F2)
- Stiffness (K)
- Deviation from solid height (%f_pacco)
- Static safety factor (n_stat)
- Fatigue safety factor (n_fat)

Compression spring – robust analysis setup

Stochastic input variables → 3
- Dext (external diameter)
- Lo (spring free length)
- D_filo (wire diameter)

Output variable with percentiles → 7

All stochastic inputs influence the outputs of interest



Project objectives:

- K (spring stiffness) → MINIMIZE
- F1 (first working load)→ TARGET VALUE
- F2 (second working load) → MINIMIZE

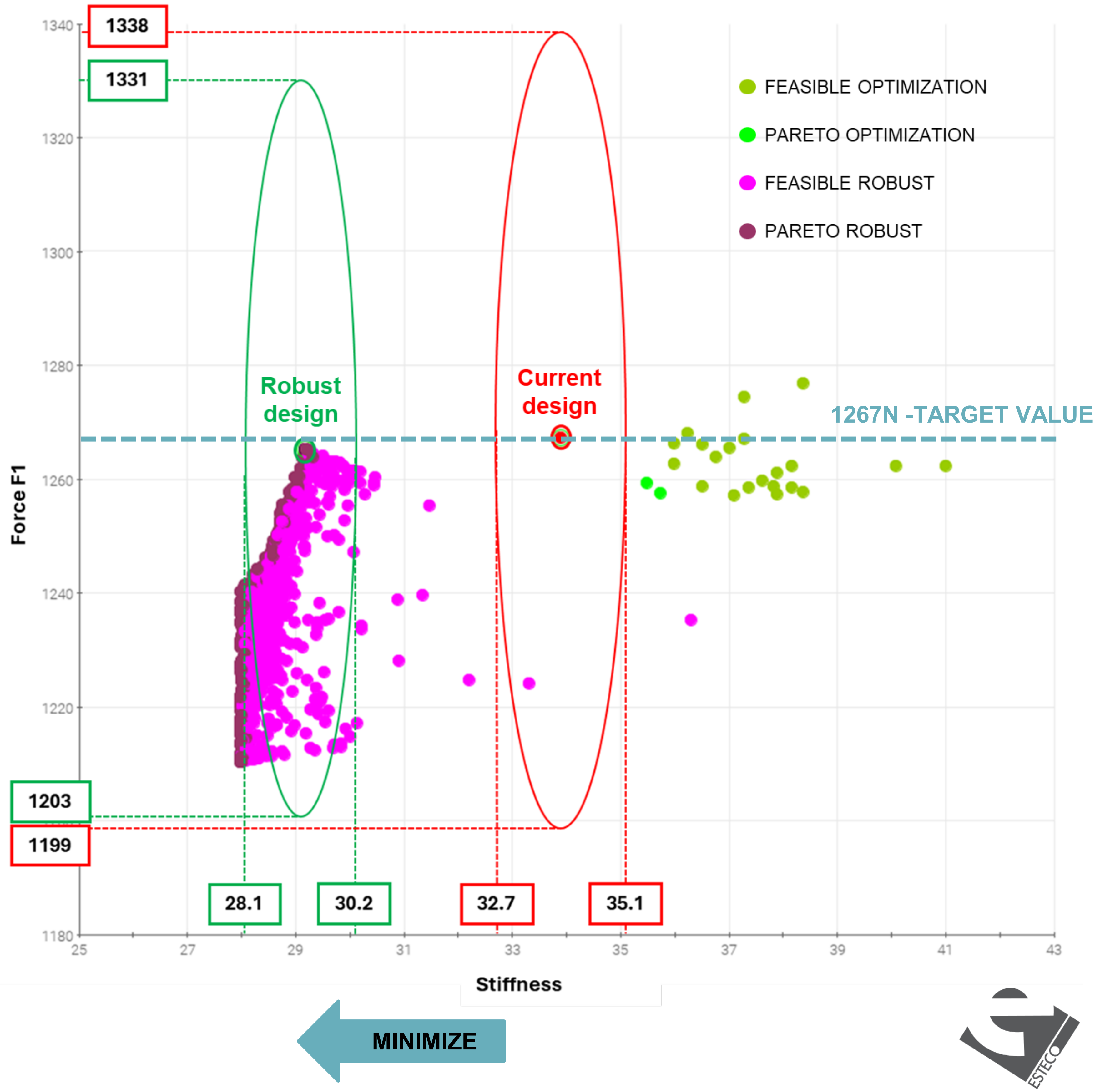
RELATED OBJECTIVES

It was decided to leave the objectives unchanged to be able to compare the results with the classical optimization

Compression spring – results analysis

		Stochastic variable?	Current design		
Input	D_{ext} [mm]	Y	49.00		
	d_{filo} [mm]	Y	6.00		
	n_{spire} [adim]	N	4.75		
	L_0 [mm]	Y	86.70		
	L2_0deg [mm]	N	46.65		
	L1_21deg [mm]	N	49.30		
	Optimization check constraints		**Mean**	**St.Dev**	**Percentile 99%**
Output	%f_pacco [%]	>12%	13.30	0.29	>12.65
	F1_fmin [N]	1257 <F1< 1277	1267.42	29.86	1198.9 <F1< 1337.9
	F2_fmax [N]	<1410	1357.51	30.79	<1430.2
	n_STAT [adim]	>1.1	1.15	0.02	>1.10
	n_FAT [adim]	>1.2	1.35	0.02	>1.29
	K [N/mm]	30 <K< 42	33.89	0.52	32.71 <K< 35.12
	fn [Hz]	-	243.90	1.74	-
	Δblocco [mm]	>0	6.15	0.00	-

		Stochastic variable?	Robust design		
Input	D_{ext} [mm]	Y	50.2		
	d_{filo} [mm]	Y	5.9		
	n_{spire} [adim]	N	4.77		
	L_0 [mm]	Y	92.68		
	L2_0deg [mm]	N	46.65		
	L1_21deg [mm]	N	49.30		
	Robust analysis constraints		**Mean**	**St.Dev**	**Percentile 99%**
Output	%f_pacco [%]	>12%	12.56	0.25	> 12%
	F1_fmin [N]	1150 <F1< 1350	1265.54	27.49	1202.5 <F1< 1330.5
	F2_fmax [N]	<1410	1343.09	28.34	< 1410
	n_STAT [adim]	>1.05	1.09	0.02	>1.05
	n_FAT [adim]	>1.1	1.29	0.02	>1.24
	K [N/mm]	27 <K< 42	29.17	0.45	28.16 <K< 30.22
	fn [Hz]	-	225.83	1.58	-
	Δblocco [mm]	>0	6.61	0.00	-



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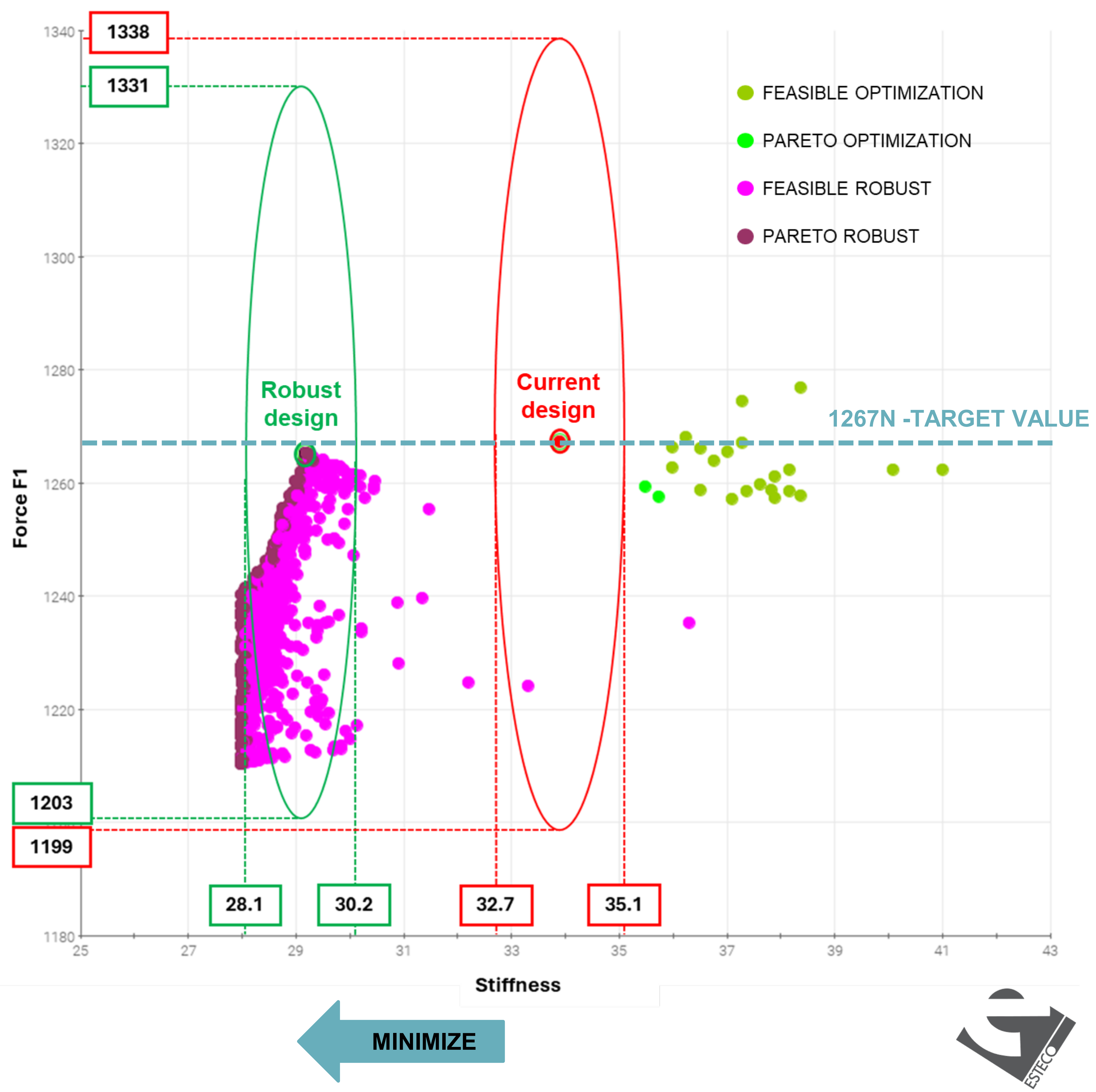
Compression spring – results analysis

- The design obtained through deterministic optimization is not robust.

- The design obtained through robust optimization shows a more compact point cloud, indicating greater stability of the parameters around their nominal values.

- The introduction of robustness into the optimization process makes it possible to achieve an optimal and robust design with higher levels of performance.



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Second case study – balancing plate

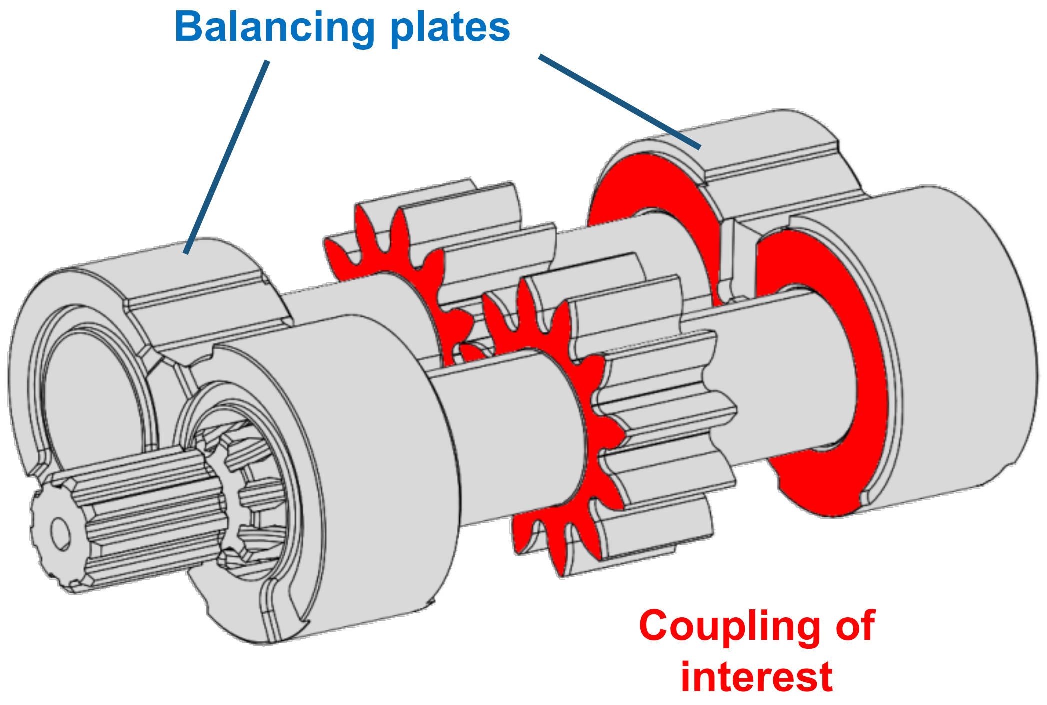
- Working principle
- Casappa optimization method
- Robust analysis setup
- Result analysis

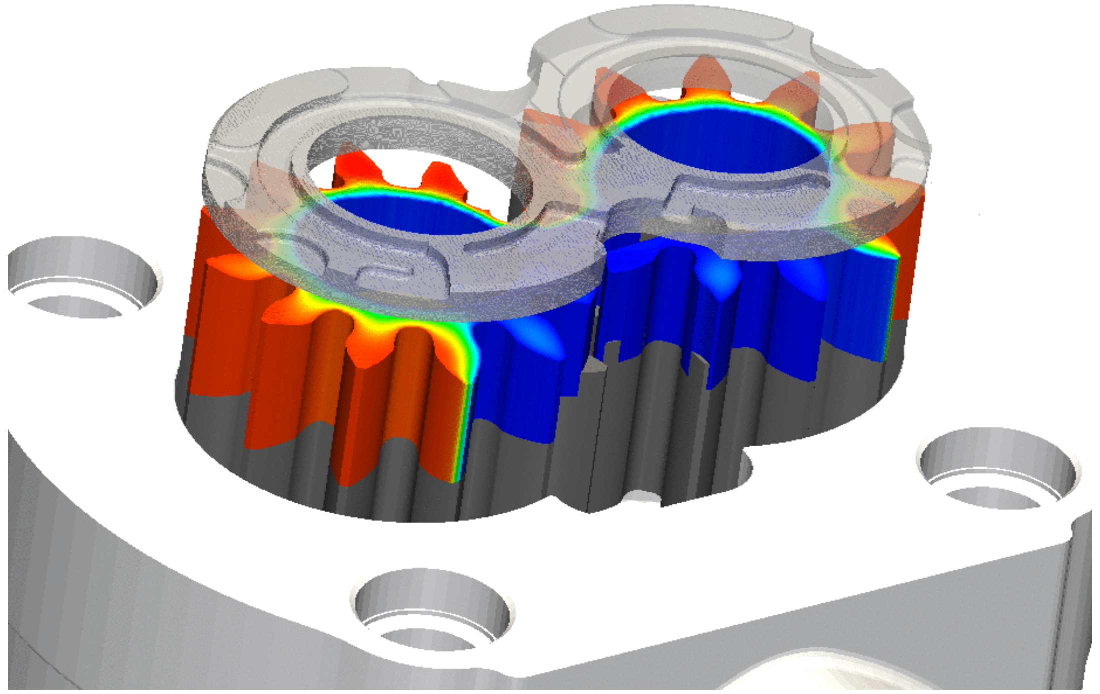
Balancing plate – working principle

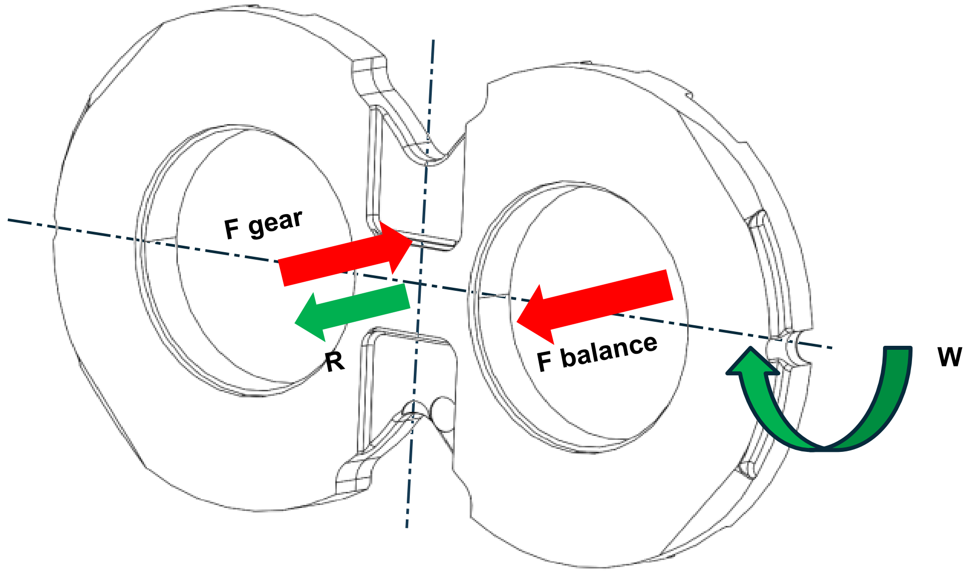
The second case study focuses on the balancing plate, a pressure-balanced component used in an external gear pump.

The function of the balancing plates is to confine the oil within the gear chambers during operation, while minimizing both leakage and friction. In order for this to occur, the resultant force (R), defined as the balance between the forces acting on the gear side (Fgear) and those acting on the seal side (Fbalance), must be small and always directed toward the gears.

Incorrect sizing of the balance plate may lead to seizure and poor performance.

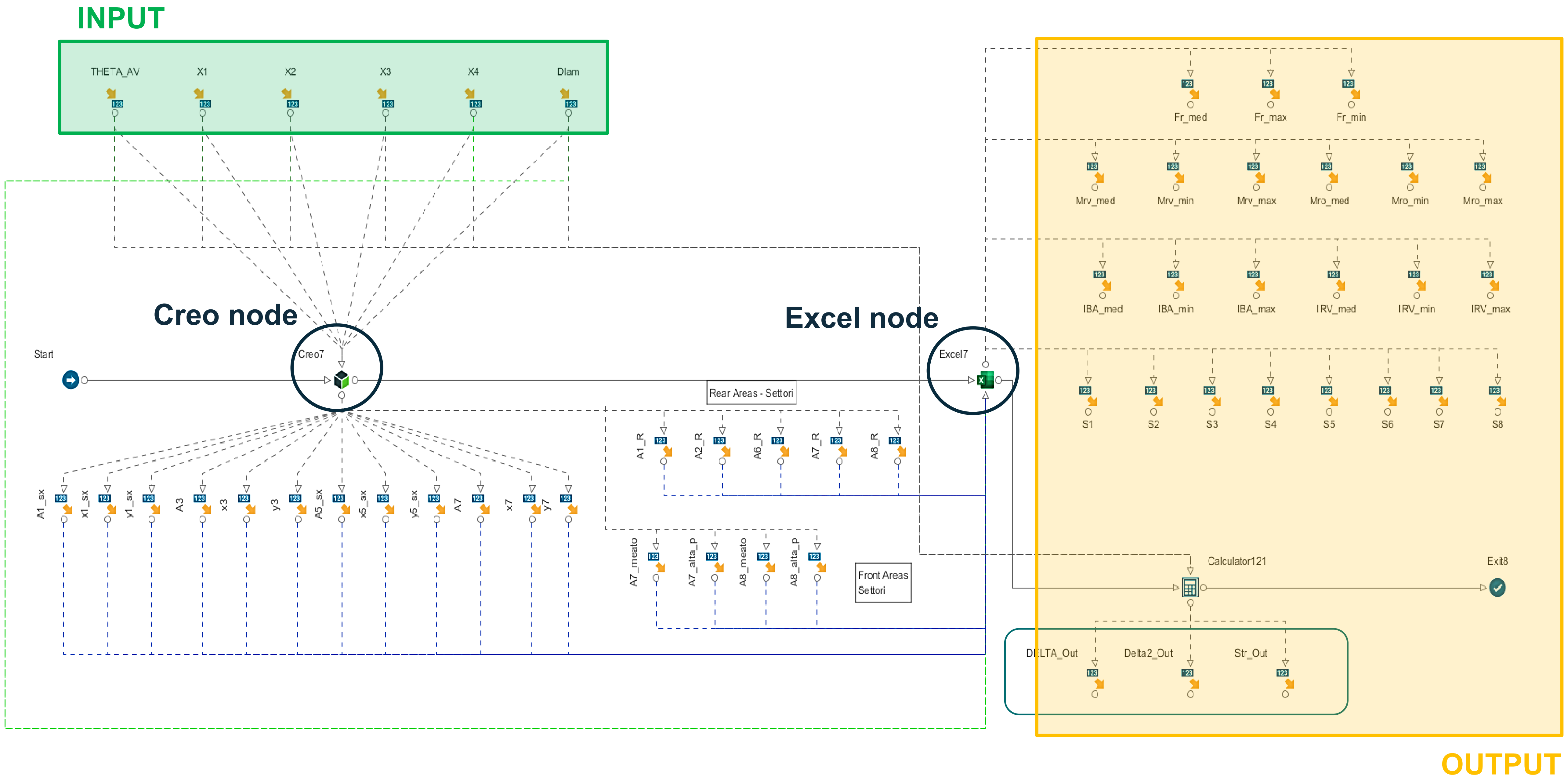


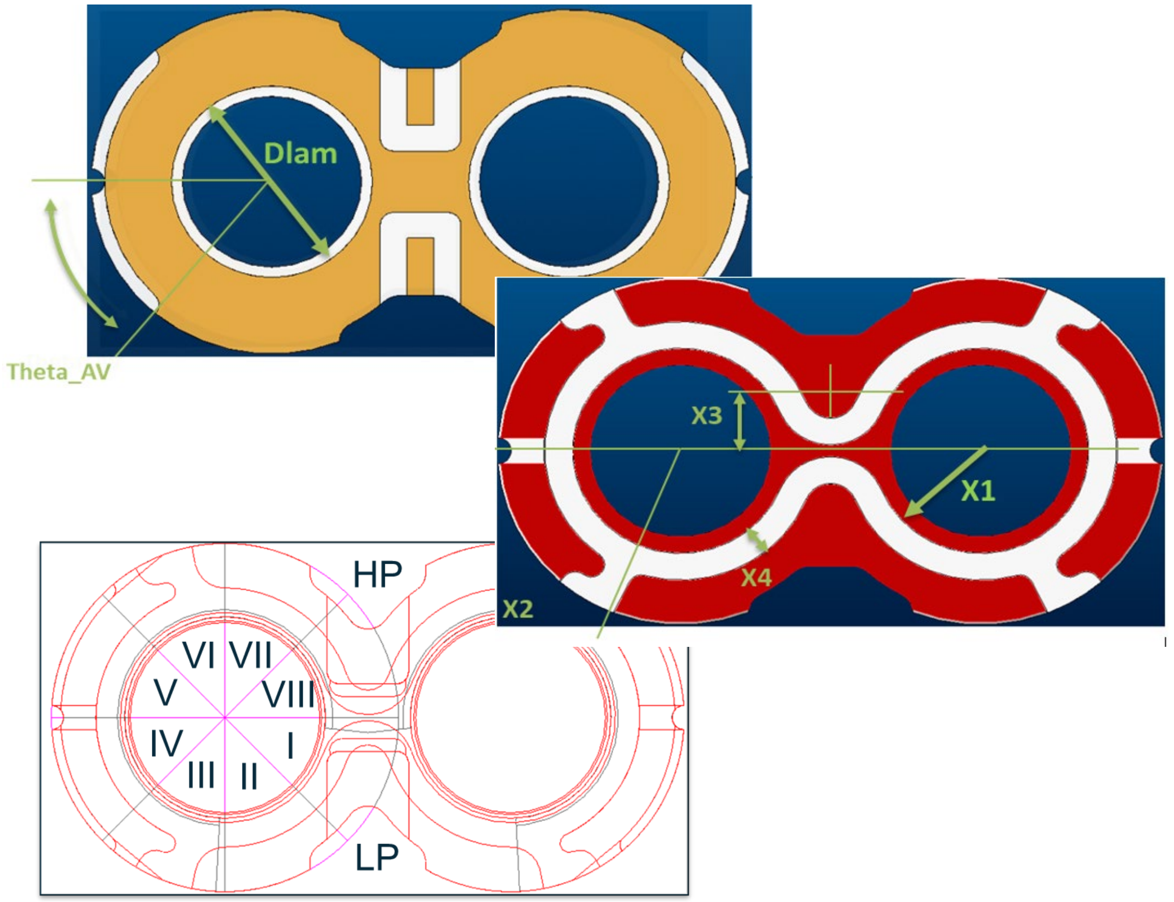




Balancing plate – Casappa optimization method

The standard Casappa method for balancing plate optimization is based on a parametric CAD model and an Excel calculation tool integrated into the modeFRONTIER workflow shown below.





Main input variables:

- Drain diameter (Dlam)
- High speed groove angle (Theta_AV)
- Seal groove internal diameter (X1)
- Seal foot angle (X2)
- Distance from the seal groove radius center to the horizontal axis (X3)

Main output variables:

- Axial residual force (Fr)
- Vertical overturning moment (Mrv)
- Area of sectors I-II...VIII (S1, S2, ... S8)

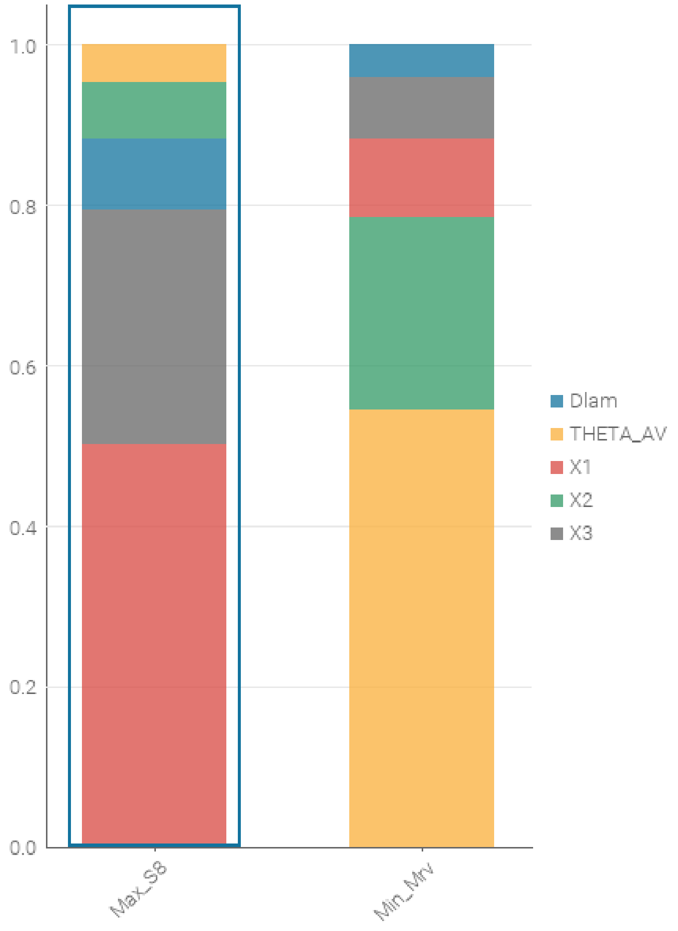
Balancing plate – robust analysis setup

Stochastic input variables → 5

- Dlam (drain diameter)
- Theta_AV (high speed groove angle)
- X1 (seal groove internal diameter)
- X2 (seal foot angle)
- X3 (distance from the seal groove radius center to the horizontal axis)

Output variable with percentiles → 11

All stochastic inputs influence the outputs of interest



	DELTA_Out	Delta2_Out	Fr_med	Fr_min	IBA_med	IRV_med	Mrv_med	S3	S4	S8	Str_Out
DELTA_Out											
Delta2_Out	0.098										
Fr_med	0.299	0.555									
Fr_min	0.302	0.556	1.000								
IBA_med	0.339	0.589	0.993	0.994							
IRV_med	0.018	-0.160	-0.296	-0.295	-0.290						
Mrv_med	0.855	0.245	0.195	0.200	0.279	0.068					
S3	0.974	0.197	0.335	0.339	0.394	0.005	0.917				
S4	0.059	0.567	0.830	0.832	0.845	-0.334	0.018	0.155			
S8	0.024	0.877	0.793	0.794	0.801	-0.282	0.017	0.108	0.837		
Str_Out	-0.245	-0.262	-0.141	-0.152	-0.229	0.034	-0.477	-0.403	-0.271	-0.244	

UNRELATED OBJECTIVES

Project objectives:

- Mrv (vertical overturning moment) → MINIMIZE
- S8 area → MAXIMIZE

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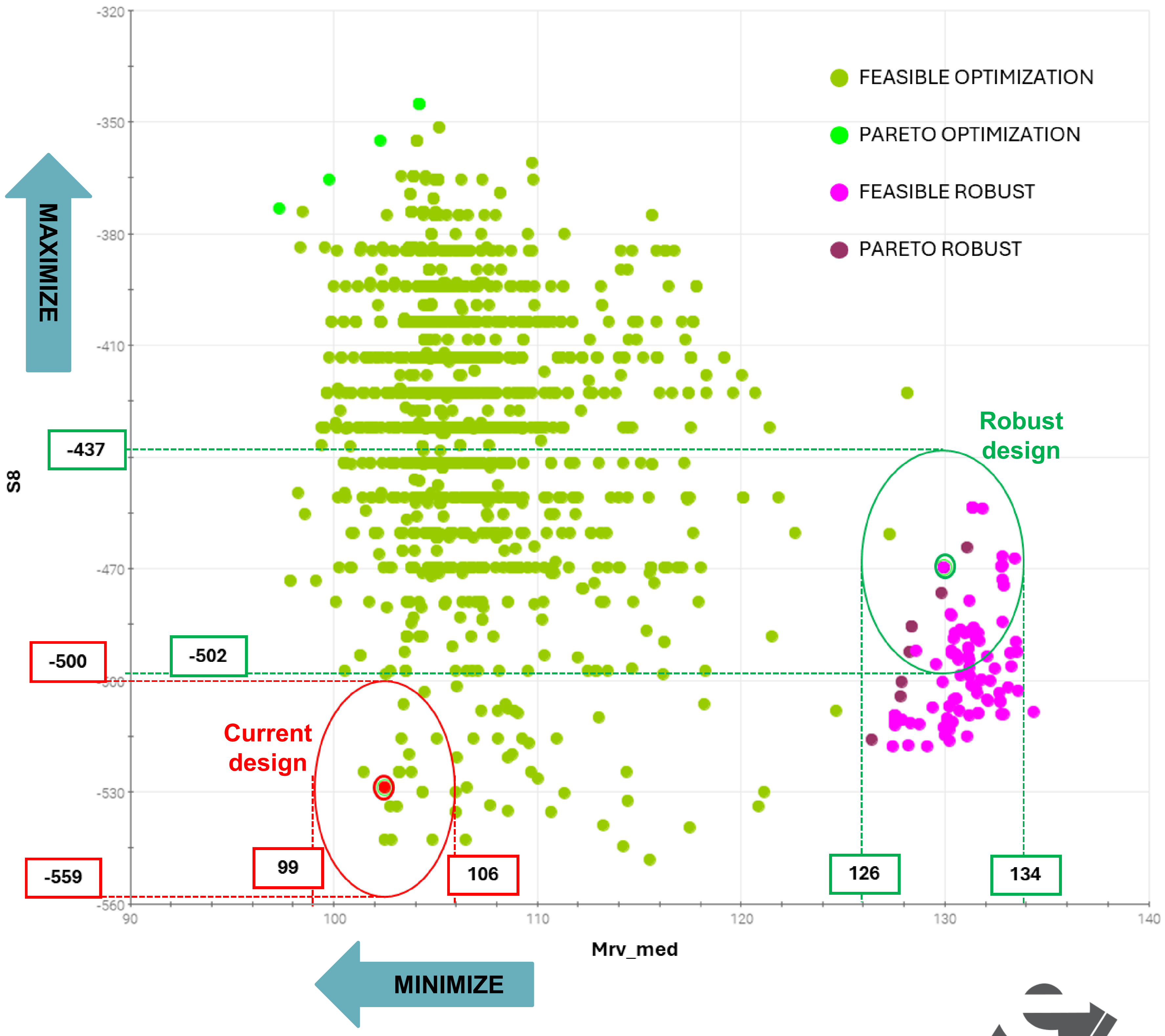
Balancing plate – results analysis

INPUT			CURRENT DESIGN		
Variable		Dlam	37.3		
		THETA_AV	51.2		
		X1	19.7		
		X2	63.8		
		X3	12.0		
Constant		X4	4.0		
INPUT CONSTRAINTS			Mean	St.dev	Perc 99%
S_tr_out	> 4.9		7.91	0.05	7.80
DELTA_out	> 12		12.60	0.18	12.19
delta2_out	< -0.9		-2.07	0.04	-1.98
OUTPUT CONSTRAINTS			Mean	St.dev	Perc 99%
Fr_min_GT_1500N	> 1500		5797.75	128.45	5490.15
Frmed_lower_8000N	< 8000		7760.67	128.39	8072.00
IRV_med_less_08	< 0.8		0.40	0.01	0.41
S3_greater_400N	> 400		707.29	21.81	657.22
S4_greater_150	> 150		161.79	10.68	137.15
S8_greater_meno550N	> -550		-528.64	13.17	-559.98
OBJECTIVES	Minimize	Mrv_med	102.45	1.59	106.19
	Maximize	S8	-528.64	13.17	-559.98

INPUT			ROBUST DESIGN		
Variable		Dlam	37.2		
		THETA_AV	41.1		
		X1	20.0		
		X2	53.5		
		X3	10.4		
Constant		X4	4.0		
INPUT CONSTRAINTS			Mean	St.dev	Perc 99%
S_tr_out	> 4.9		8.34	0.05	8.23
DELTA_out	> 12		12.42	0.18	12.01
delta2_out	< -0.9		-1.09	0.04	-1.00
OUTPUT CONSTRAINTS			Mean	St.dev	Perc 99%
Fr_min_GT_1500N	> 1500		5721.53	110.02	5472.75
Frmed_lower_8000N	< 8000		7691.00	110.13	7958.70
IRV_med_less_08	< 0.8		0.51	0.01	0.53
S3_greater_400N	> 400		840.97	17.61	800.22
S4_greater_150	> 150		182.56	12.18	154.74
S8_greater_meno550N	> -550		-469.56	13.68	-502.08
OBJECTIVES	Minimize	Mrv_med	129.92	1.62	133.71
	Maximize	S8	-469.56	13.68	-502.08



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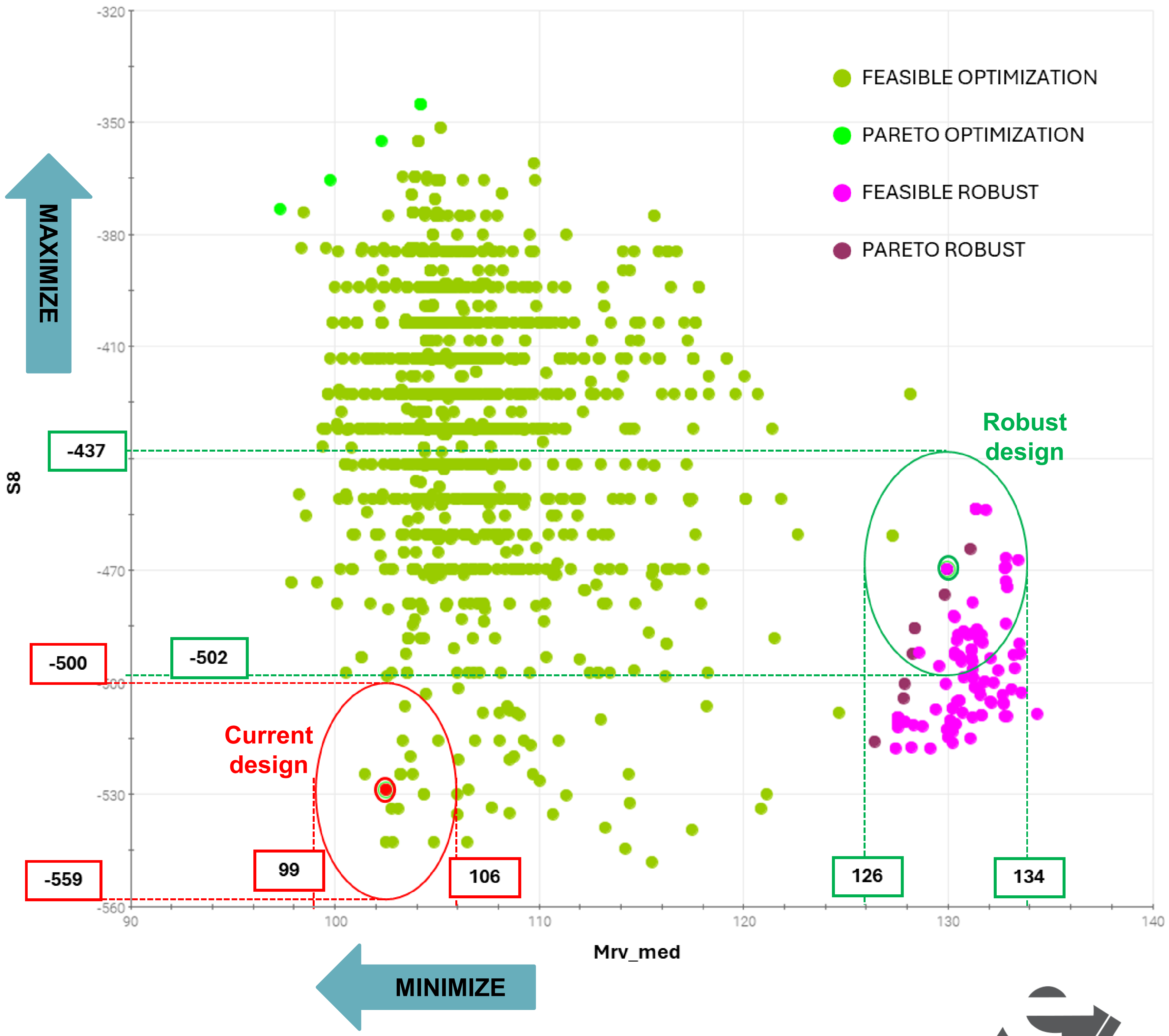
Balancing plate – results analysis

- The design obtained through deterministic optimization is not robust.
- The point clouds obtained for the current design and the robust design are similar: the stability of the parameters of interest remains unchanged.
- In robust optimization, the best designs are located in a different region of the acceptable range of the parameters of interest, leading to an improvement in one objective (S8) and a deterioration in the other (Mrv).



Third case study – valve plate

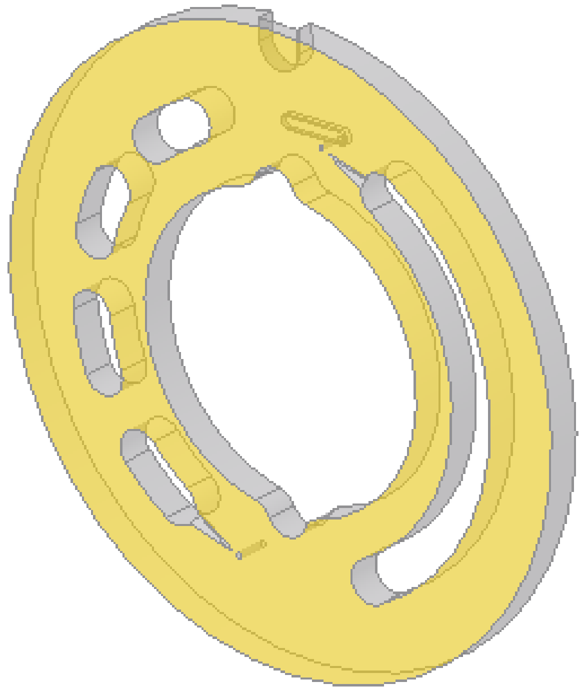
- Working principle
- Casappa optimization method
- Robustness check
- Result analysis

Valve plate – working principle

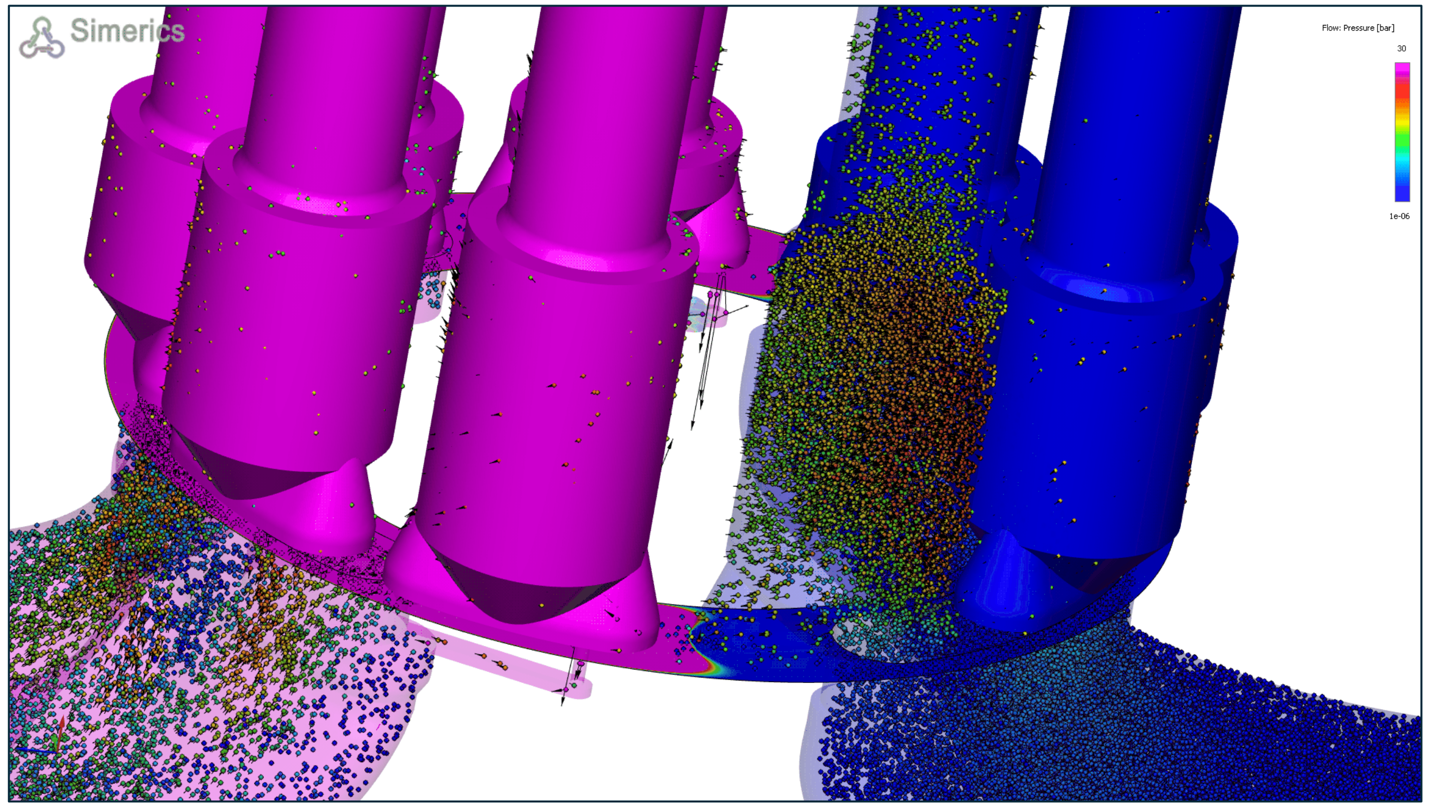
The third case study focuses on the valve plate, a key component of a swashplate axial piston pump.
The geometry of the valve plate defines the angular opening and closing of the suction and delivery phases, thus directly influencing the performance of the pump.

Variables influenced by the geometry of the plate

- pressure peaks → noise of the pump and fatigue life
- internal transient flows → noise of the pump
- pressure pulsation → noise of the entire hydraulic circuit
- pump average flow and absorbed torque → efficiency (machine fuel consumption)
- cavitation → maximum speed of the pump

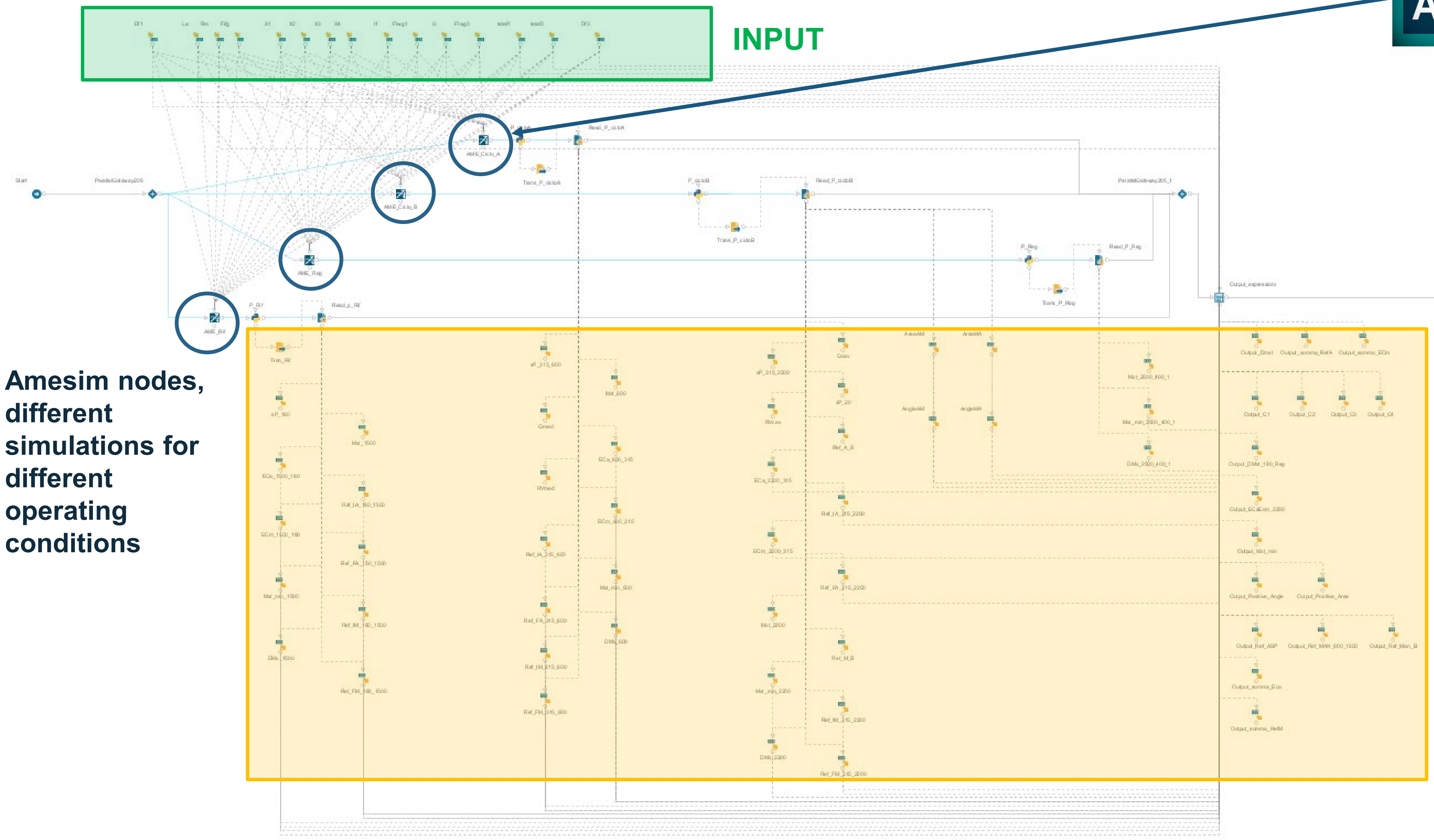


Influence of plate geometry on oil particles

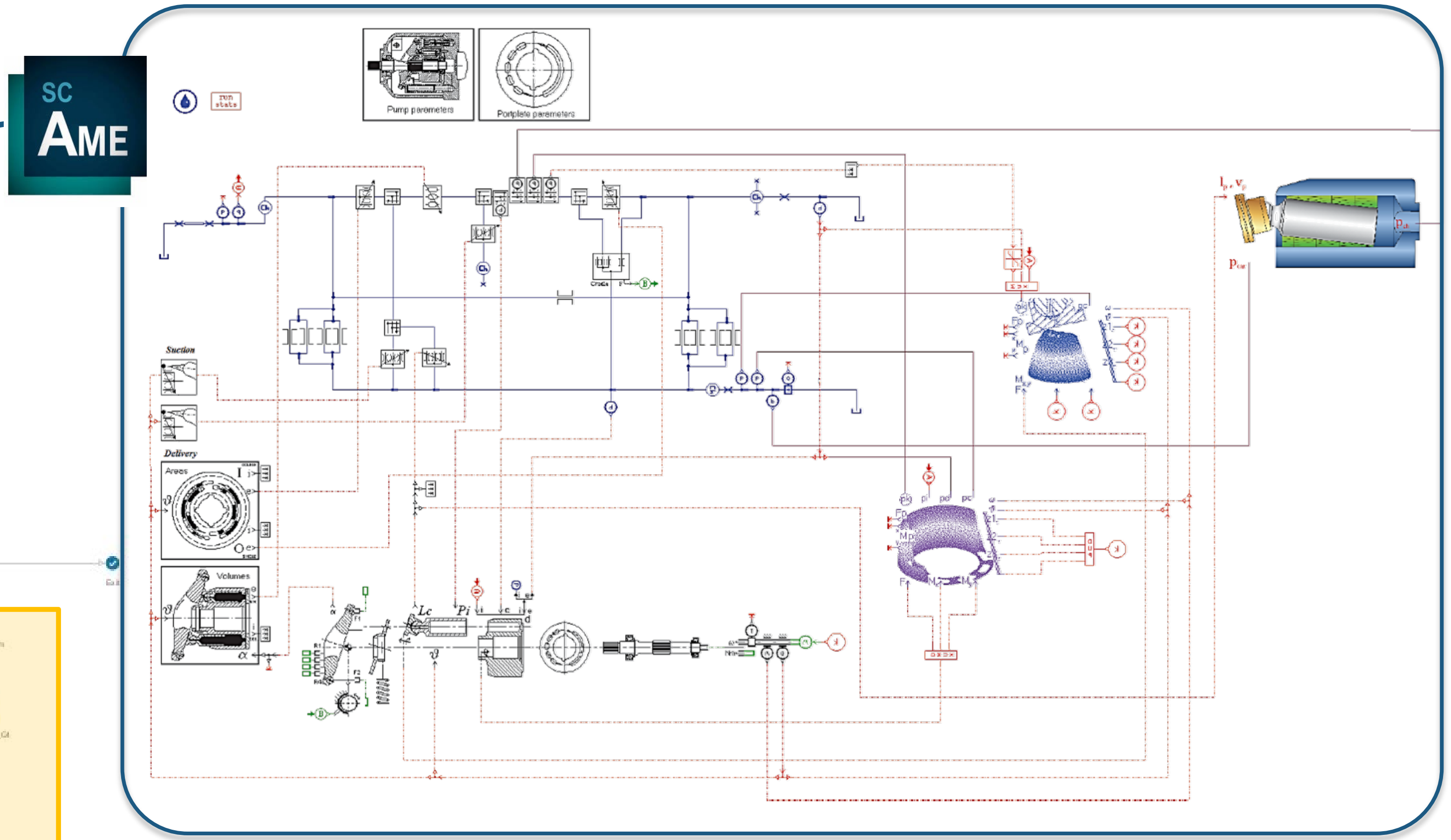


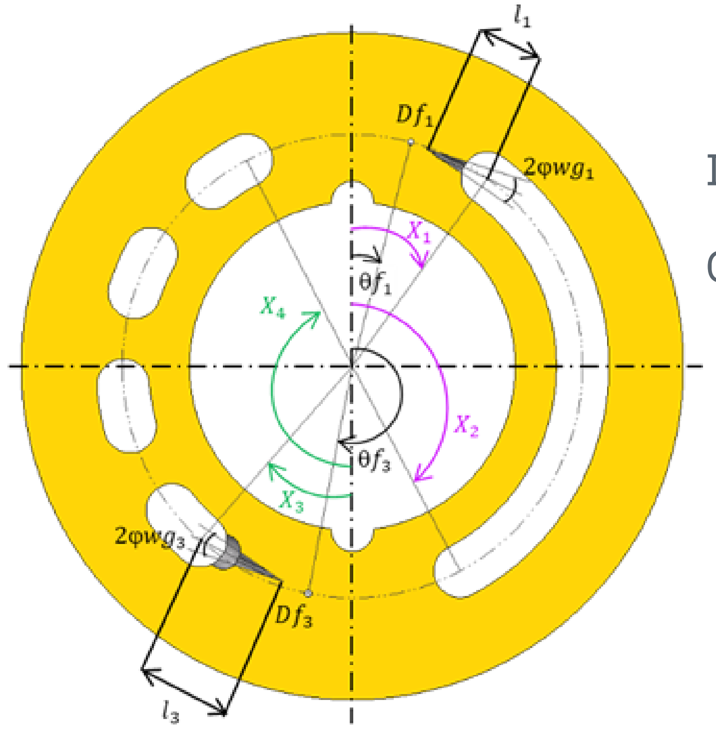
Valve plate – Casappa optimization method

The component is optimized within the modeFrontier workflow using 4 lumped-parameter Amesim models and an equivalent number of Python scripts for data processing.



Amesim nodes, different simulations for different operating conditions





Input variables →15

Output variables →40

Valve plate – robustness check

Considering the high computational cost (2.5 minutes per design) and the complexity of the case study, only a robustness check was performed on the best feasible designs obtained from classical optimization for the valve plate.

Objectives used in the standard optimization:

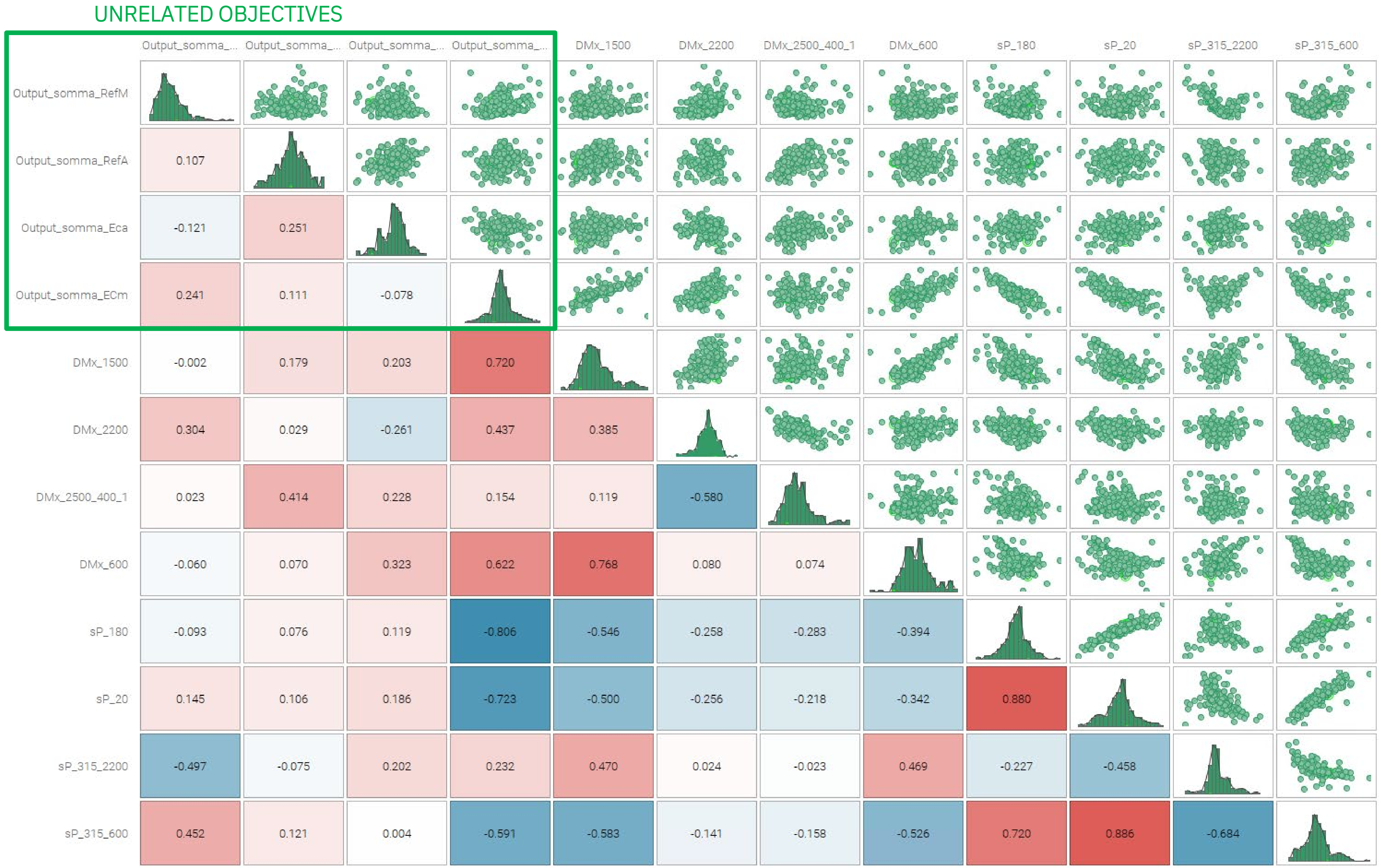
- ∑RefA (suction backflow) → MINIMIZE
- ∑RefM (delivery backflow)→ MINIMIZE
- ∑Eca (suction flow ripple energy content) → MINIMIZE
- ∑Ecm (delivery flow ripple energy content)→ MINIMIZE

Check was performed using:

Stochastic input variables → 8

- X1 (suction opening angle)
- X2 (suction closing angle)
- X3 (delivery opening angle)
- X4 (delivery closing angle)
- l1 (suction groove length)
- l3 (delivery groove length)
- thetaf1 (suction hole angular position)
- thetaf3 (delivery hole angular position)

Output variable with percentiles → 35



	Output_somma_...	Output_somma_...	Output_somma_...	Output_somma_...	DMx_1500	DMx_2200	DMx_2500_400_1	DMx_600	sP_180	sP_20	sP_315_2200	sP_315_600
Output_somma_RefM												
Output_somma_RefA	0.107											
Output_somma_Eca	-0.121	0.251										
Output_somma_ECm	0.241	0.111	-0.078									
DMx_1500	-0.002	0.179	0.203	0.720								
DMx_2200	0.304	0.029	-0.261	0.437	0.385							
DMx_2500_400_1	0.023	0.414	0.228	0.154	0.119	-0.580						
DMx_600	-0.060	0.070	0.323	0.622	0.768	0.080	0.074					
sP_180	-0.093	0.076	0.119	-0.806	-0.546	-0.258	-0.283	-0.394				
sP_20	0.145	0.106	0.186	-0.723	-0.500	-0.256	-0.218	-0.342	0.880			
sP_315_2200	-0.497	-0.075	0.202	0.232	0.470	0.024	-0.023	0.469	-0.227	-0.458		
sP_315_600	0.452	0.121	0.004	-0.591	-0.583	-0.141	-0.158	-0.526	0.720	0.886	-0.684	

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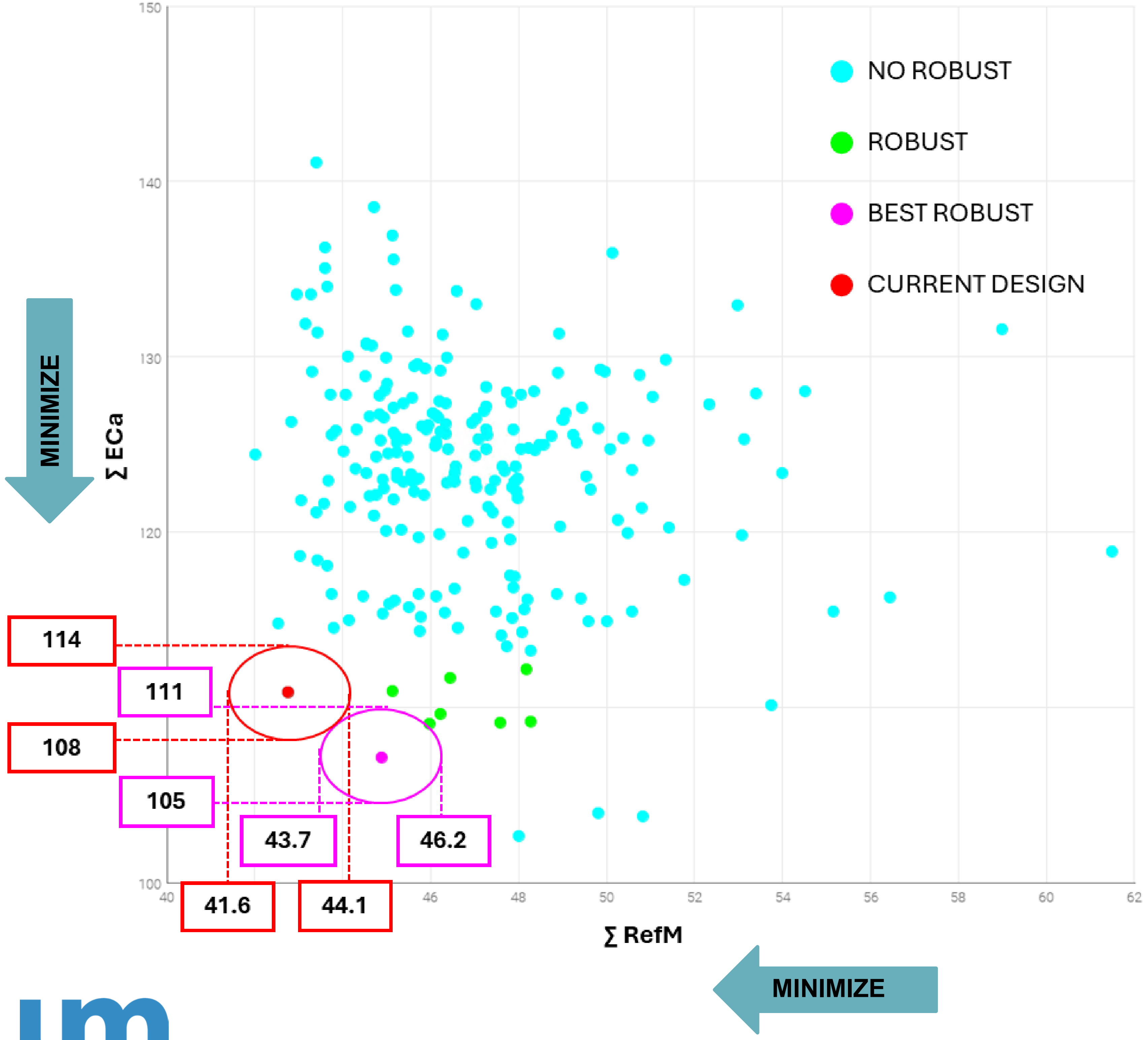
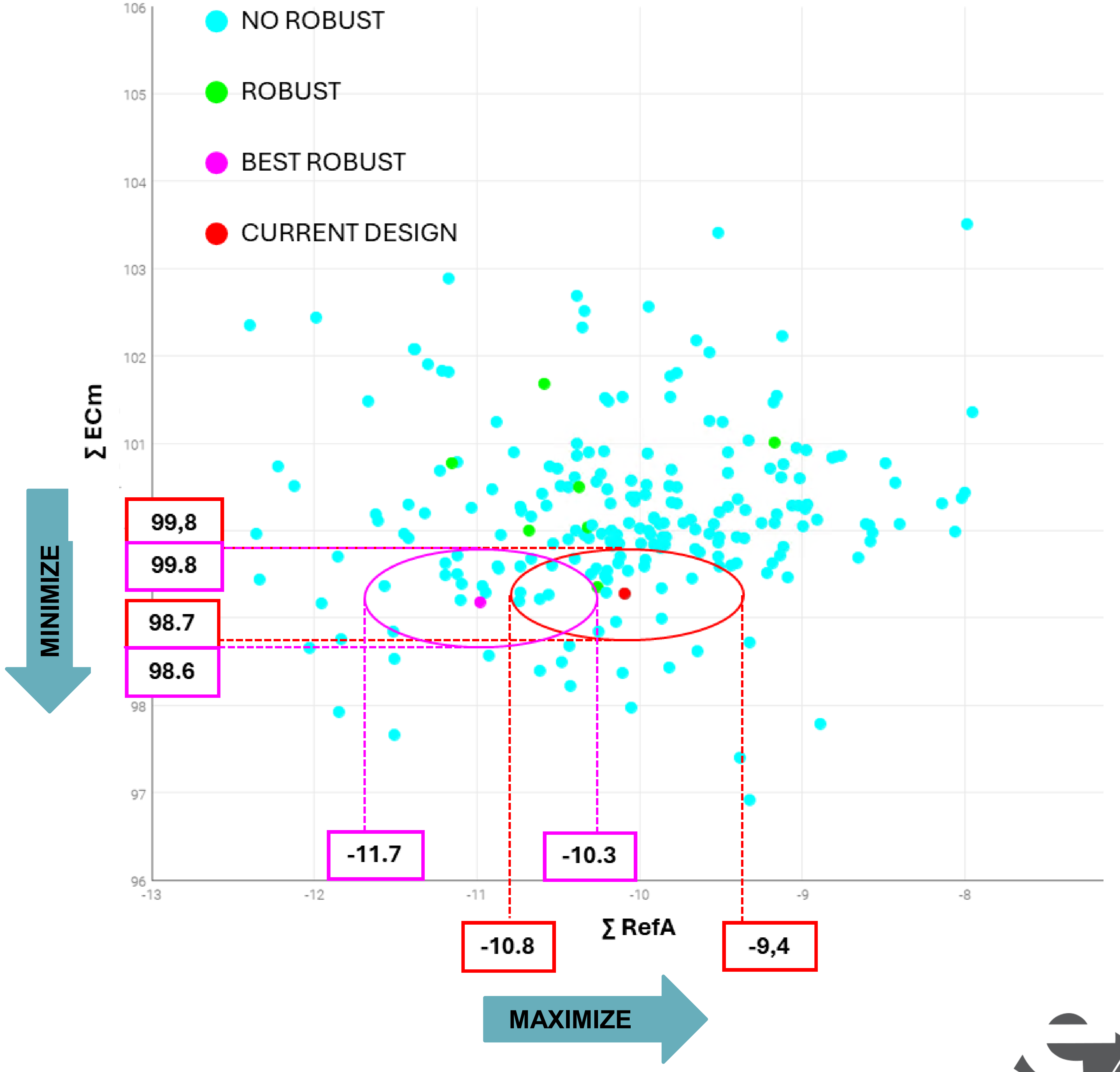
Valve plate – results analysis

		Constraints		Current design		
				Mean	STD dev	Perc 99%
Pressure peak [bar]	sP_180_1500	<	23	23.12	0.32	23.89
	sP_nmax	<	14	7.56	0.11	-
	sP_600			9.86	0.15	-
	sP_20	<	42	38.45	1.26	42.26
Suction backflow [lpm]	Ref_IA_600	>	-7	-0.01	0.00	-0.02
	Ref_FA_600			-6.26	0.19	-6.69
	Ref_IA_180_1500			-0.43	0.02	-0.51
	Ref_FA_180_1500			-0.39	0.09	-0.61
	Ref_IA_nmax			-3.02	0.06	-3.20
	Ref_FA_nmax			0.00	0.00	0.00
	Σ Ref_suction	>	**-12**	**-10.08**	**0.25**	**-10.75**
Delivery backflow [lpm]	Ref_IM_600	<	15	13.01	0.00	13.01
	Ref_FM_600			0.02	0.02	0.06
	Ref_IM_180_1500			9.85	0.00	9.85
	Ref_FM_180_1500			0.00	0.00	0.00
	Ref_IM_nmax	<	30	19.89	0.57	21.36
	Ref_FM_nmax			0.00	0.00	0.00
	Σ Ref_delivery	<	**50**	**42.84**	**0.51**	**44.08**
Efficiency [%]	Rv_600	>	**95.5**	95.77	0.03	95.70
	Rvcav	>	**95.5**	99.24	0.01	99.21
Overtuning moment [Nm]	Mxt_min_nmax	>	80	99.33	1.84	95.14
	Mxt_min_1500			108.55	0.62	106.95
	Mxt_min_600			238.90	1.38	235.62
	Mxt_min_Reg			113.81	1.61	110.17
	DMxt_nmax	<	280	264.72	2.24	270.90
	DMxt_1500		240	173.96	0.51	175.11
	DMxt_600		310	309.73	0.87	311.75
	DMxt_Reg		240	224.64	2.10	230.01
Flow ripple energy content [bar-rms]	ECa_nmax	<	70	60.66	1.87	64.99
	ECm_nmax			56.37	0.23	56.90
	ECa_180_1500			42.75	0.34	43.62
	ECm_180_1500			31.98	0.06	32.13
	Eca_600			7.07	0.18	7.60
	ECm_600			10.93	0.03	11.00
	ECa_tot	<	**115**	**110.99**	**1.06**	**113.91**
	ECm_tot	<	**103**	**99.29**	**0.24**	**99.84**

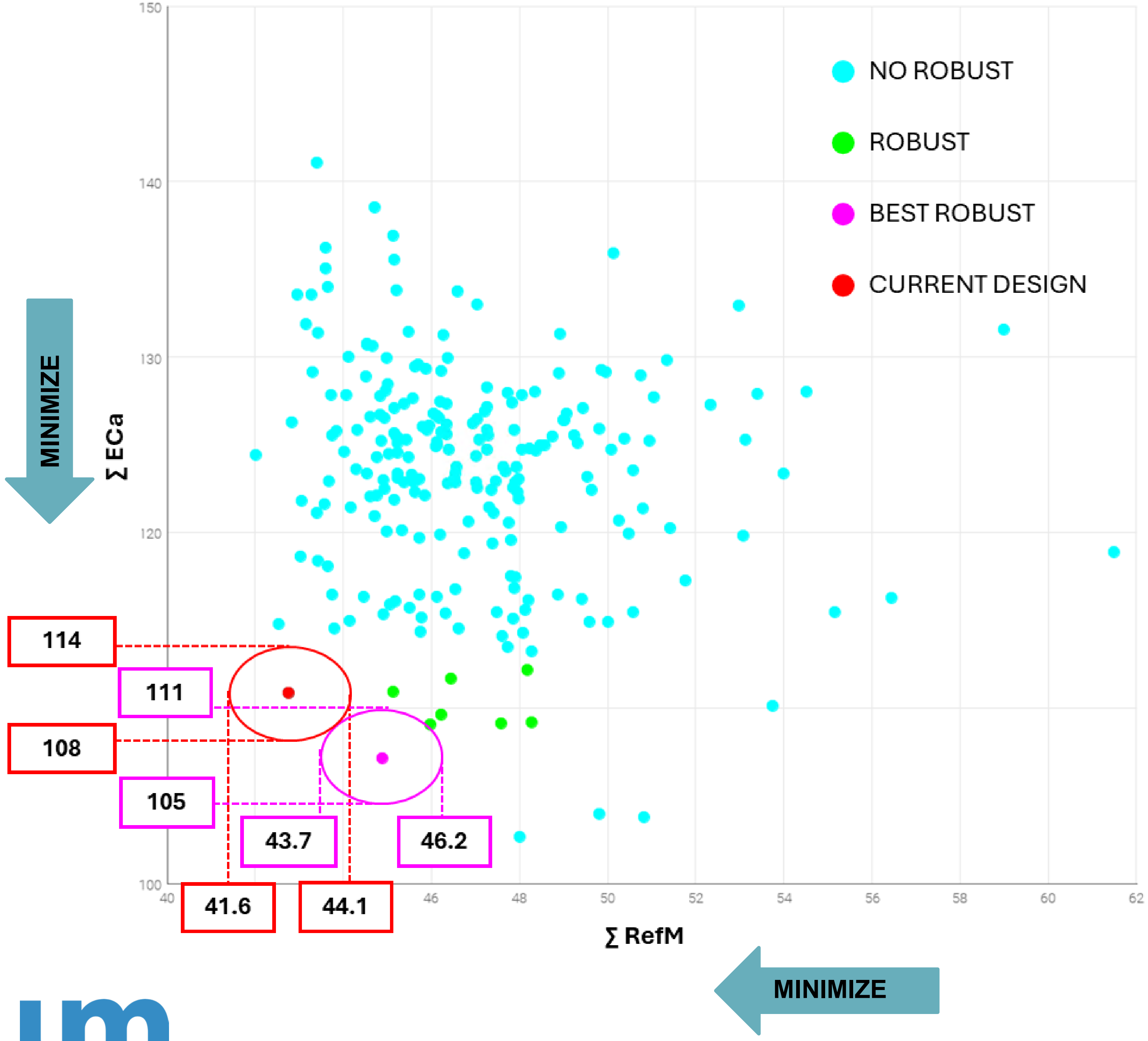
		Constraints		Best robust design		
				Mean	STD dev	Perc 99%
Pressure peak [bar]	sP_180_1500	<	23	19.73	0.27	20.39
	sP_nmax	<	14	7.05	0.10	-
	sP_600			9.01	0.17	-
	sP_20	<	42	34.37	0.49	35.52
Suction backflow [lpm]	Ref_IA_600	>	-7	-0.01	0.00	-0.02
	Ref_FA_600			-6.84	0.16	-7.21
	Ref_IA_180_1500			-0.45	0.03	-0.52
	Ref_FA_180_1500			-0.62	0.10	-0.86
	Ref_IA_nmax			-3.07	0.07	-3.24
	Ref_FA_nmax			0.00	0.00	0.00
	Σ Ref_suction	>	**-12**	**-10.98**	**0.28**	**-11.65**
Delivery backflow [lpm]	Ref_IM_600	<	15	13.01	0.00	13.02
	Ref_FM_600			0.30	0.13	0.66
	Ref_IM_180_1500			9.85	0.00	9.85
	Ref_FM_180_1500			0.00	0.00	0.00
	Ref_IM_nmax	<	30	21.78	0.55	23.08
	Ref_FM_nmax			0.00	0.00	0.00
	Σ Ref_delivery	<	**50**	**44.93**	**0.52**	**46.18**
Efficiency [%]	Rv_600	>	**95.5**	95.63	0.03	95.55
	Rvcav	>	**95.5**	99.23	0.01	99.20
Overtuning moment [Nm]	Mxt_min_nmax	>	80	104.08	1.83	99.88
	Mxt_min_1500			111.59	0.43	110.57
	Mxt_min_600			242.95	1.49	239.45
	Mxt_min_Reg			120.15	1.63	116.51
	DMxt_nmax	<	280	263.03	1.92	267.40
	DMxt_1500		240	169.67	0.40	170.59
	DMxt_600		310	303.02	0.85	305.00
	DMxt_Reg		240	228.56	2.41	234.01
Flow ripple energy content [bar-rms]	ECa_nmax	<	70	59.34	0.70	61.42
	ECm_nmax			56.93	0.23	57.45
	ECa_180_1500			41.46	0.45	42.58
	ECm_180_1500			31.29	0.06	31.43
	Eca_600			7.09	0.13	7.41
	ECm_600			10.97	0.03	11.04
	ECa_tot	<	**115**	**107.88**	**1.14**	**110.79**
	ECm_tot	<	**103**	**99.19**	**0.25**	**99.76**

Valve plate – results analysis





Valve plate – results analysis



- The design obtained through deterministic optimization is not robust.
- By applying a robustness check to the best designs obtained from deterministic optimization, some designs were found to be robust.
- Incorporating robustness into the optimization process would have led to the selection of an optimal design different from the one currently in use

Conclusion

Conclusions

In this work, the effect of integrating robustness analysis is assessed across three case studies of hydraulic pump components with increasing complexity.

The results vary depending on the case:

- For the simplest case, the compression spring, incorporating robustness leads to a more compact design cloud (representing the variation of the parameters of interest around their nominal values) compared to that obtained through deterministic optimization, while still meeting the predefined objectives.
- For the medium-complexity case, the balancing plate, the search for robust designs shifts toward a different region of the design space than the one where the deterministic optimum is located. Robust designs can be obtained by accepting a slight degradation in performance.
- For the most complex case, the valve plate, only a robustness check was performed on the best feasible designs obtained from deterministic optimization. The results show that accounting for uncertainties in the analysis would have led to the selection of a design different from the current one, which proves to be non-robust.

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Thank you

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