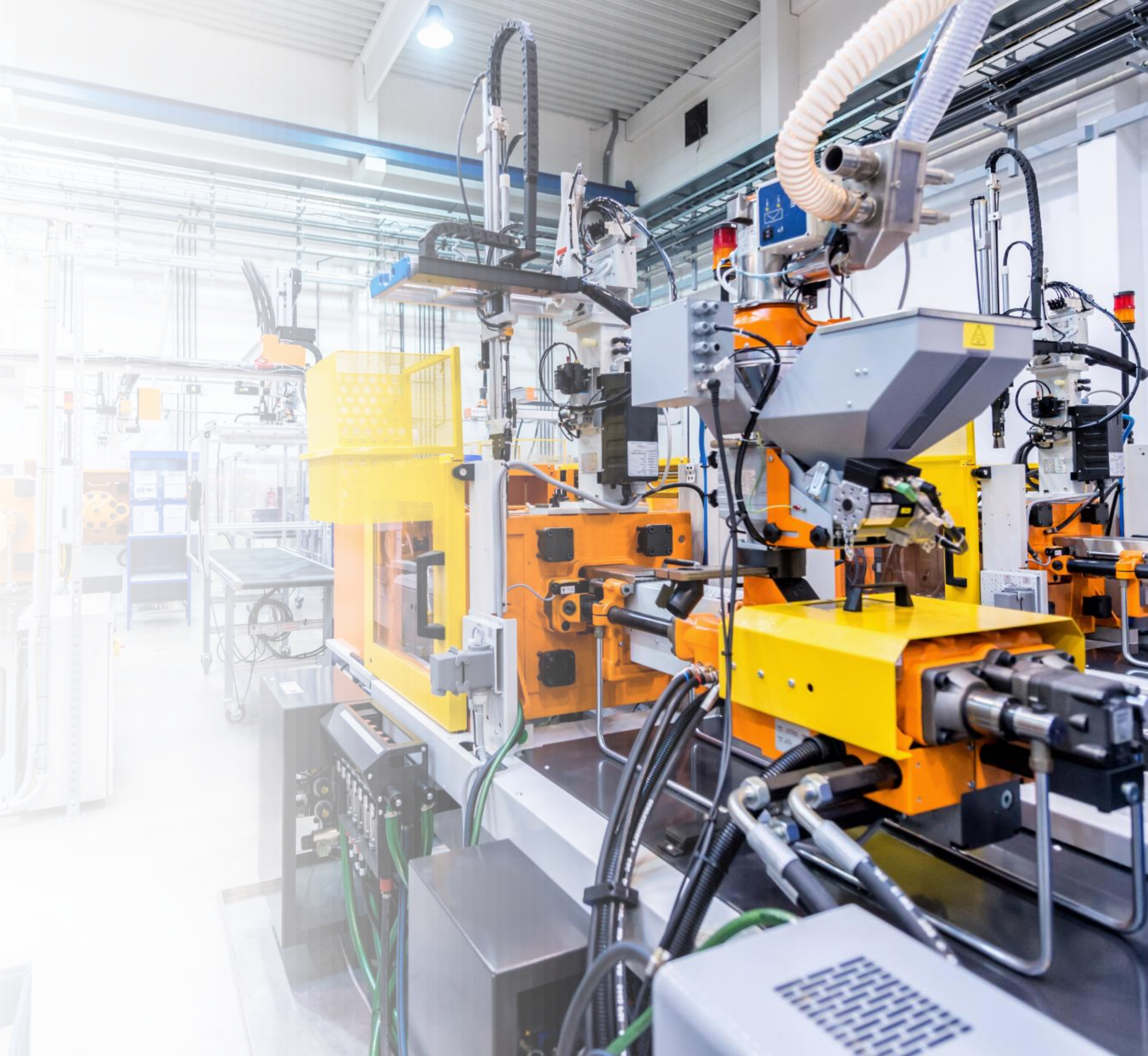
Case Study: Utilizing Quantum XL for Product Design with Multifactorial Parameters



Plackett-Burman Design for Development of Servo-hydraulic Power Units

by Ramon Balisnomo

May 4, 2026

History Behind Screening DOE

- The British Ministry of Supply asked **Robin Plackett** and **Peter Burman** to develop a method for efficient learning under severe experimental constraints. Their goal was to study many variables with very few experimental runs.

- They assumed **interaction effects were negligible**, allowing focus on main effects only.

- Oxford University Press published their journal **The Design of Optimal Multifactorial Experiments** in June 1946.

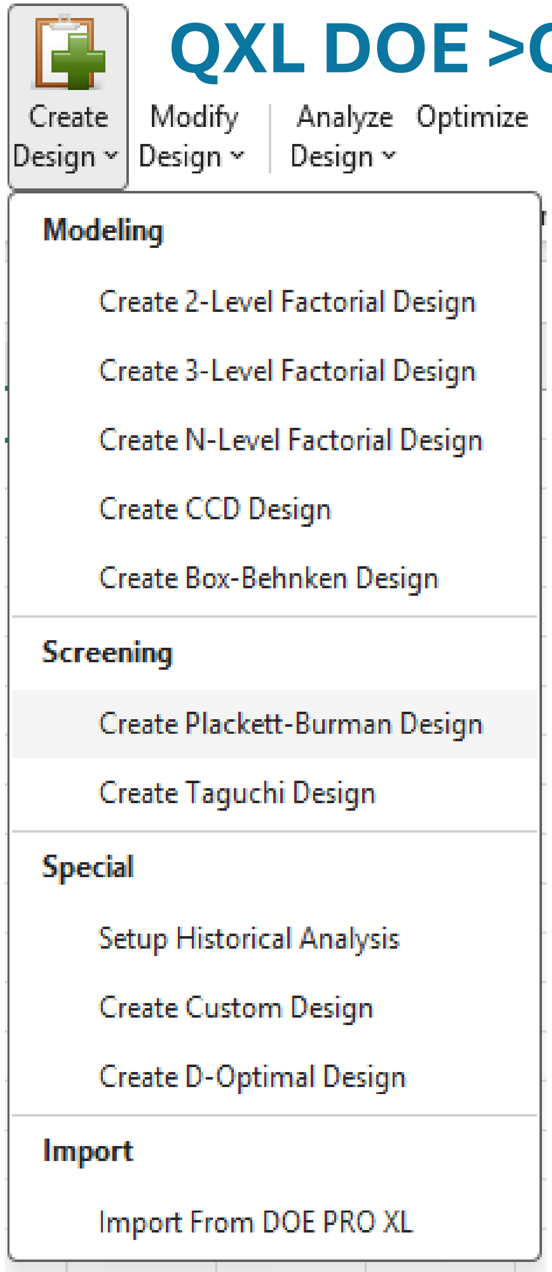
Background

Identify the design variables that most significantly impact system efficiency or pressure ripple during the early development of a servo-hydraulic power unit. The coefficient of determination must be at least 85 percent.

11 Design Variables

Factor	Variable (Typical Eaton Relevance)	Low (–1)	High (+1)
X1	Pump displacement (cc/rev)	18	24
X2	Pump rotational speed (rpm)	1800	2400
X3	System operating pressure (bar)	180	250
X4	Oil viscosity @ 40 °C (cSt)	32	68
X5	Valve spool land overlap (mm)	0.02	0.08
X6	Orifice diameter (mm)	1.2	1.8
X7	Case drain back-pressure (bar)	0.5	2.0
X8	Electrical supply voltage (V)	22	28
X9	Solenoid coil resistance (Ω)	6	10
X10	Ambient temperature (°C)	0	40
X11	Internal leakage clearance (μm)	8	14

QXL DOE >Create Design >Create Plackett-Burman Design



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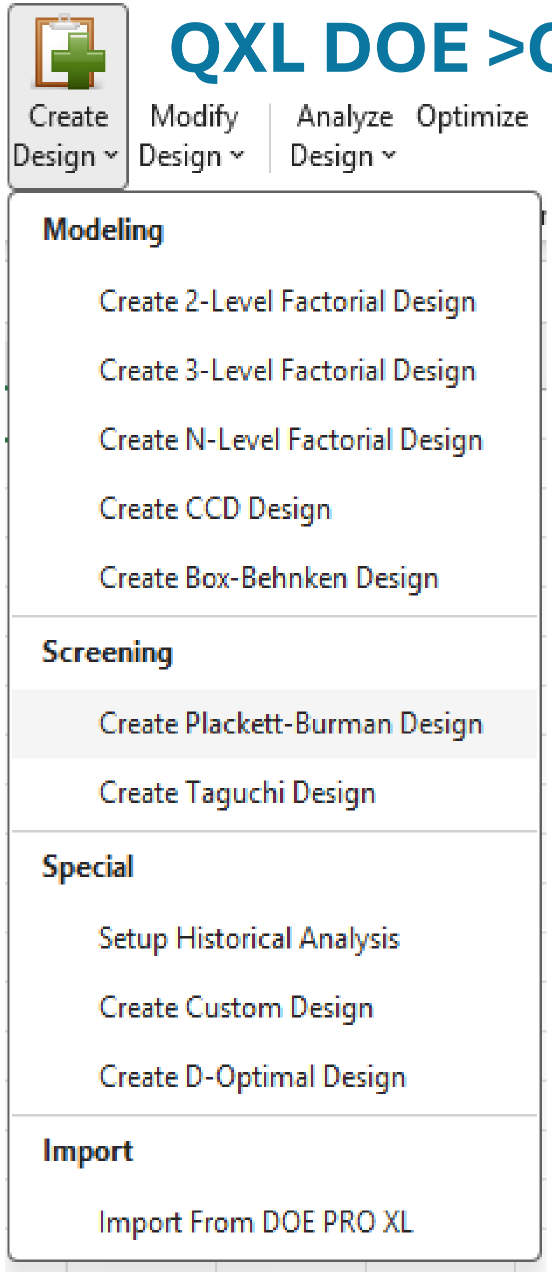

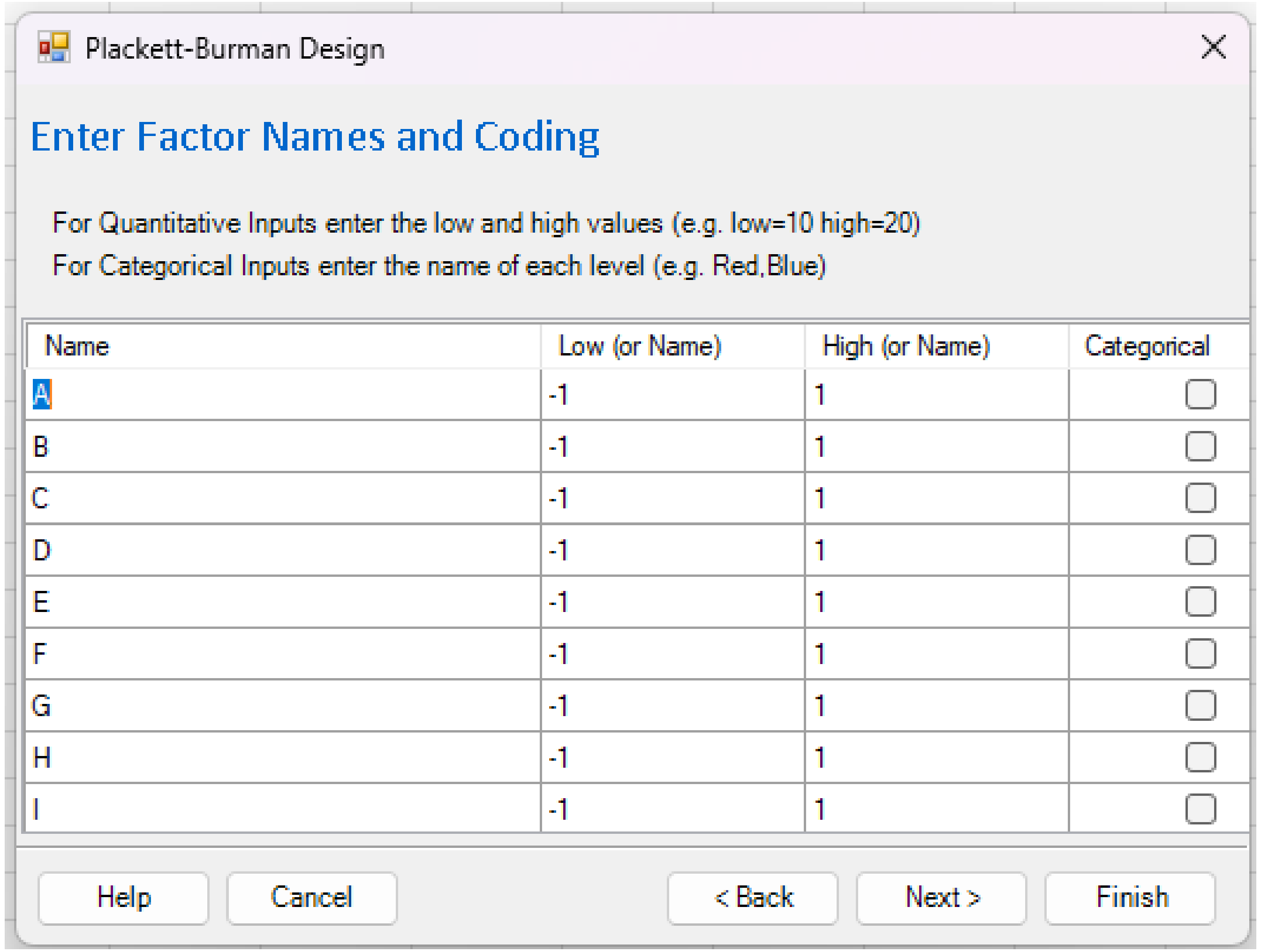

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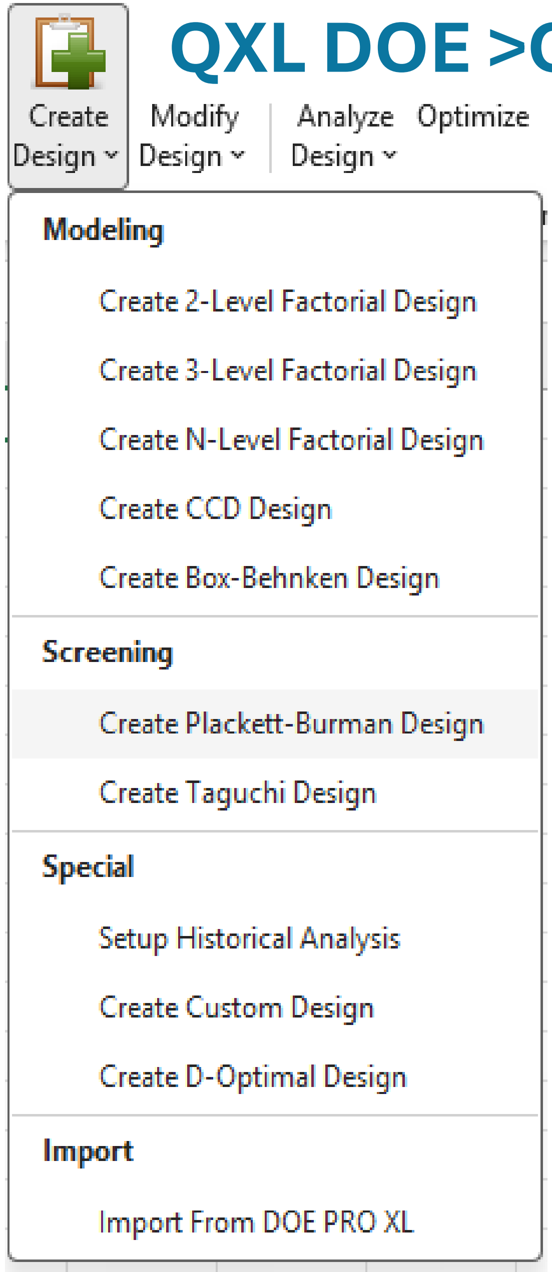

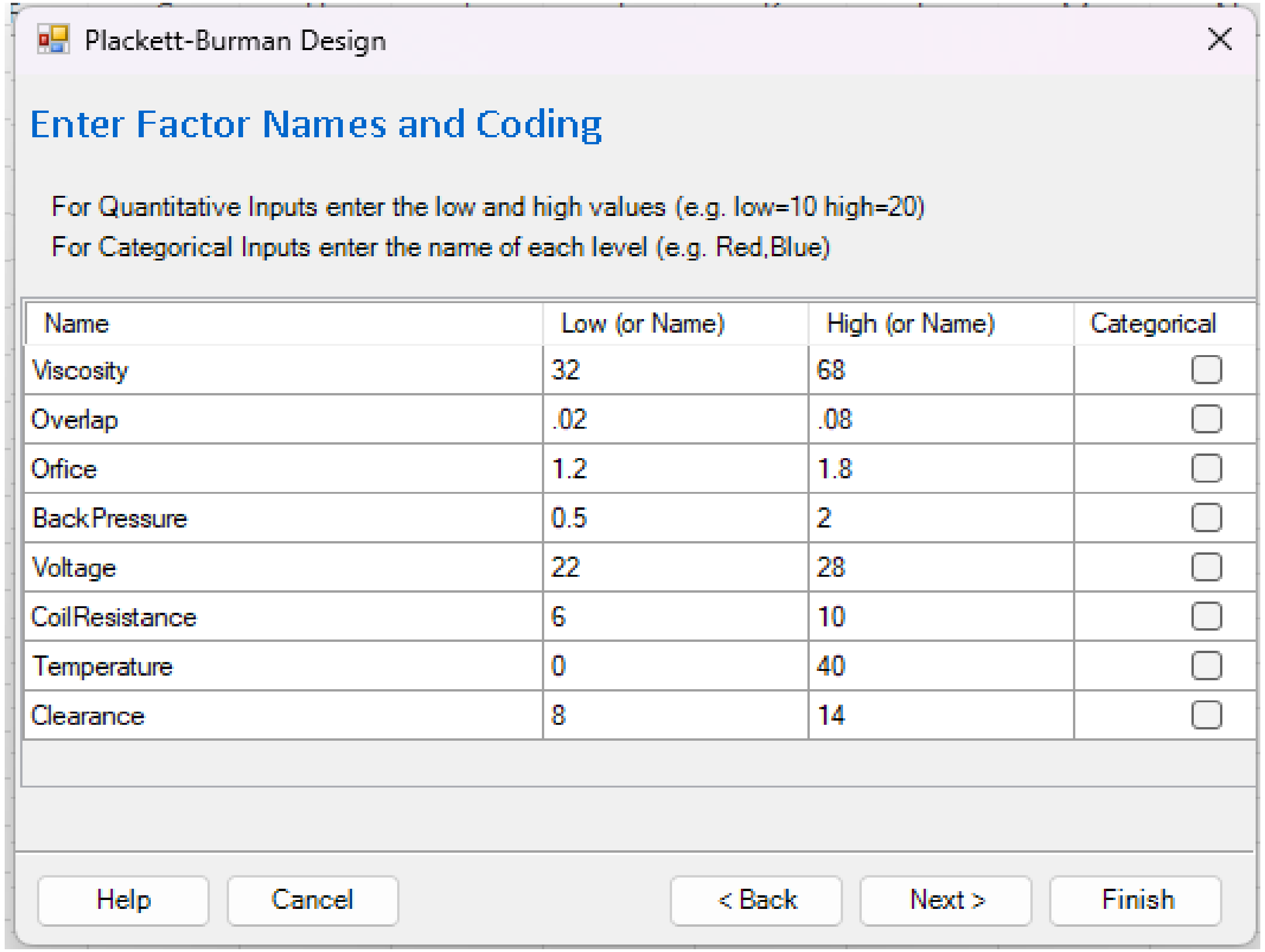

Name	Low (or Name)	High (or Name)	Categorical
Viscosity	32	68	☐
Overlap	.02	.08	☐
Orfice	1.2	1.8	☐
BackPressure	0.5	2	☐
Voltage	22	28	☐
CoilResistance	6	10	☐
Temperature	0	40	☐
Clearance	8	14	☐

4 Response Variables

Measure the following performance metrics per run:
Y_1: Overall system **efficiency (%)**
Y_2: Pressure ripple amplitude (**bar** RMS)
Y_3: Valve response time (**ms**)
Y_4: Power loss / heat generation (**W**)

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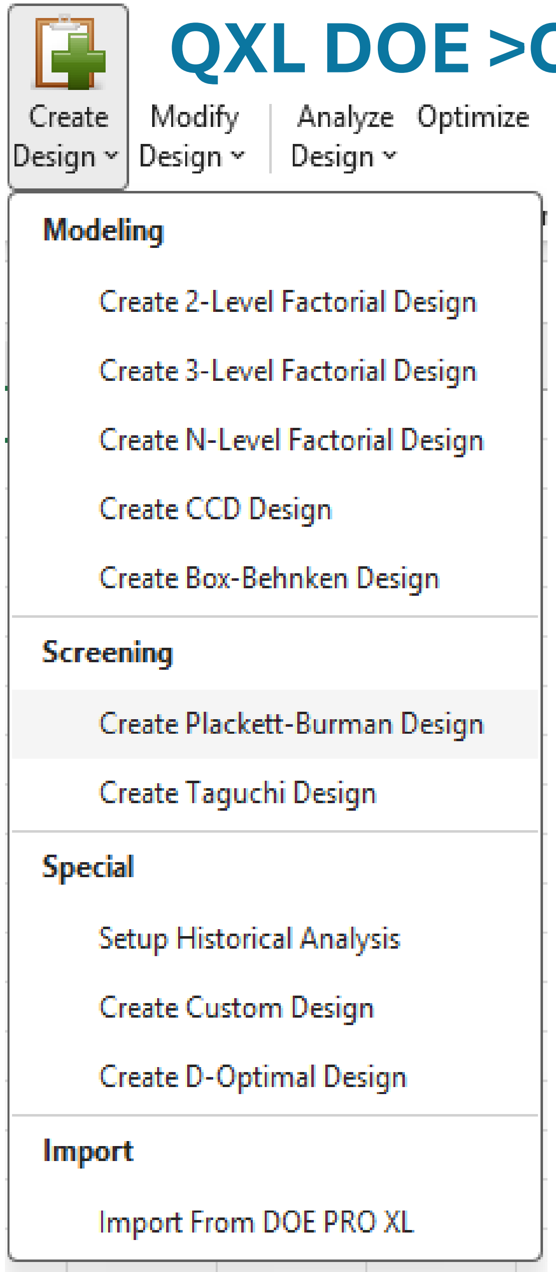

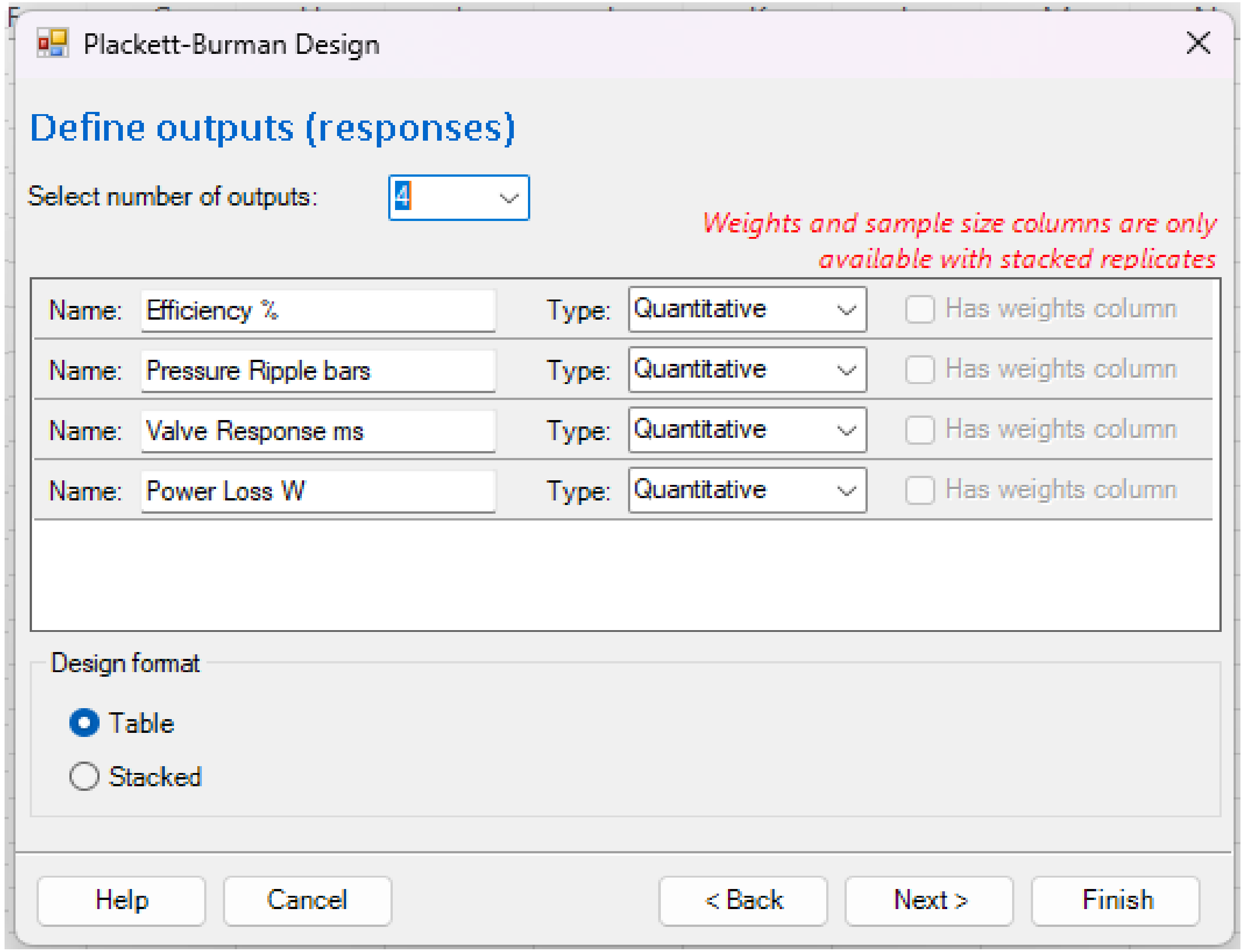

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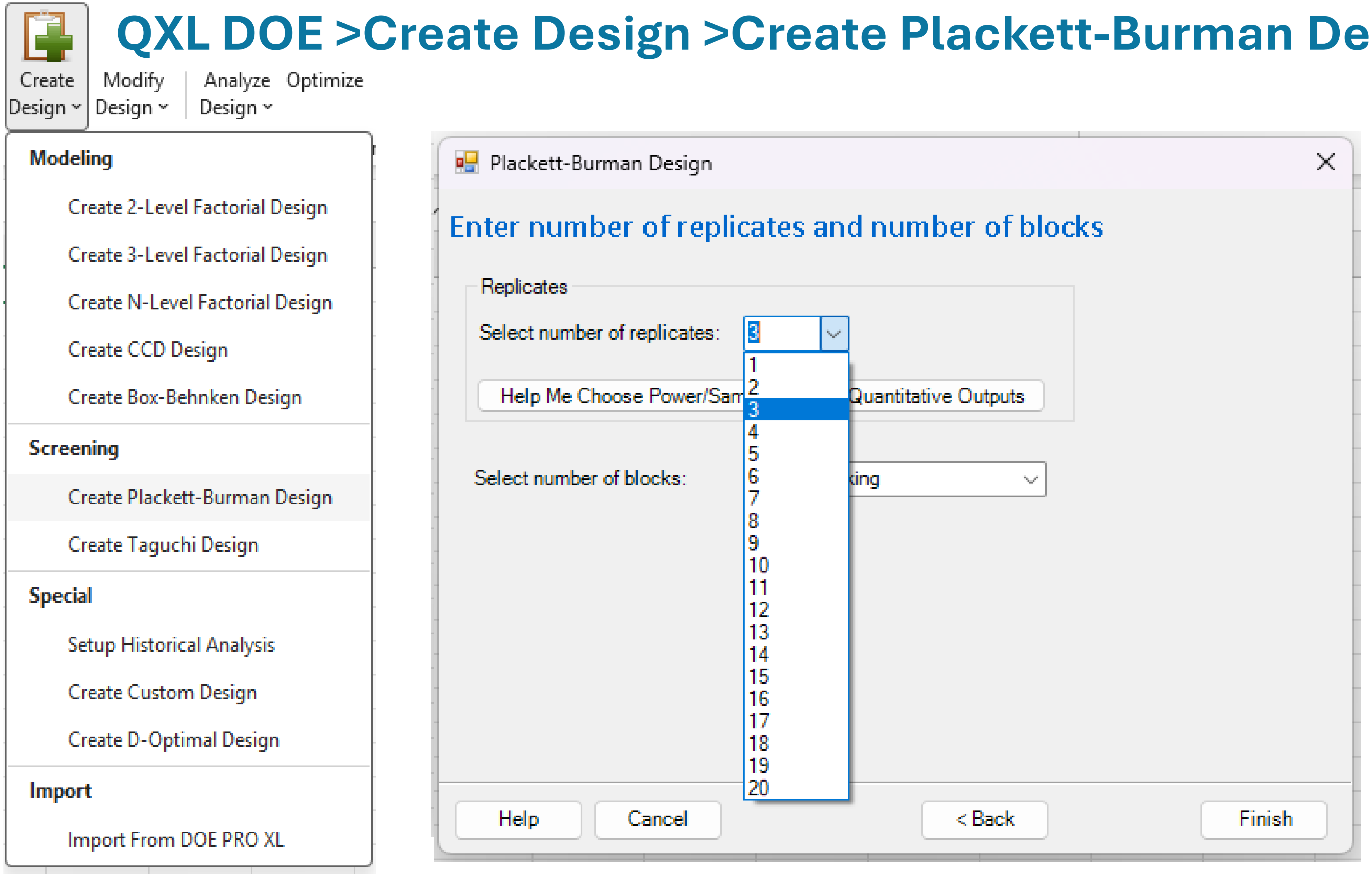


Quantum XL

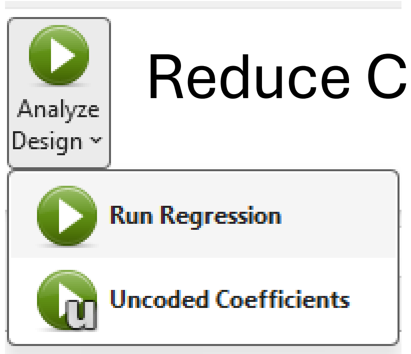
Plackett-Burman Design

11 Factors in 12 Runs

Number of replicates: 3

Run	A Pump_Displacement	B Speed	C Pressure	D Viscosity	E Overlap	F Orifice	G BackPressure	H Voltage	I CoilResistance	J AmbientTemp	K Clearance
1	24	2400	180	68	0.08	1.8	0.5	22	6	40	8
2	18	2400	250	32	0.08	1.8	2	22	6	0	14
3	24	1800	250	68	0.02	1.8	2	28	6	0	8
4	18	2400	180	68	0.08	1.2	2	28	10	0	8
5	18	1800	250	32	0.08	1.8	0.5	28	10	40	8
6	18	1800	180	68	0.02	1.8	2	22	10	40	14
7	24	1800	180	32	0.08	1.2	2	28	6	40	14
8	24	2400	180	32	0.02	1.8	0.5	28	10	0	14
9	24	2400	250	32	0.02	1.2	2	22	10	40	8
10	18	2400	250	68	0.02	1.2	0.5	28	6	40	14
11	24	1800	250	32	0.08	1.2	0.5	22	10	0	14
12	18	1800	180	32	0.02	1.2	0.5	22	6	0	8

	Efficiency %					Pressure Ripple bars					Valve Response ms					Power Loss W				
	USL					USL					USL					USL				
	LSL					LSL					LSL					LSL				
Run	Y1	Y2	Y3	Y-bar	S	Y1	Y2	Y3	Y-bar	S	Y1	Y2	Y3	Y-bar	S	Y1	Y2	Y3	Y-bar	S
1	83.47	83.09	83.01	83.19	0.25	6.80	6.78	6.77	6.78	0.01	47.20	48.91	48.36	48.16	0.88	452.43	407.30	367.05	408.92	42.71
2	72.75	73.07	72.97	72.93	0.16	6.10	6.07	5.98	6.05	0.06	47.73	42.36	46.55	45.55	2.83	508.49	580.28	646.57	578.44	69.06
3	80.58	80.18	80.22	80.33	0.22	2.98	2.99	3.06	3.01	0.05	33.64	36.62	34.11	34.79	1.60	468.29	467.34	543.96	493.19	43.96
4	76.11	75.15	76.12	75.79	0.56	4.26	4.28	4.33	4.29	0.04	42.41	44.76	40.99	42.72	1.90	497.56	486.27	472.58	485.47	12.51
5	81.09	80.94	80.51	80.85	0.30	4.98	5.00	5.01	4.99	0.02	47.16	46.93	45.05	46.38	1.16	475.26	494.41	531.18	500.28	28.42
6	69.28	69.87	69.97	69.71	0.37	3.54	3.64	3.53	3.57	0.06	51.65	55.48	53.80	53.64	1.92	514.86	514.60	581.30	536.92	38.43
7	79.68	78.92	79.08	79.23	0.40	2.83	2.82	2.84	2.83	0.01	40.17	39.68	40.44	40.10	0.39	561.49	583.49	599.71	581.56	19.18
8	82.50	82.28	82.91	82.57	0.32	4.46	4.45	4.56	4.49	0.06	47.57	40.13	47.56	45.09	4.29	485.32	511.07	484.31	493.56	15.17
9	82.32	82.14	81.49	81.99	0.44	3.10	3.10	3.08	3.09	0.01	50.17	53.29	53.87	52.45	1.99	556.06	464.68	554.55	525.09	52.33
10	73.83	74.46	74.08	74.12	0.32	2.68	2.59	2.64	2.63	0.05	38.16	37.64	40.25	38.68	1.38	581.55	619.95	543.43	581.64	38.26
11	81.52	81.83	81.17	81.51	0.33	3.04	3.11	3.04	3.06	0.04	47.02	51.01	50.81	49.61	2.25	513.63	587.19	545.80	548.87	36.88
12	80.36	81.36	80.13	80.62	0.65	0.83	0.86	0.85	0.85	0.02	42.35	42.03	40.71	41.69	0.87	394.38	439.30	443.97	425.88	27.38



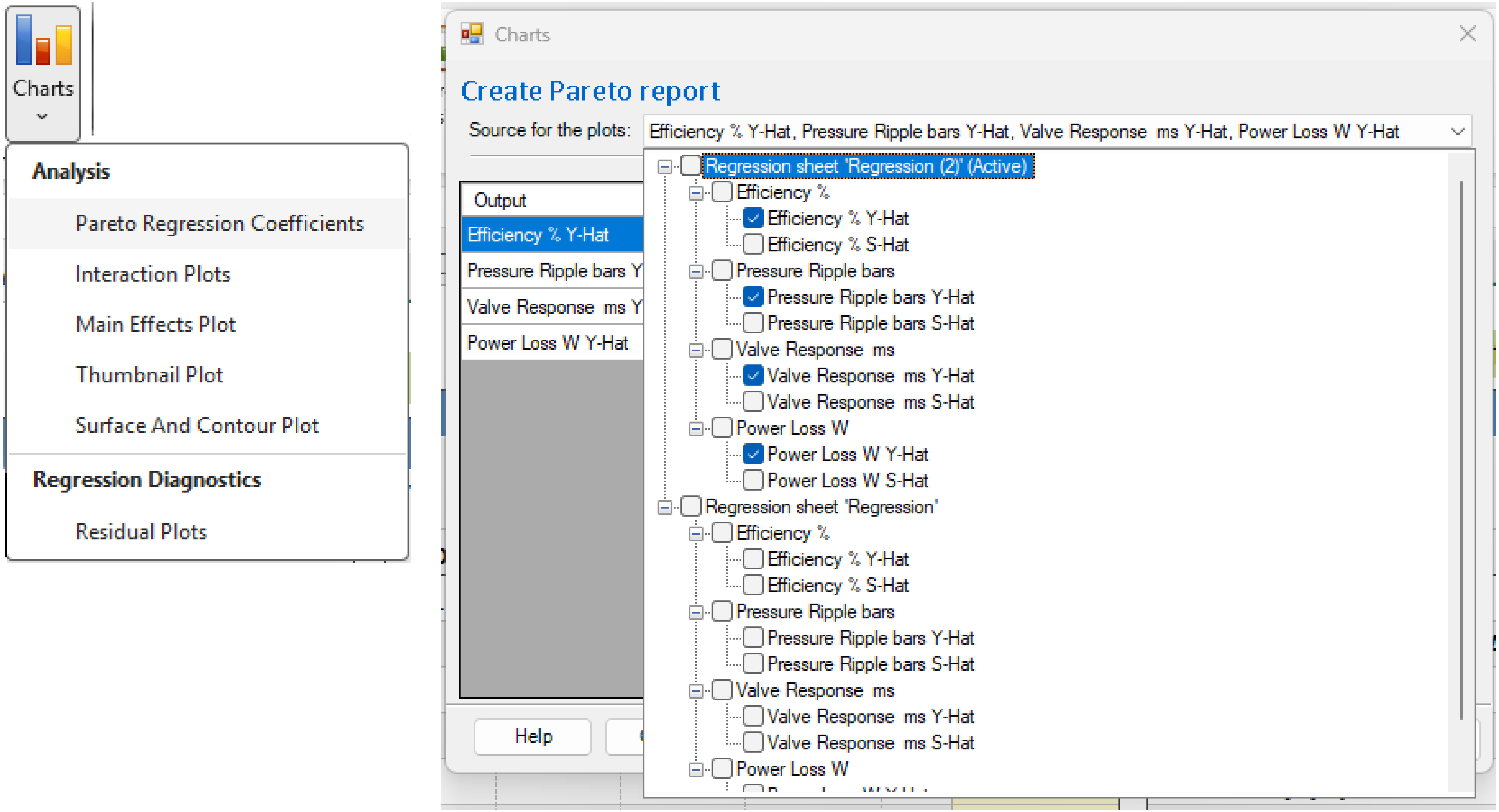
Reduce Coded Model: **QXL DOE >Analyze Design >Run Regression**

Efficiency %

Y-Hat

Factor	Coeff	SE	T	P	VIF	In Model
Const	78.35	0.07	1170.71	0.00		
Pump_Displacement (A)	2.68	0.07	39.98	0.00	1.04	☑
Speed (B)						☐
Pressure (C)	-0.17	0.07	-2.56	0.02	1.04	☑
Viscosity (D)	-1.34	0.07	-17.95	0.00	1.25	☑
Overlap (E)	0.12	0.07	1.85	0.07	1.04	☑
Orifice (F)						☐
BackPressure (G)	-1.68	0.07	-25.16	0.00	1.04	☑
Voltage (H)	0.47	0.07	7.01	0.00	1.04	☑
CoilResistance (I)						☐
AmbientTemp (J)	-0.17	0.07	-2.48	0.02	1.04	☑
Clearance (K)	-2.11	0.07	-31.60	0.00	1.04	☑

R^2	0.99
Adj R^2	0.99



Charts
Analysis
Pareto Regression Coefficients
Interaction Plots
Main Effects Plot
Thumbnail Plot
Surface And Contour Plot
Regression Diagnostics
Residual Plots
Charts
Create Pareto report
Source for the plots:
Efficiency % Y-Hat, Pressure Ripple bars Y-Hat, Valve Response ms Y-Hat, Power Loss W Y-Hat
Output
Efficiency % Y-Hat
Pressure Ripple bars Y
Valve Response ms Y
Power Loss W Y-Hat
Help
Regression sheet 'Regression (2)' (Active)
Efficiency %
Efficiency % Y-Hat
Efficiency % S-Hat
Pressure Ripple bars
Pressure Ripple bars Y-Hat
Pressure Ripple bars S-Hat
Valve Response ms
Valve Response ms Y-Hat
Valve Response ms S-Hat
Power Loss W
Power Loss W Y-Hat
Power Loss W S-Hat
Regression sheet 'Regression'
Efficiency %
Efficiency % Y-Hat
Efficiency % S-Hat
Pressure Ripple bars
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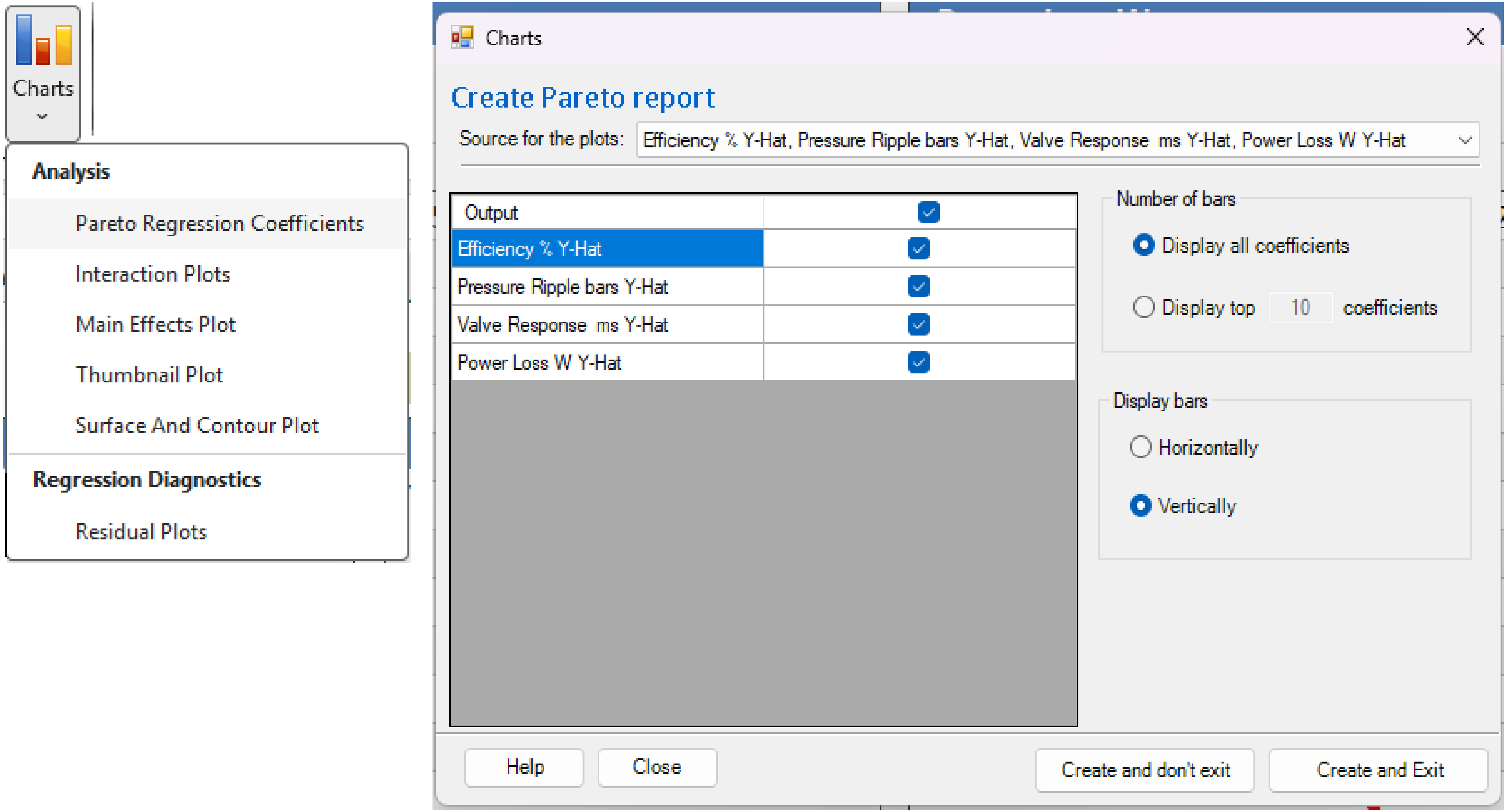
Valve Response ms
Valve Response ms Y-Hat
Valve Response ms S-Hat
Power Loss W



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Valve Response ms Y-Hat
Power Loss W Y-Hat
Number of bars
Display all coefficients
Display top
10
coefficients
Display bars
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Help
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Create and don't exit
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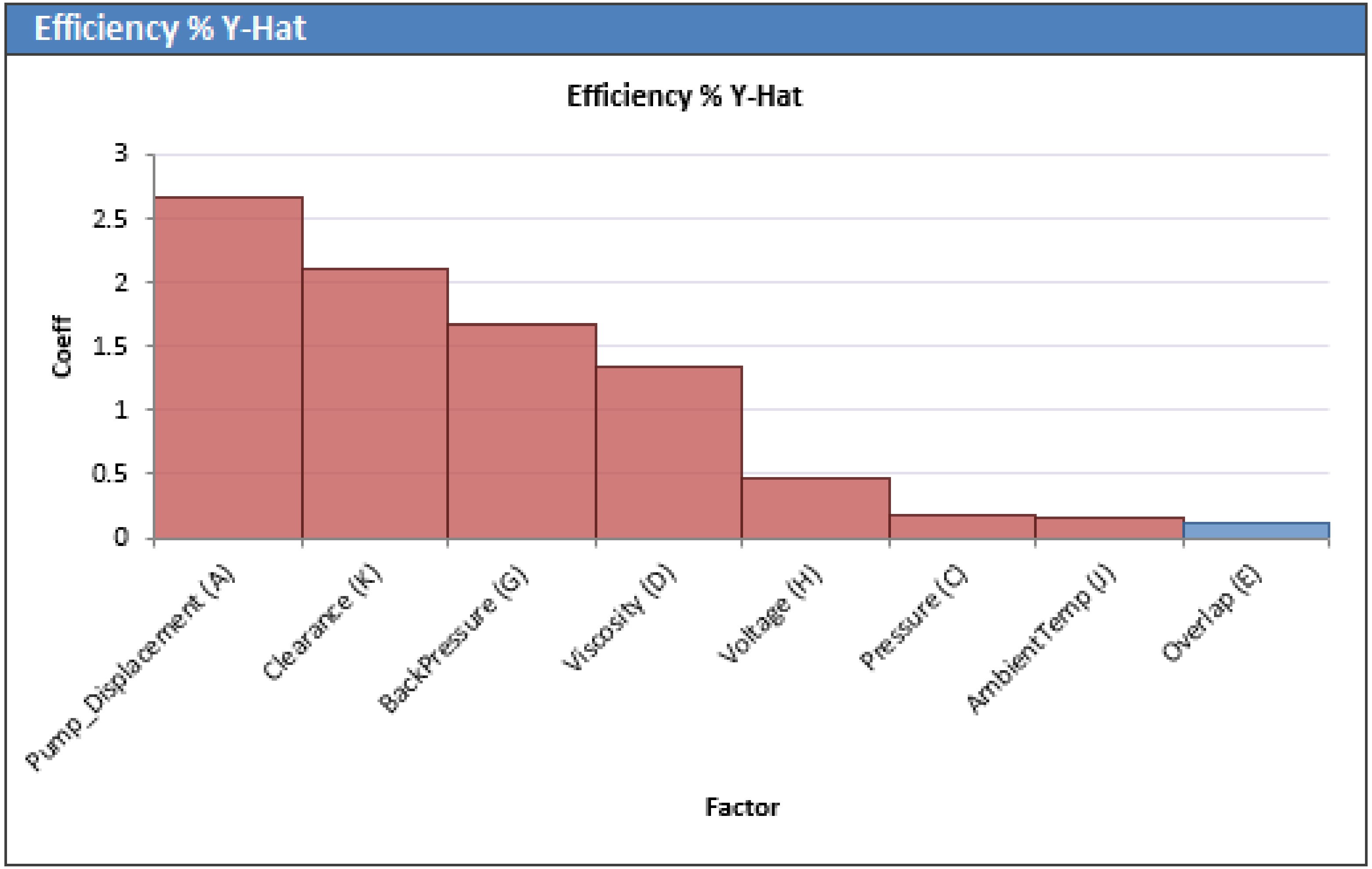
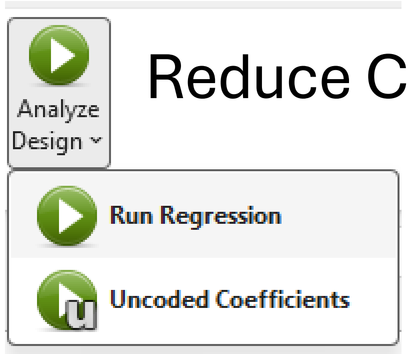
Pareto Analysis of Factor Influence for Each Response Variable



R^2 = 99%



Reduce Coded Model: **QXL DOE >Analyze Design >Run Regression**

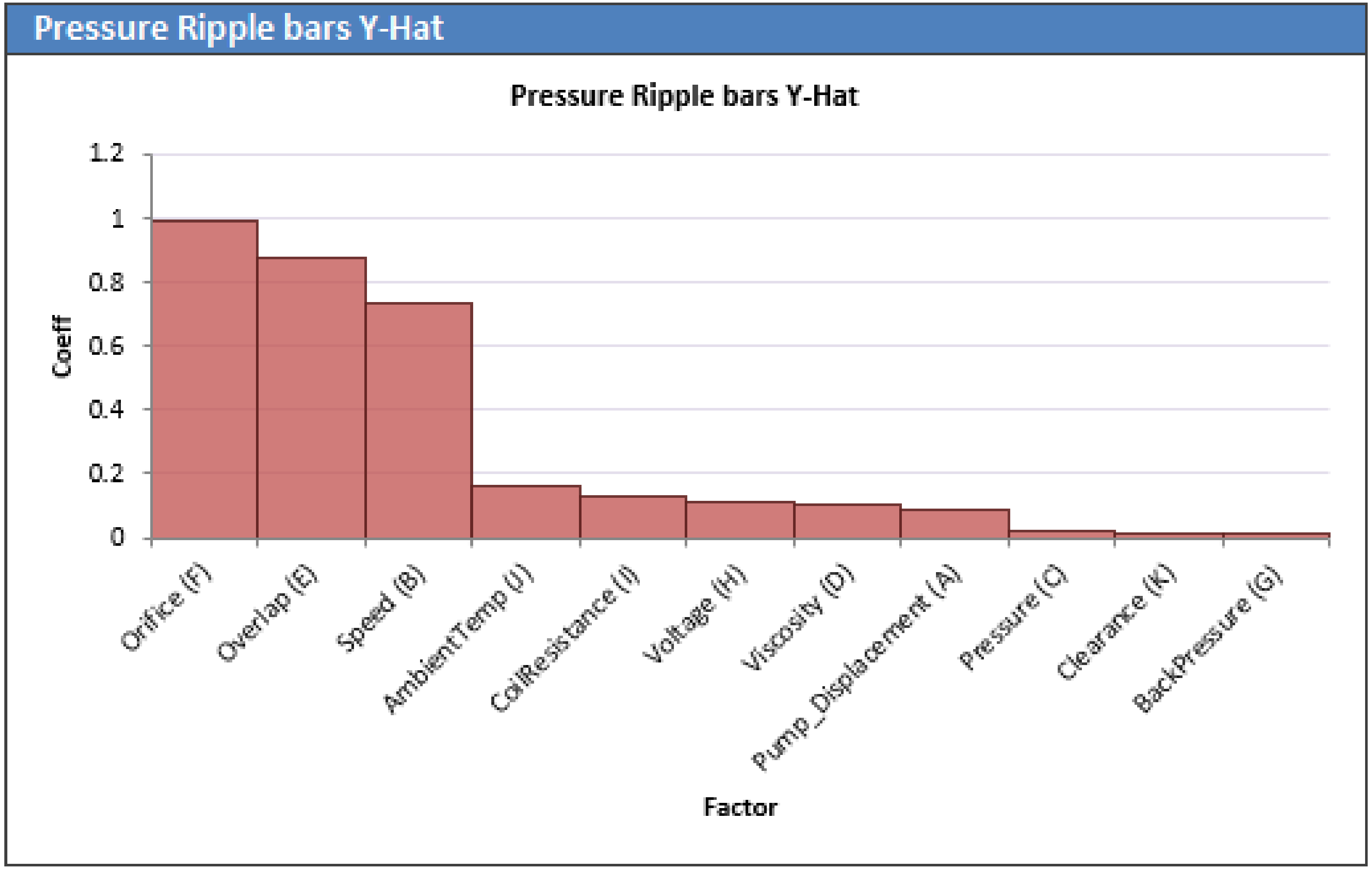
Pressure Ripple bars

Y-Hat

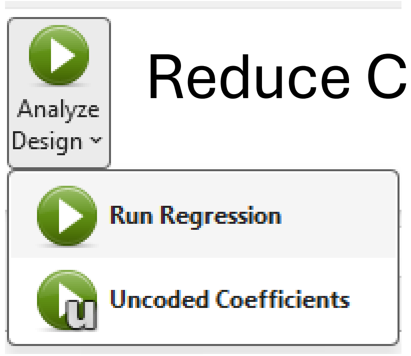
Factor	Coeff	SE	T	P	VIF	In Model
Const	3.82	0.01	558.53	0.00		
Pump_Displacement (A)	0.09	0.01	13.28	0.00	1.04	☑
Speed (B)	0.73	0.01	107.33	0.00	1.04	☑
Pressure (C)	0.02	0.01	3.08	0.01	1.04	☑
Viscosity (D)	0.10	0.01	13.02	0.00	1.40	☑
Overlap (E)	0.88	0.01	128.77	0.00	1.04	☑
Orifice (F)	0.99	0.01	145.32	0.00	1.04	☑
BackPressure (G)	-0.01	0.01	-2.11	0.05	1.04	☑
Voltage (H)	-0.11	0.01	-16.68	0.00	1.04	☑
CoilResistance (I)	0.13	0.01	18.92	0.00	1.04	☑
AmbientTemp (J)	0.16	0.01	23.70	0.00	1.04	☑
Clearance (K)	-0.01	0.01	-2.13	0.04	1.04	☑

R^2	1.00
Adj R^2	1.00

Pareto Analysis of Factor Influence for Each Response Variable



$R^2 = 100\%$



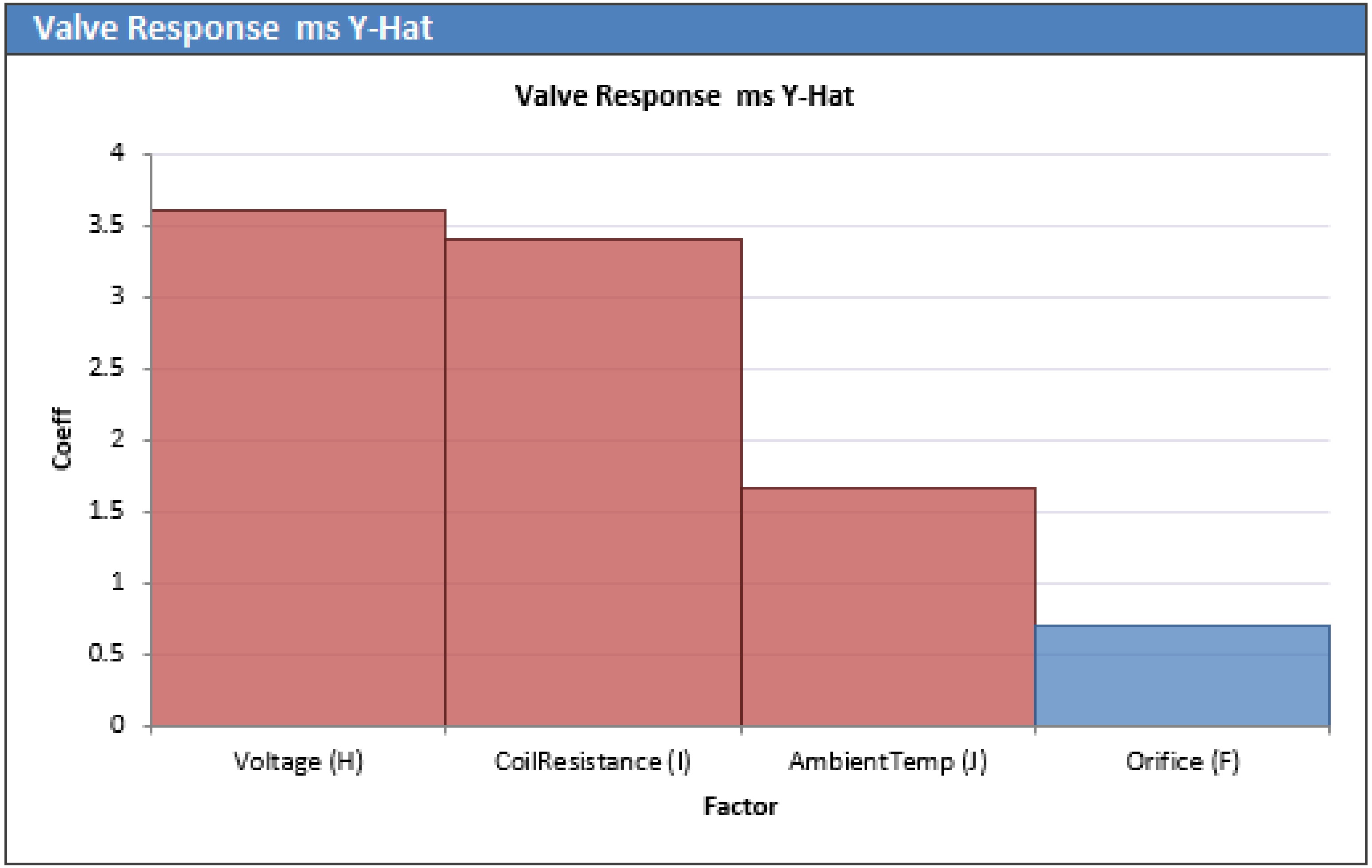
Reduce Coded Model: **QXL DOE >Analyze Design >Run Regression**

Valve Response ms

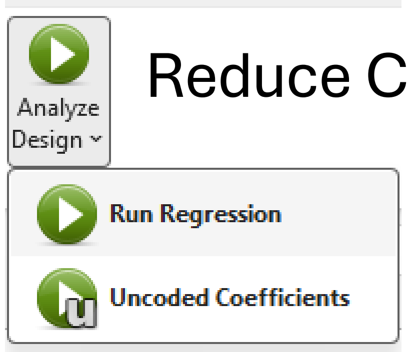
Y-Hat

Factor	Coeff	SE	T	P	VIF	In Model
Const	44.90	0.35	127.42	0.00		
Pump_Displacement (A)						☐
Speed (B)						☐
Pressure (C)						☐
Viscosity (D)						☐
Overlap (E)						☐
Orifice (F)	0.70	0.35	1.97	0.06	1.00	☑
BackPressure (G)						☐
Voltage (H)	-3.61	0.35	-10.25	0.00	1.00	☑
CoilResistance (I)	3.41	0.35	9.68	0.00	1.00	☑
AmbientTemp (J)	1.66	0.35	4.72	0.00	1.00	☑
Clearance (K)						☐
R^2	0.88					
Adj R^2	0.86					

Pareto Analysis of Factor Influence for Each Response Variable



$R^2 = 88\%$



Reduce Coded Model: **QXL DOE >Analyze Design >Run Regression**

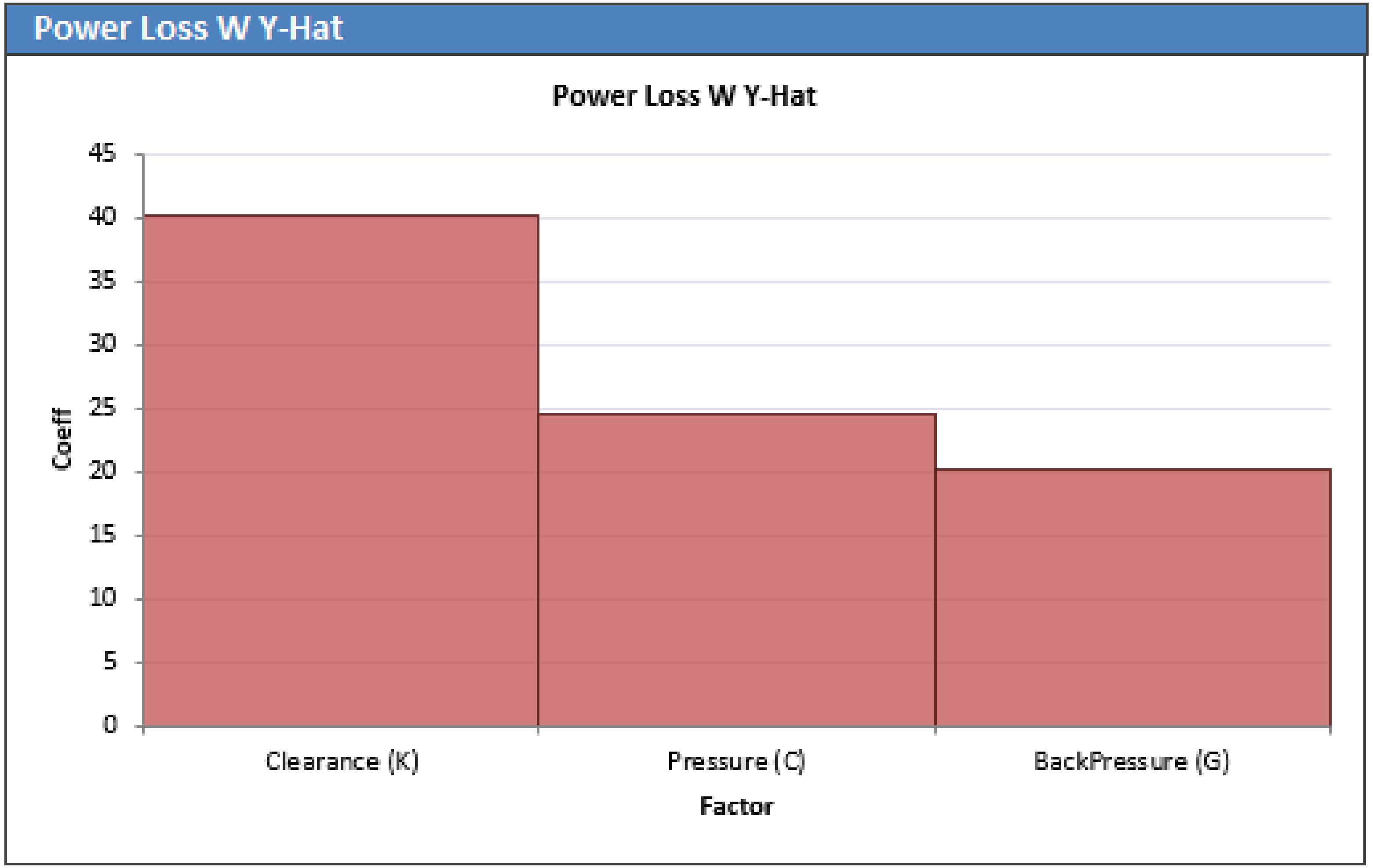
Power Loss W

Y-Hat

Factor	Coeff	SE	T	P	VIF	In Model
Const	513.32	6.50	78.95	0.00		
Pump_Displacement (A)						☐
Speed (B)						☐
Pressure (C)	24.60	6.50	3.78	0.00	1.00	☑
Viscosity (D)						☐
Overlap (E)						☐
Orifice (F)						☐
BackPressure (G)	20.13	6.50	3.10	0.00	1.00	☑
Voltage (H)						☐
CoilResistance (I)						☐
AmbientTemp (J)						☐
Clearance (K)	40.18	6.50	6.18	0.00	1.00	☑

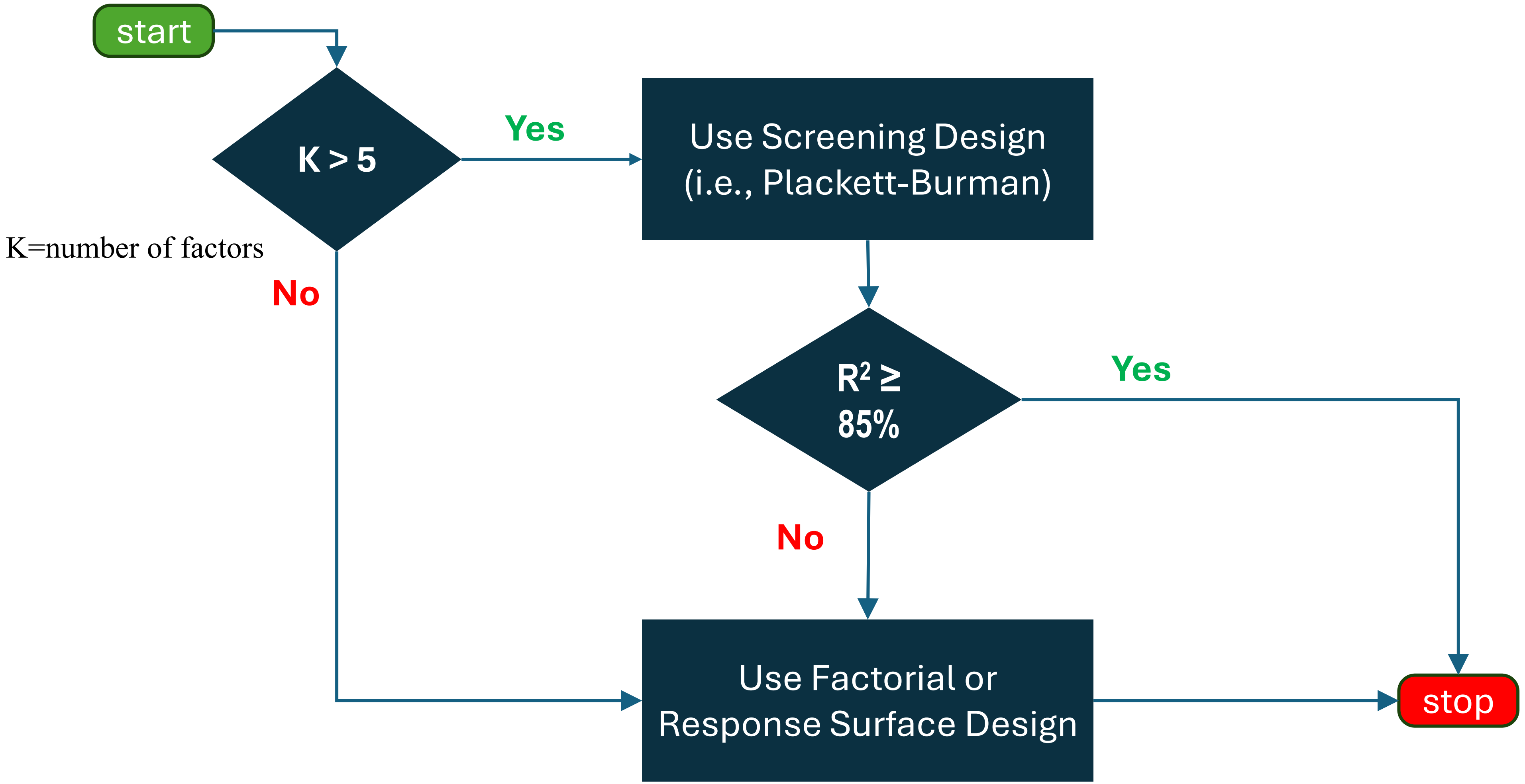
R^2	0.66
Adj R^2	0.63

Pareto Analysis of Factor Influence for Each Response Variable



$R^2 = 66\%$

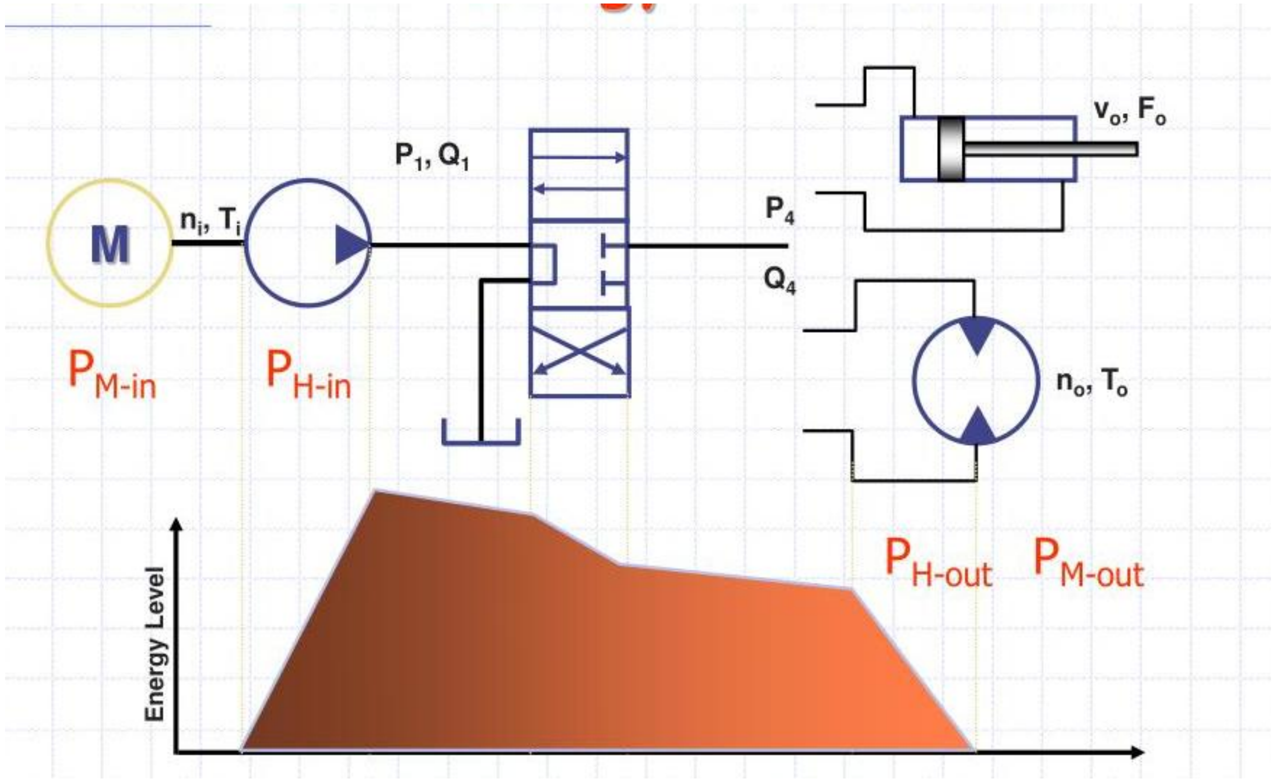
Thought Process Map for Conducting Experiments



Rationale Behind 2nd DOE for Servo-hydraulic Power Loss

The design team aims to better understand power loss. The three factors previously identified from the screening DOE are:

- System Pressure
- Case drain / return back pressure
- Internal clearance (leakage clearance)



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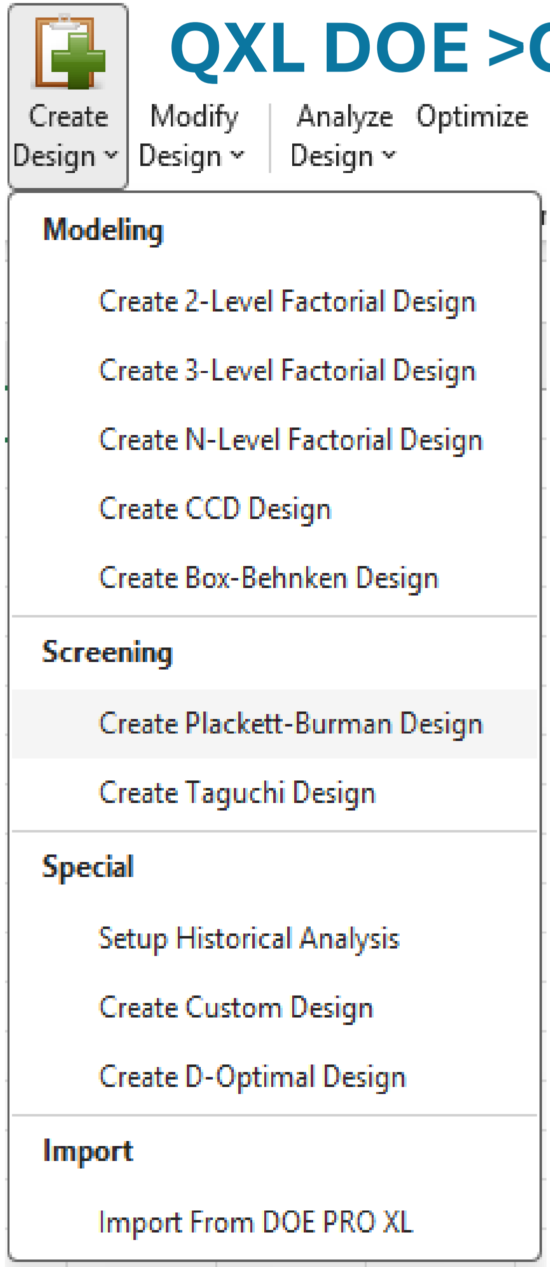
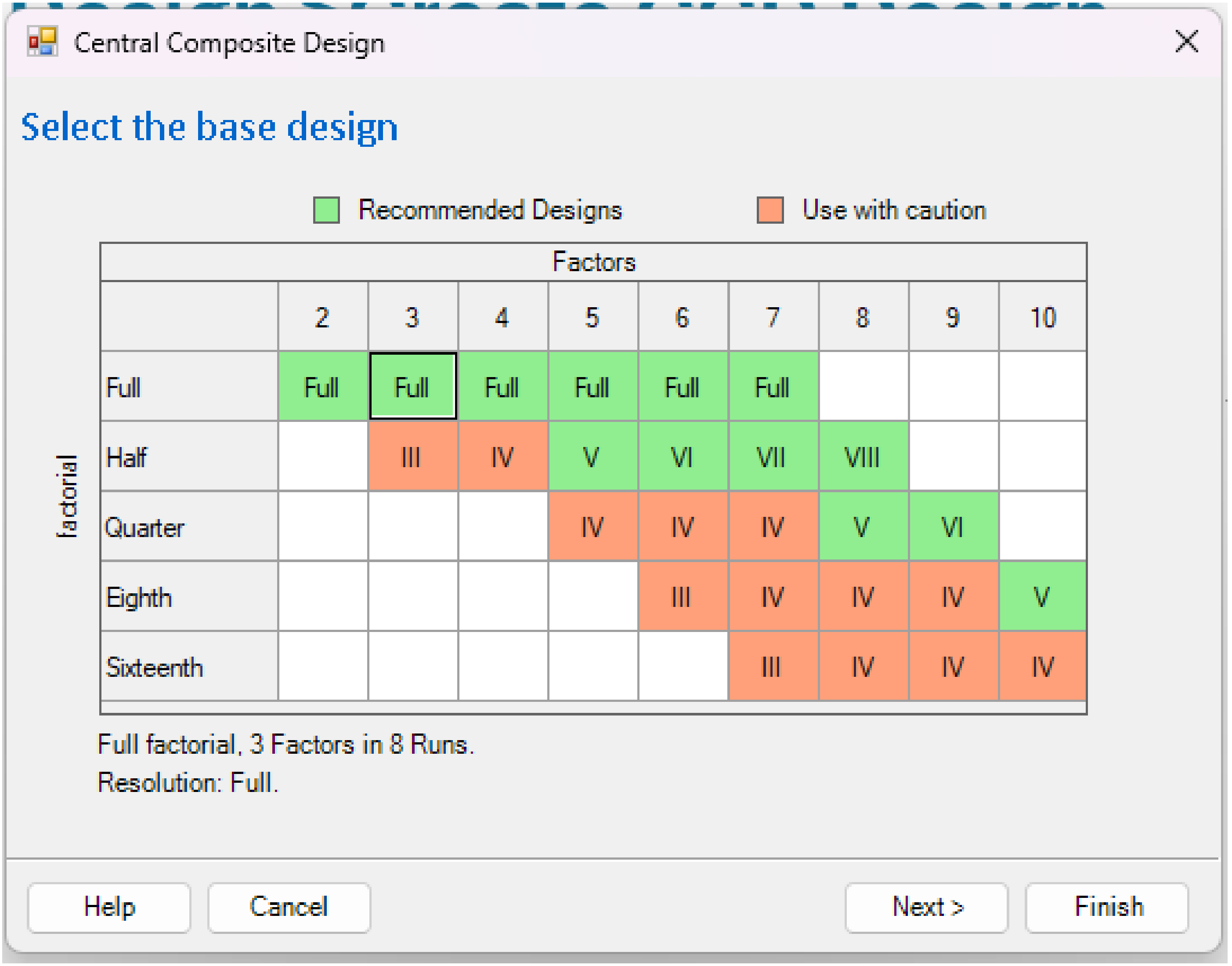
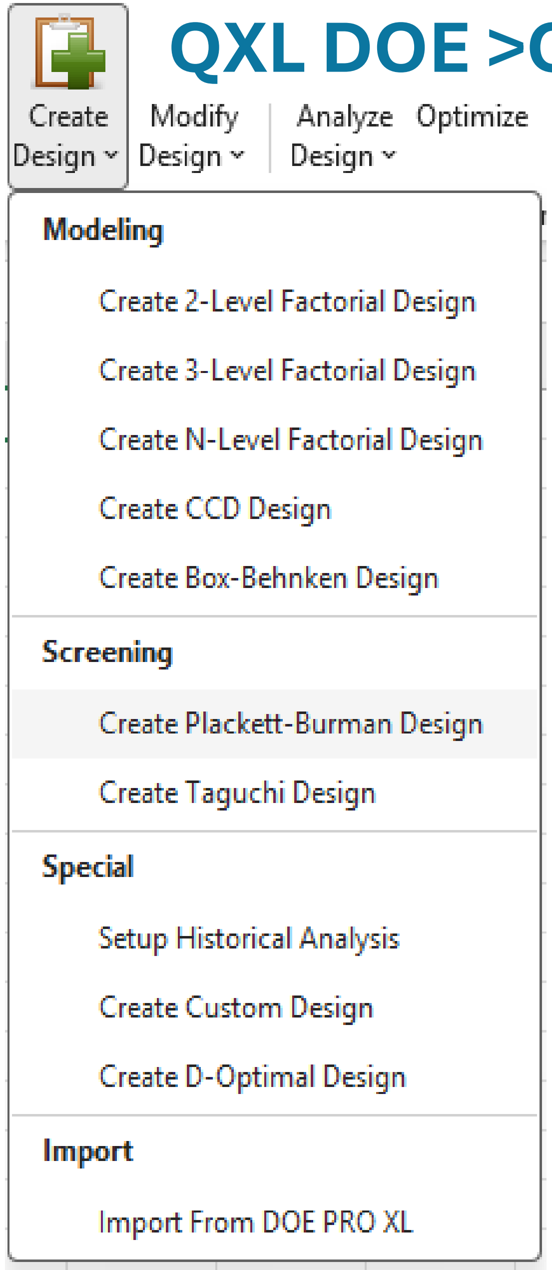
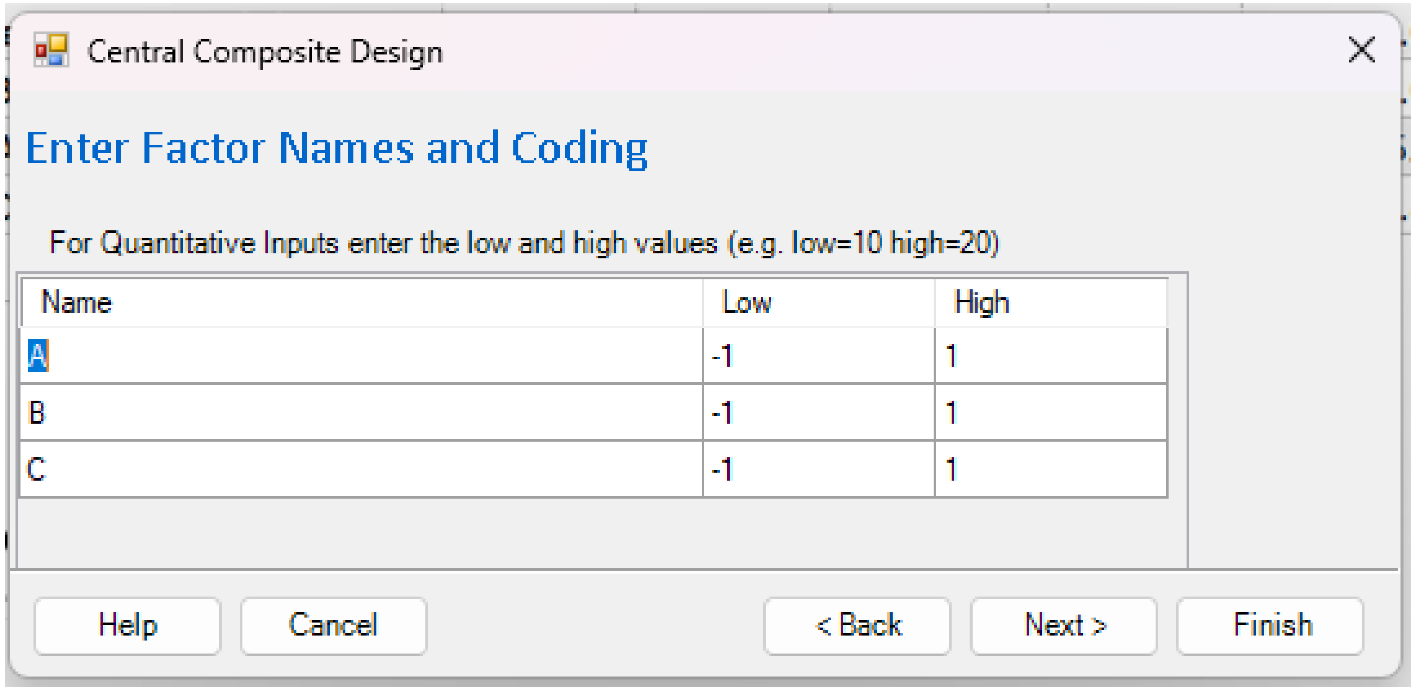




	2	3	4	5	6	7	8	9	10
Full	Full	Full	Full	Full	Full	Full			
Half		III	IV	V	VI	VII	VIII		
Quarter				IV	IV	IV	V	VI	
Eighth					III	IV	IV	IV	V
Sixteenth						III	IV	IV	IV

QXL DOE >Create Design >Create CCD Design





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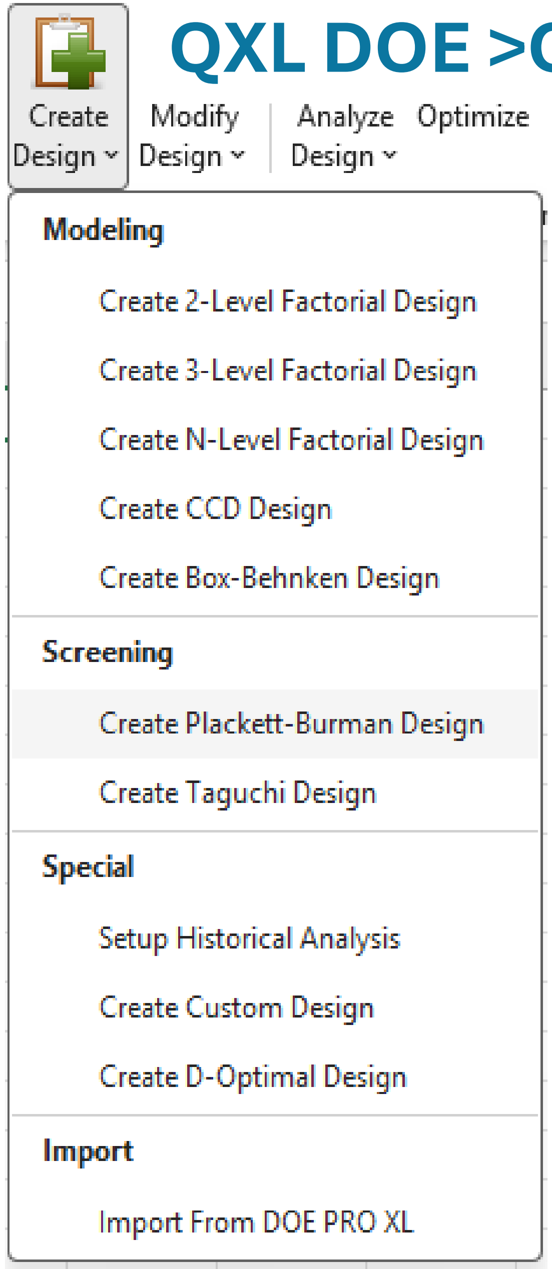

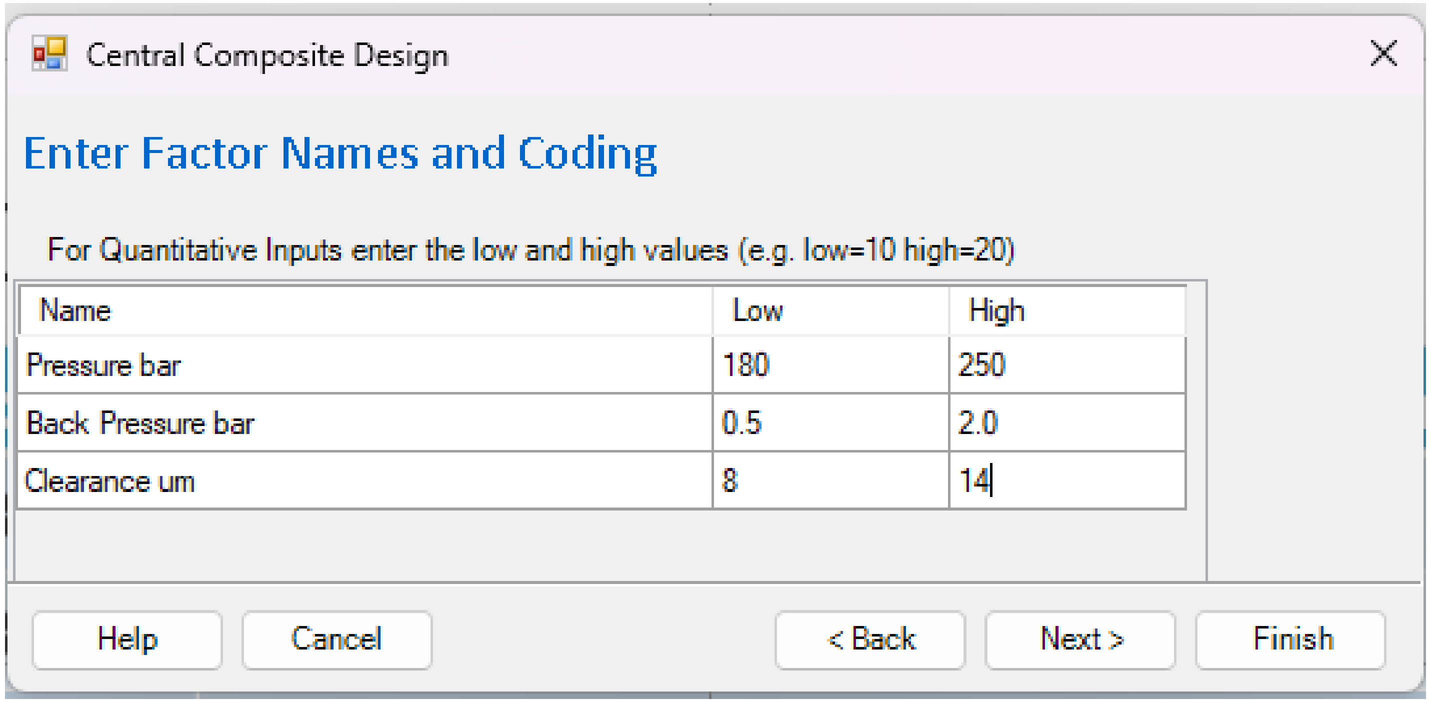

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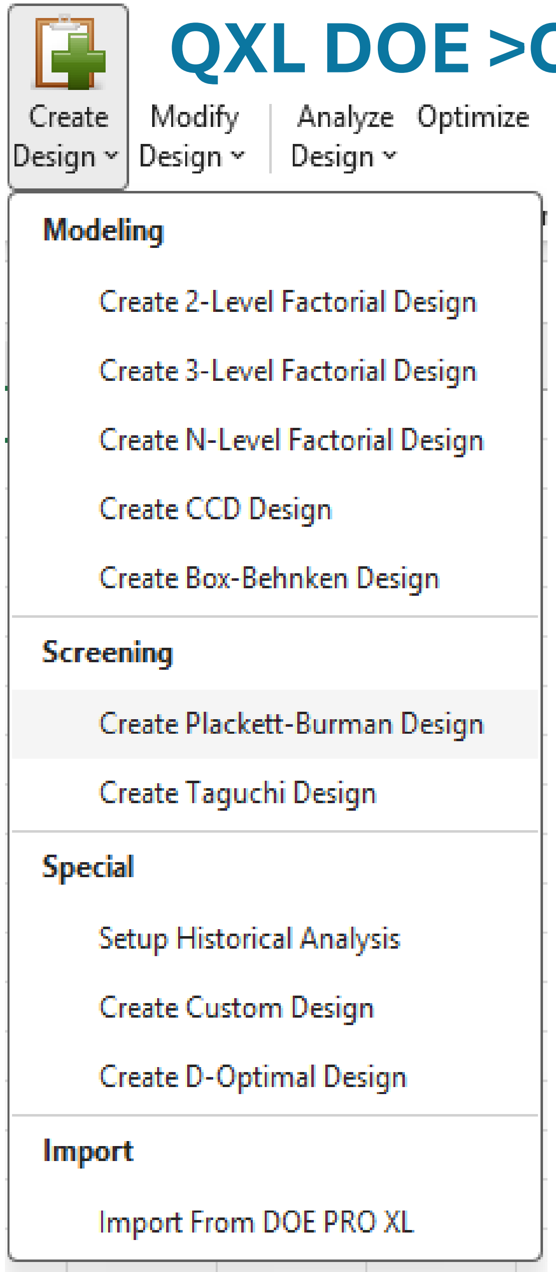

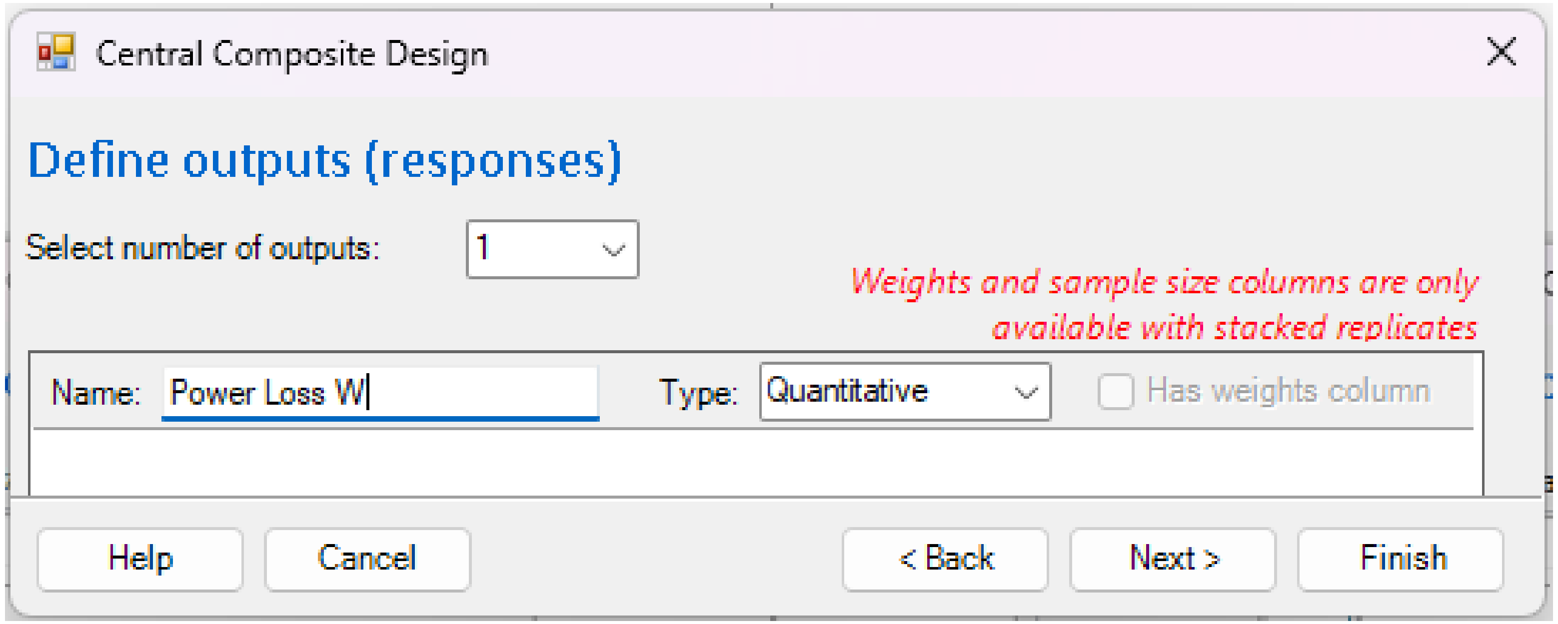

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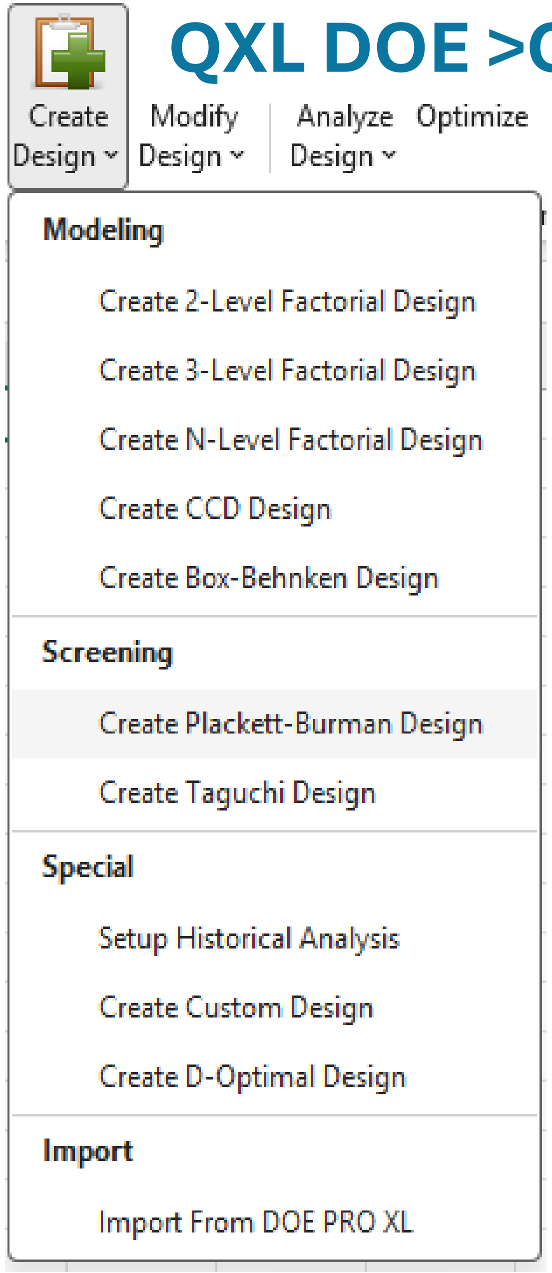
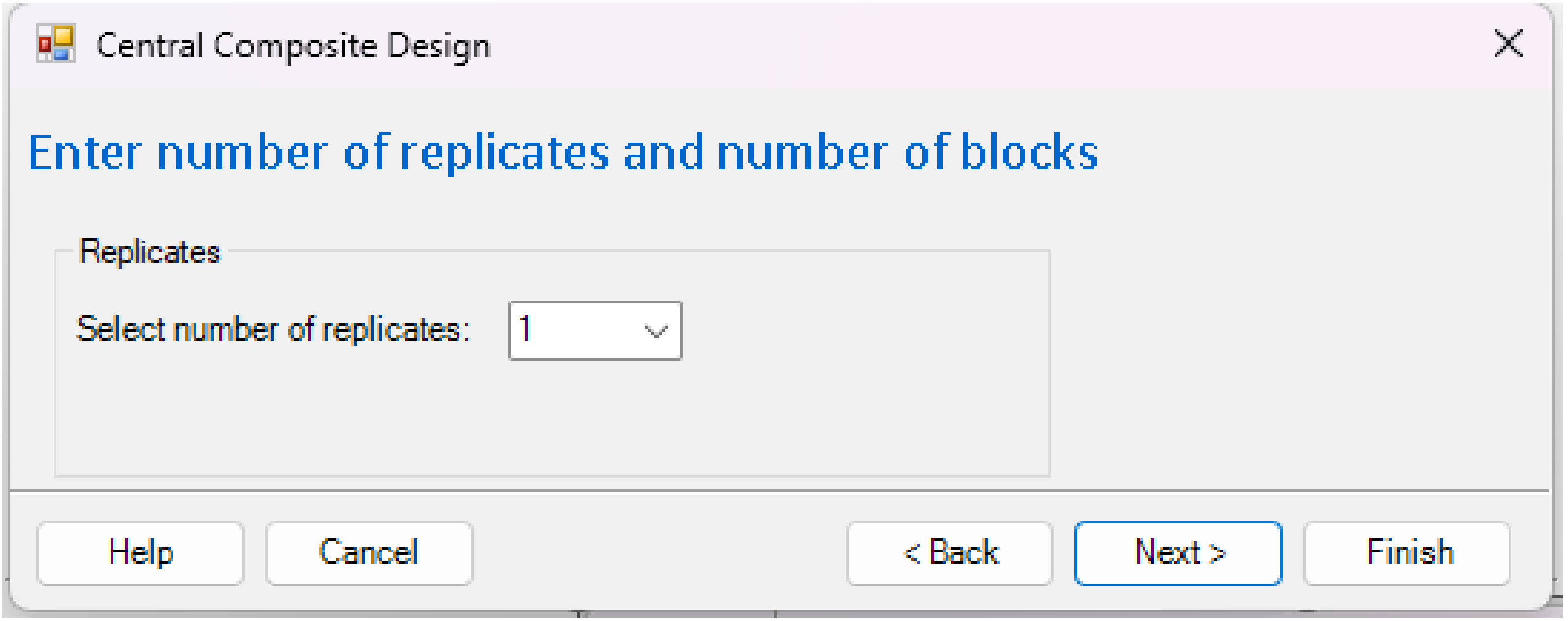
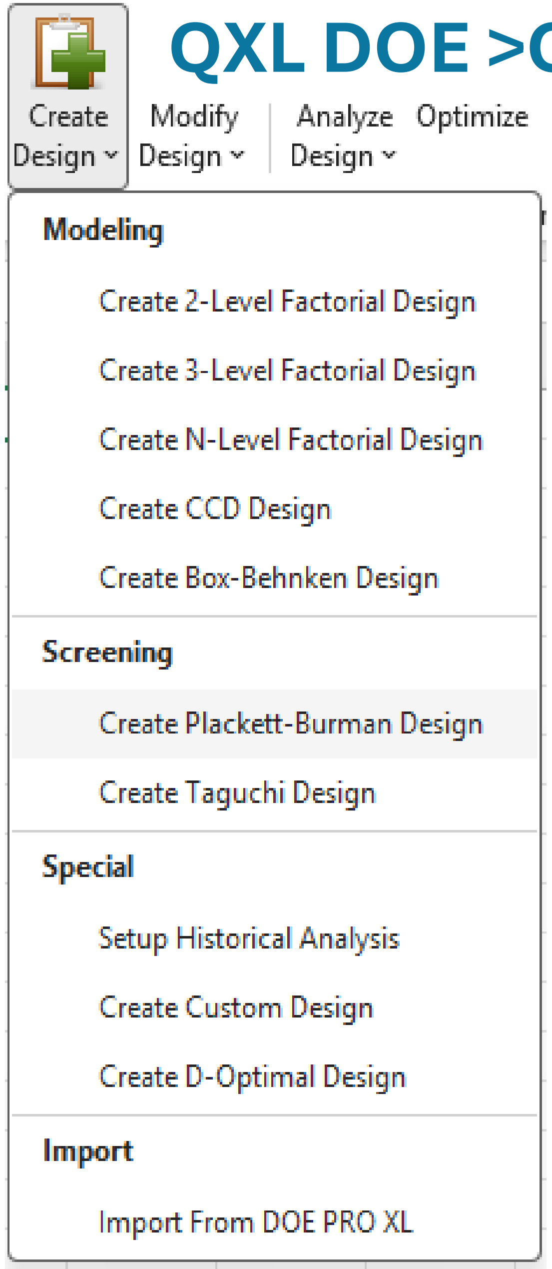
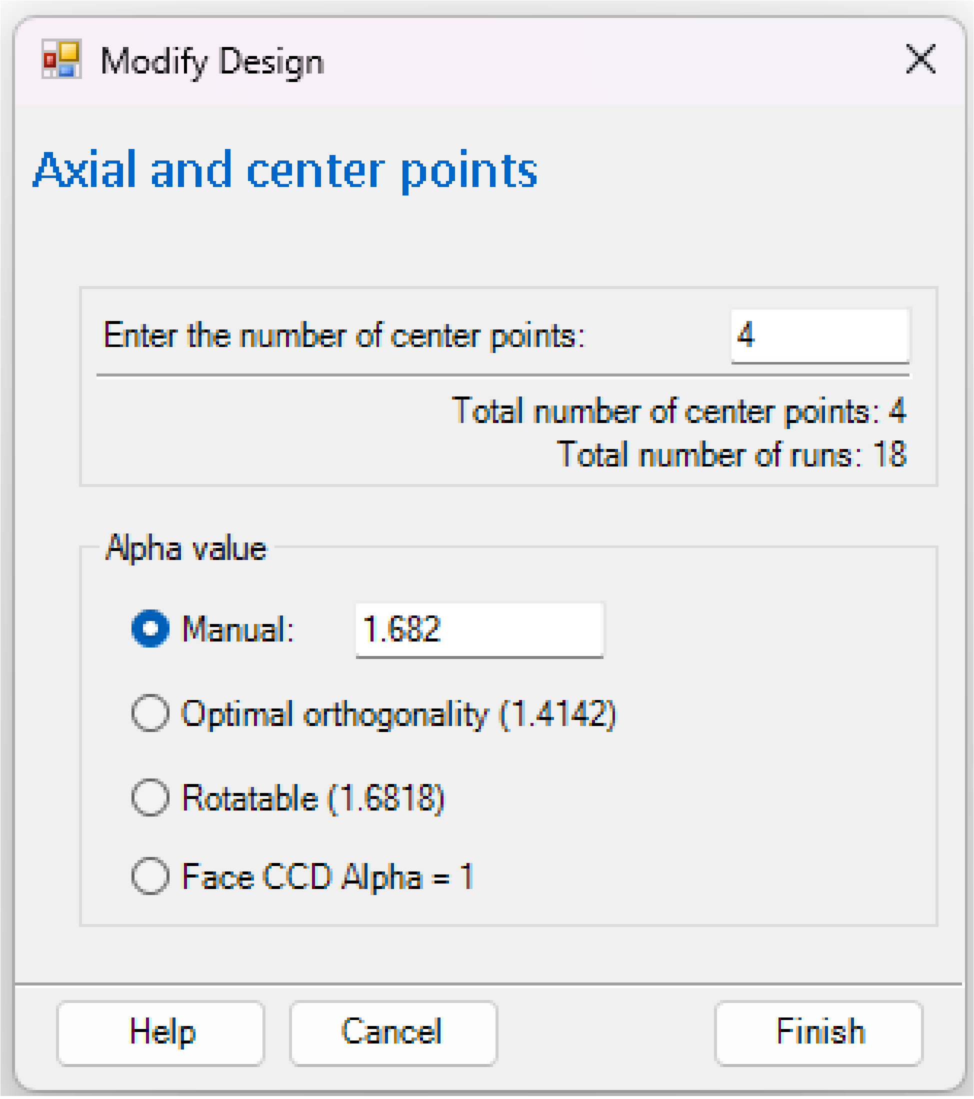




QXL DOE >Create Design >Create CCD Design





Quantum XL

Central Composite Design

Base design: Full factorial

3 Factors in 18 Runs

4 Center points. Alpha = 1.682

Design is not replicated.

edit response name (optional) --> **Power Loss W**

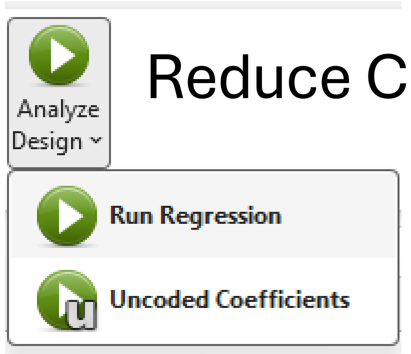
enter spec limits (optional) --> USL: (blank) LSL: (blank)

<-- enter factor names

enter response data here -->

	A	B	C	Power Loss W
Run	**Pressure_bar**	**BackPressure_bar**	**Clearance_um**	**Data**
1	180	0.5	8	462.3
2	250	0.5	8	508
3	180	2	8	491
4	250	2	8	557
5	180	0.5	14	550.5
6	250	0.5	14	619.8
7	180	2	14	598.8
8	250	2	14	647.7
9	156	1.25	11	489
10	274	1.25	11	591.8
11	215	0	11	489.4
12	215	2.5	11	563
13	215	1.25	6	509
14	215	1.25	16	682.9
15	215	1.25	11	518.1
16	215	1.25	11	508.4
17	215	1.25	11	524.4
18	215	1.25	11	521

Reduce Coded Model: **QXL DOE >Analyze Design >Run Regression**



Power Loss W

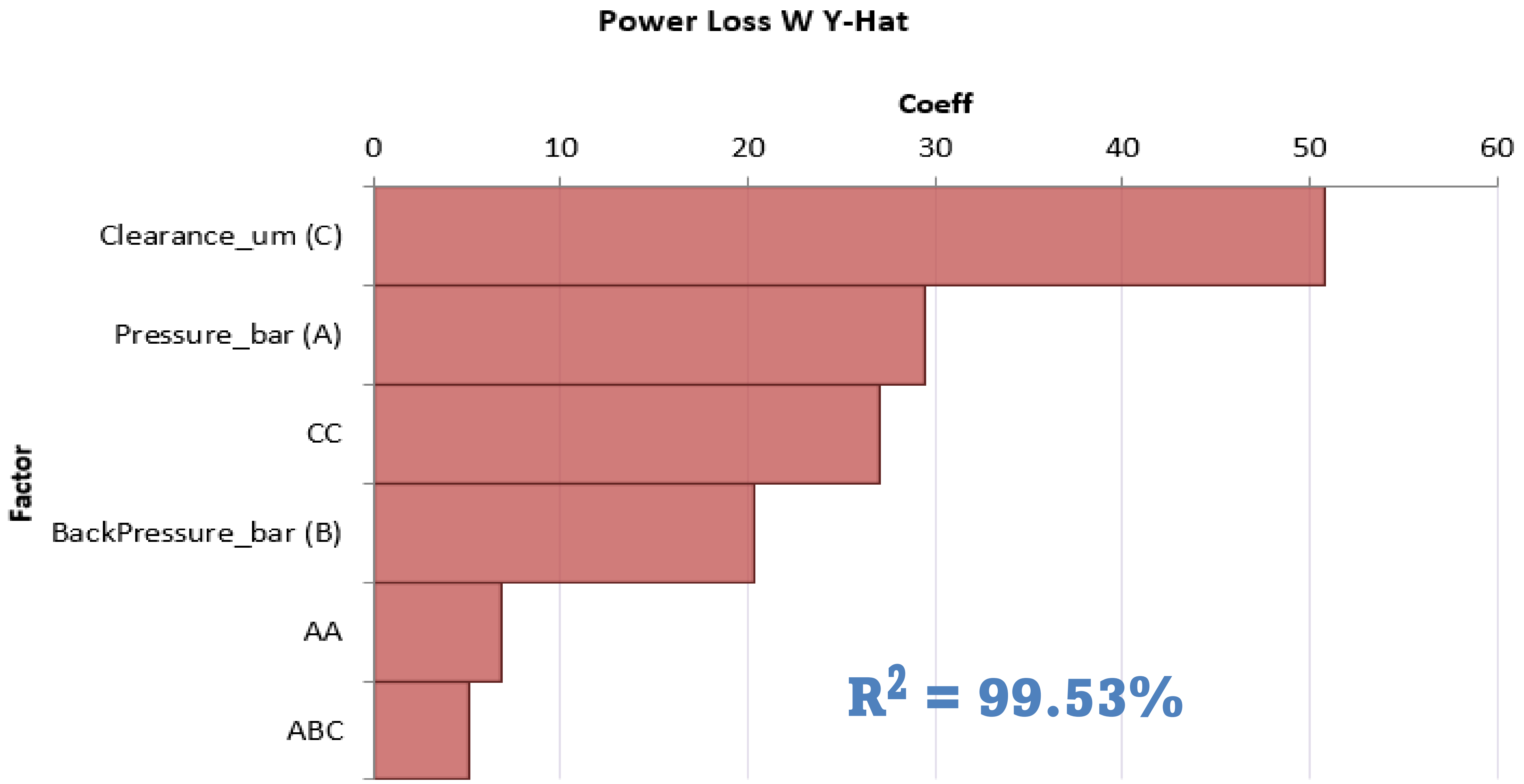
Y-Hat

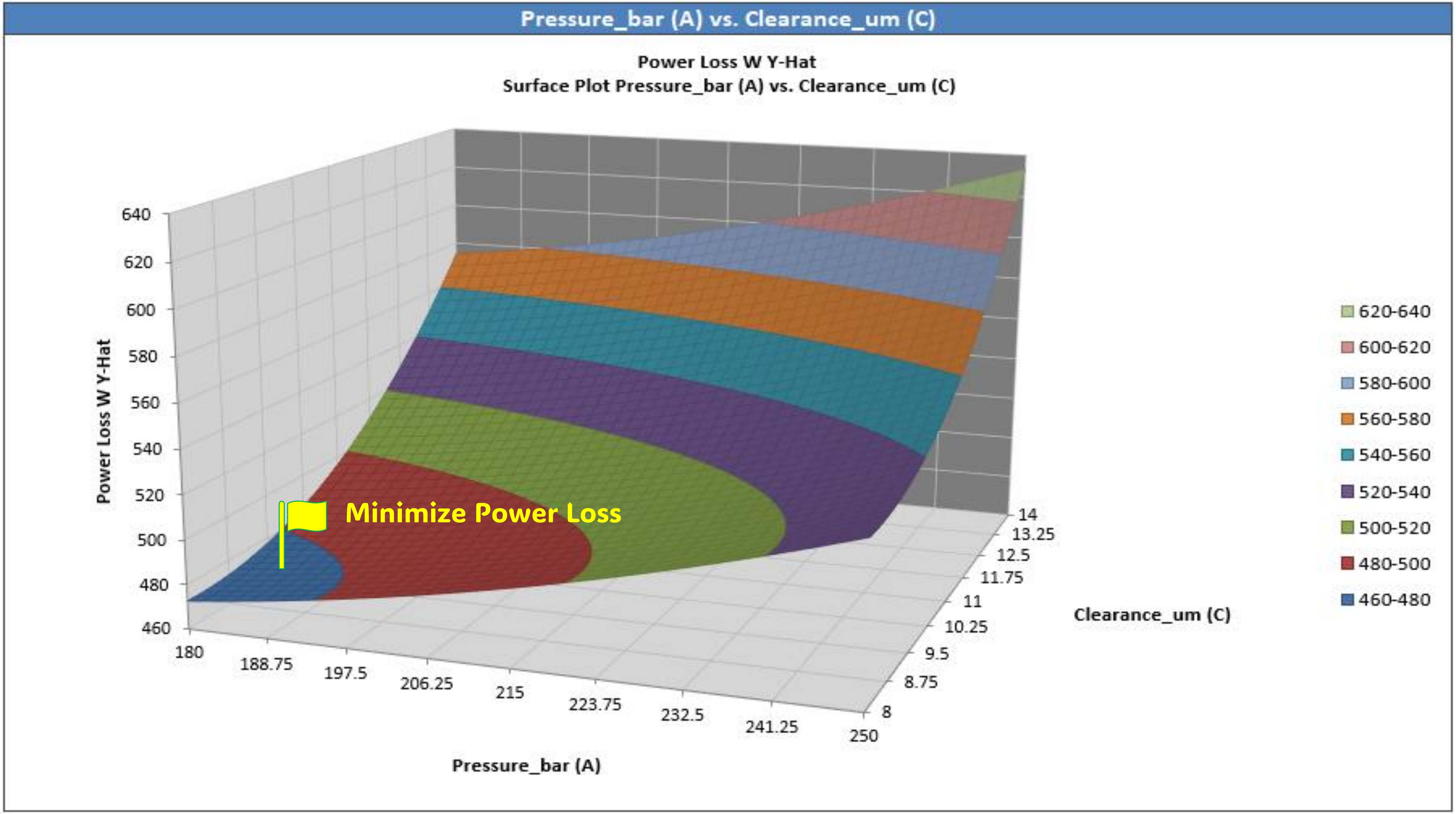
Name	Factor	Coeff	SE	T	P	VIF	In Model
	Const	520.655	2.0523	253.694	0.000		
Pressure_bar	Pressure_bar (A)	29.466	1.3958	21.11	0.000	1.0	☑
BackPressure_bar	BackPressure_bar (B)	20.402	1.4024	14.548	0.000	1.0	☑
Clearance_um	Clearance_um (C)	50.779	1.4024	36.208	0.000	1.0	☑
Pressure_bar*BackPressure_bar*Clearance_um	ABC	-5.0875	1.8255	-2.7869	0.018	1.0	☑
Pressure_bar*Pressure_bar	AA	6.8691	1.4134	4.8602	0.001	1.0301	☑
Clearance_um*Clearance_um	CC	27.023	1.4411	18.752	0.000	1.0301	☑

R^2 0.9953

Goal Met: R^2 > 85%

Power Loss W Y-Hat



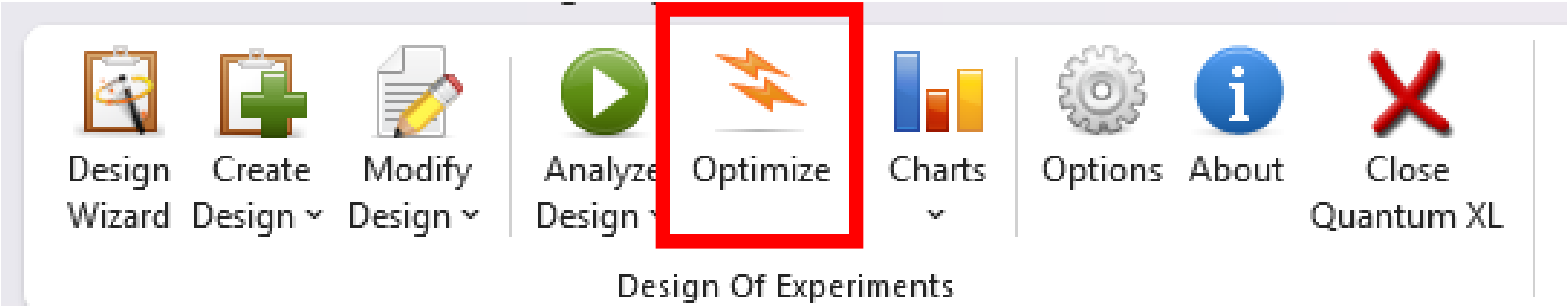

Pressure_bar (A) vs. Clearance_um (C)
Power Loss W Y-Hat
Surface Plot Pressure_bar (A) vs. Clearance_um (C)
Power Loss W Y-Hat
640
620
600
580
560
540
520
500
480
460
Minimize Power Loss
180
188.75
197.5
206.25
215
223.75
232.5
241.25
250
Pressure_bar (A)
14
13.25
12.5
11.75
11
10.25
9.5
8.75
8
Clearance_um (C)
620-640
600-620
580-600
560-580
540-560
520-540
500-520
480-500
460-480

Regression in Coded Units (Only): QXL DOE >Optimize

Quantum XL Regression Analysis

Design sheet: DOE Design

Regression in coded units

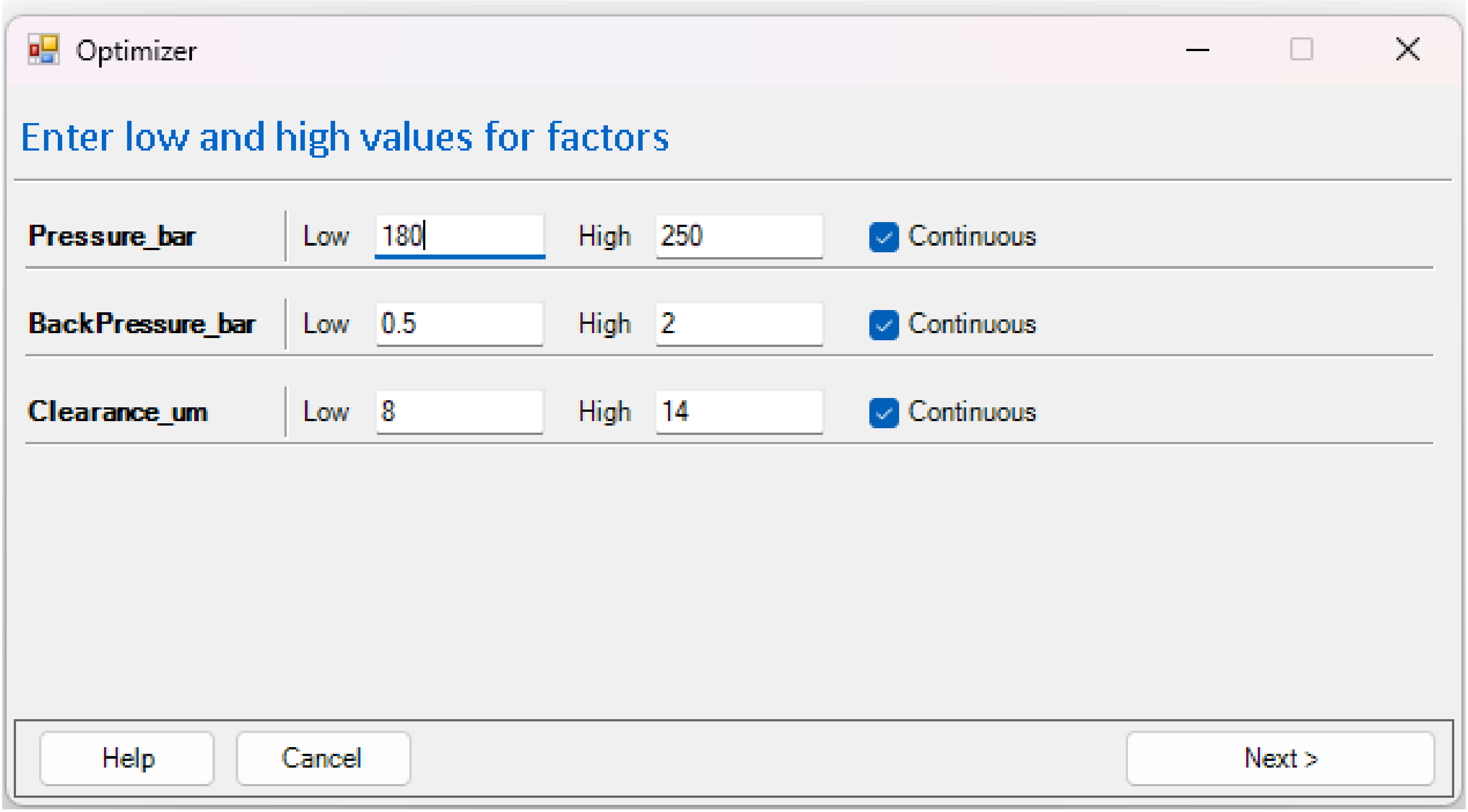


Regression in Coded Units (Only): QXL DOE >Optimize

Quantum XL Regression Analysis

Design sheet: DOE Design

Regression in coded units

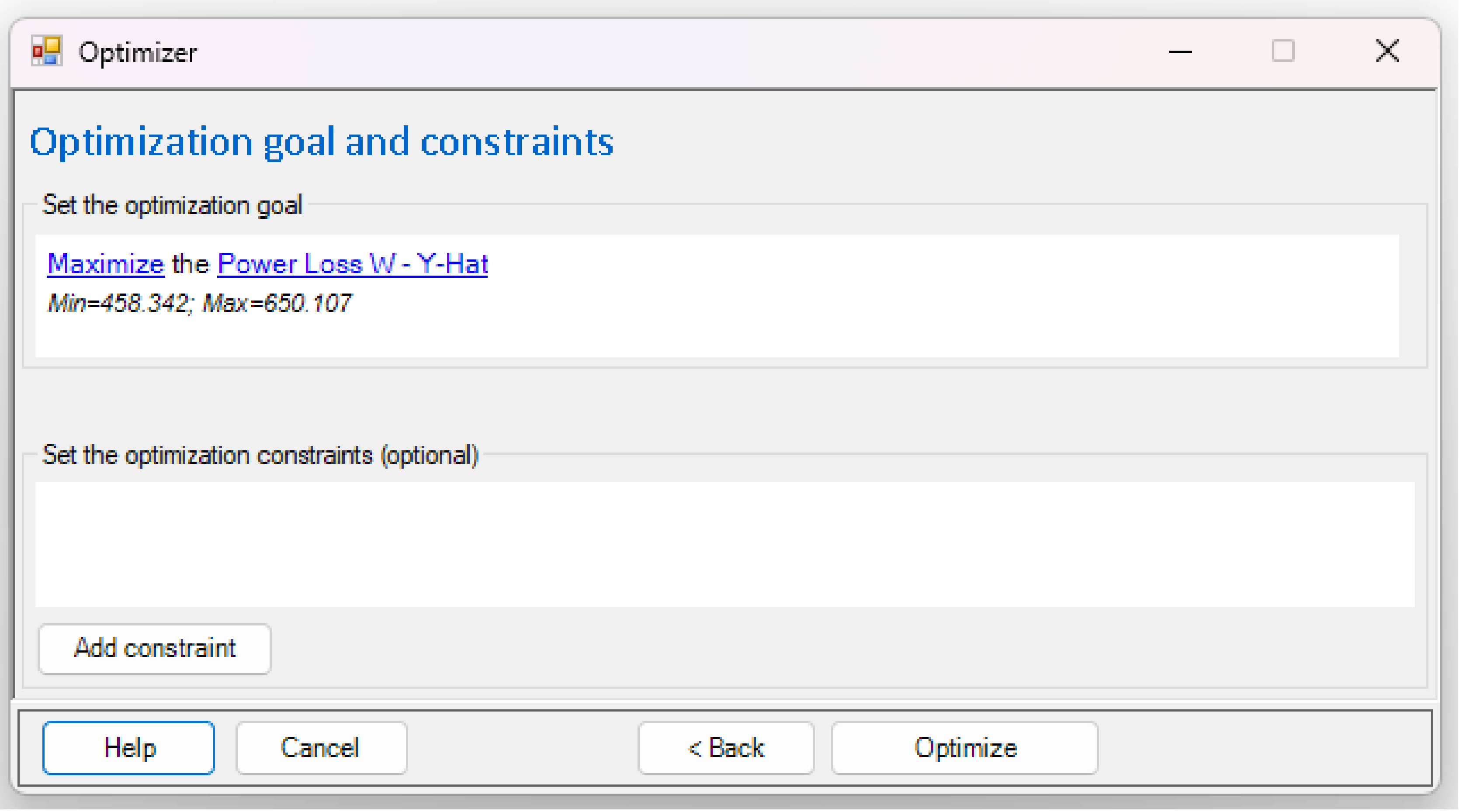


Regression in Coded Units (Only): QXL DOE >Optimize

Quantum XL Regression Analysis

Design sheet: DOE Design

Regression in coded units

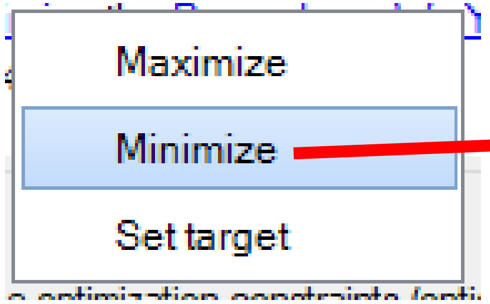


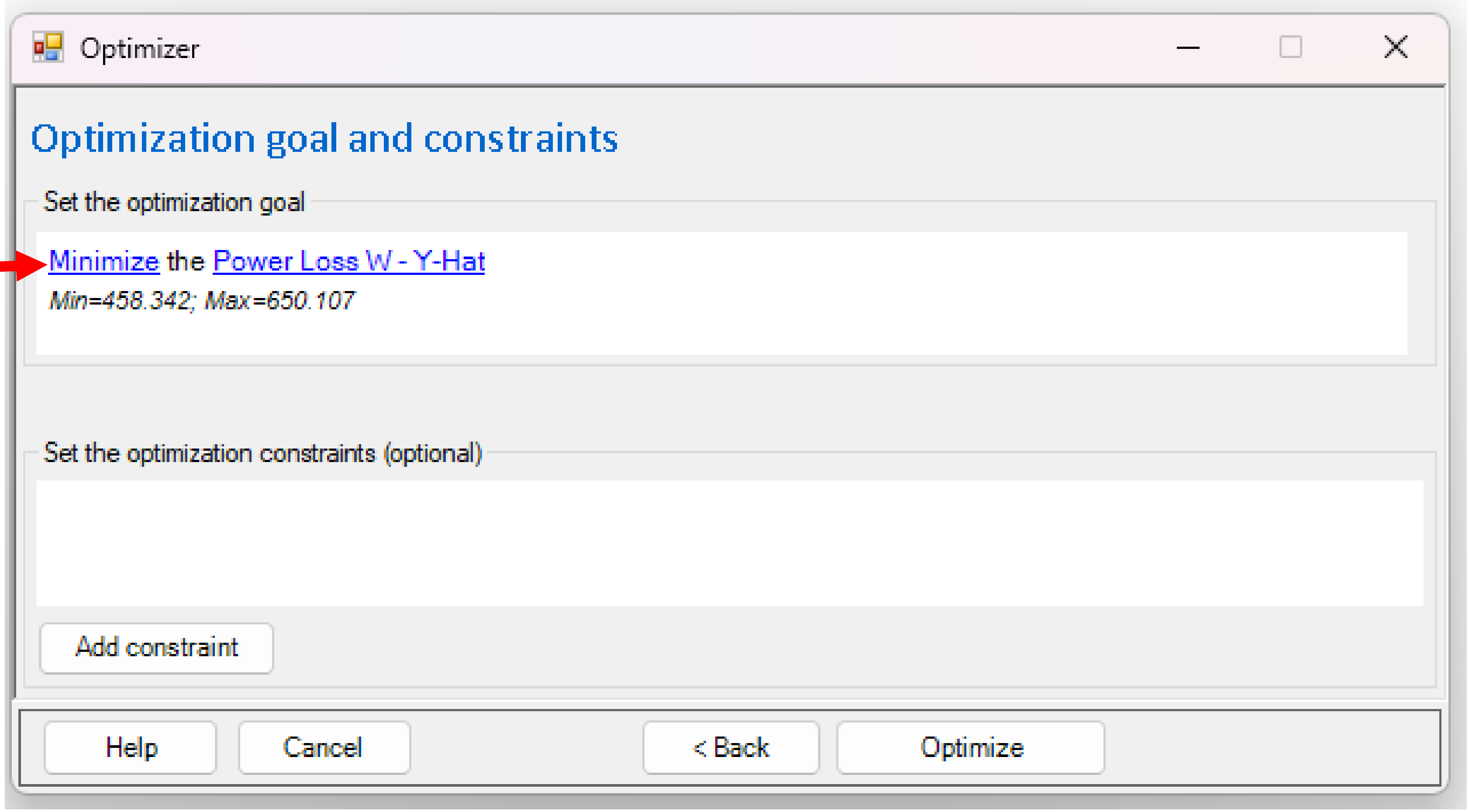
Regression in Coded Units (Only): QXL DOE >Optimize

Quantum XL Regression Analysis

Design sheet: DOE Design

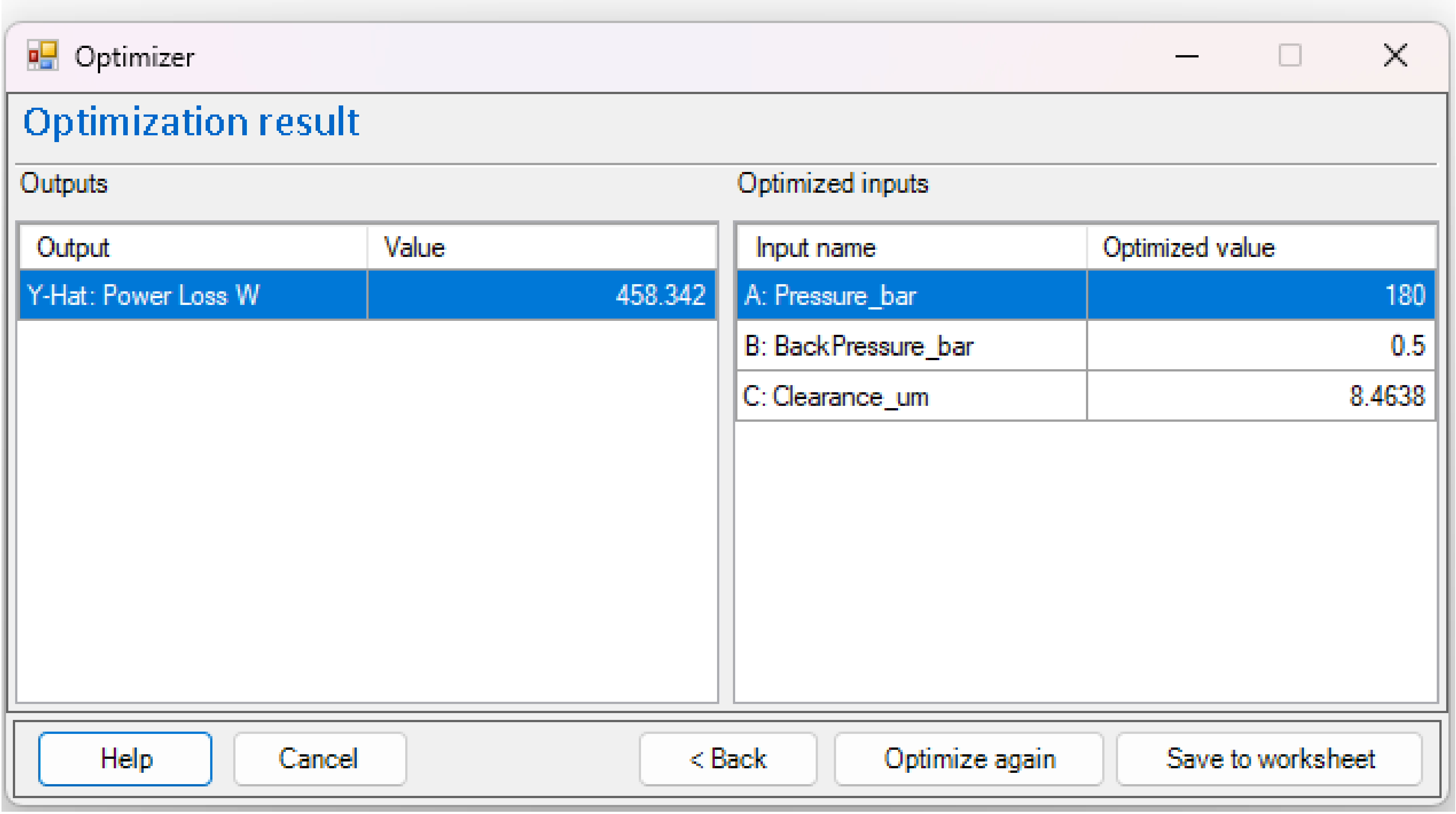
Regression in coded units





Regression in Coded Units (Only): QXL DOE >Optimize

Quantum XL Regression Analysis



Optimal Set Points to Minimize Power Loss

Quantum XL Regression Analysis

Design sheet: DOE Design

Regression in coded units

Factors				
Name	Factor	Range		Set point
		Low	High	
Pressure_bar	A	180.00	250.00	180.00
BackPressure_bar	B	0.50	2.00	0.50
Clearance_um	C	8.00	14.00	8.46

Prediction	
Power Loss W	
Y-Hat	458.34
S-Hat	5.16
PI Lower	442.85
PI Upper	473.83
USL	
LSL	
C_p	NA
C_{pk}	NA
DPM estimate	NA

Summary

- The Plackett-Burman (PB) design required only 12 runs to evaluate 11 factors, while a full-factorial design would have needed 2,048 runs ($2^{\text{number-of-factors}}$).
- In three out of the four cases studied, the main effects were sufficient for accurately predicting the critical quality performance metric.
- The PB design eliminated 8 out of the 11 factors that were suspected to influence Power Loss.
- The coefficient of determination for the Power Loss model increased from 66% to 99% when a response surface design was used.