Exploring JMP DOE design and modeling functions to improve sputtering process

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APPLIED MATERIALS®
make possible

Agenda - Six Sigma DMAIC Black Belt Project (using JMP)

Define
- **CTQ1 >= 0.5 (!)**
- **CTQ2 <= 0.05**
- **CTQ3 <= 0.05**

Measure
- Measurement system assessment
- Baseline hardware
  - 3 tuning knobs (X_1, X_2, X_3)
- Baseline capability analysis
  - ✓ Monte-Carlo simulation
- Baseline model establish
  - ✓ Augment DOE
  - ✓ RSM
  - ✓ Prediction profile
  - ✓ Interaction profile

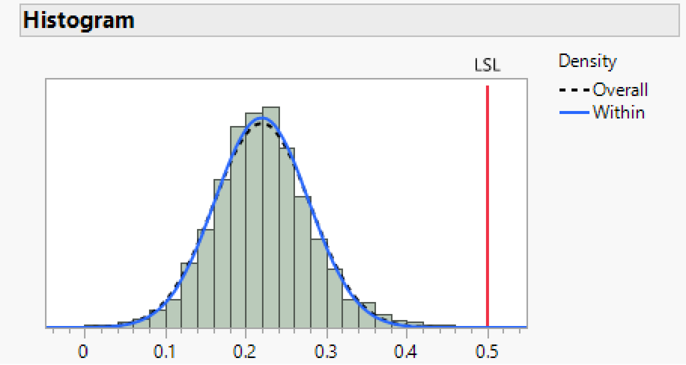
Analyze
- Root cause and capability analysis
  - ✓ Goal plot
  - ✓ Desirability function
  - ✓ Multivariate method
  - ✓ Graphic analysis

Improve
- Hardware modification
  - Introduce X_4
- Process improvement
  - ✓ Interactive graph
  - ✓ Augment DOE
  - ✓ RSM
  - ✓ Desirability function
  - ✓ Interaction profile
- Robust DOE Modeling
  - ✓ GOSS
  - ✓ Stepwise fit
  - ✓ Desirability function

Control
- Control plan and control method
- Knowledge transfer

Baseline capability – Monte Carlo Simulation

CTQ1: LSL >=0.5



Process Summary

LSL	0.5
N	10000
Sample Mean	0.219963
Within Sigma	0.058054
Overall Sigma	0.059695
Stability Index	1.028264

- Sample mean outside spec limit, -ve Ppk
- Baseline process result can not meet CTQ1 spec

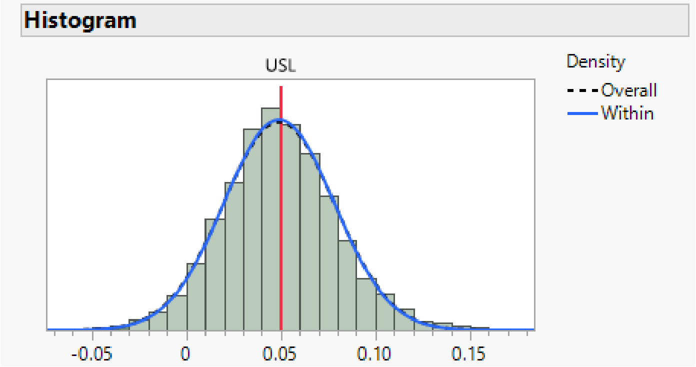
Overall Sigma Capability

Index	Estimate	Lower 95%	Upper 95%
Ppk	-1.564	-1.586	-1.541
Ppl	-1.564	-1.586	-1.541

Nonconformance

Portion	Observed %	Expected Within %	Expected Overall %
Below LSL	99.9900	99.9999	99.9999
Total Outside	99.9900	99.9999	99.9999

CTQ2: USL <=0.05



Process Summary

USL	0.05
N	10000
Sample Mean	0.049091
Within Sigma	0.029074
Overall Sigma	0.029391
Stability Index	1.010887

- Sample mean ~ upper spec limit, Ppk ~ 0
- 48% of baseline process result did not meet CTQ2 spec

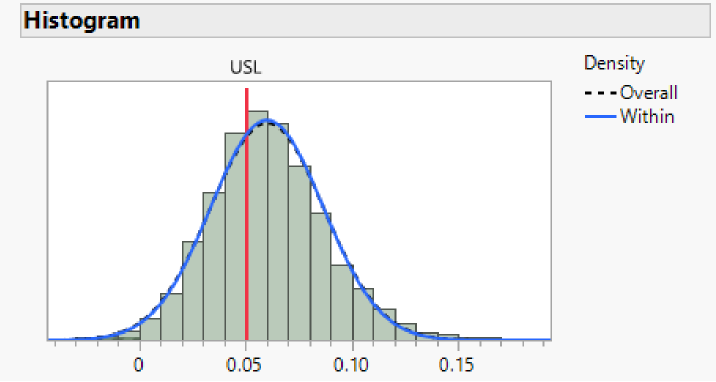
Overall Sigma Capability

Index	Estimate	Lower 95%	Upper 95%
Ppk	0.010	0.004	0.017
Ppu	0.010	0.004	0.017

Nonconformance

Portion	Observed %	Expected Within %	Expected Overall %
Above USL	47.2900	48.7536	48.7670
Total Outside	47.2900	48.7536	48.7670

CTQ3: USL <=0.05



Process Summary

USL	0.05
N	10000
Sample Mean	0.060028
Within Sigma	0.026427
Overall Sigma	0.026759
Stability Index	1.012573

- Sample mean outside spec limit, -ve Ppk
- 64% of baseline process result did not meet CTQ3 spec

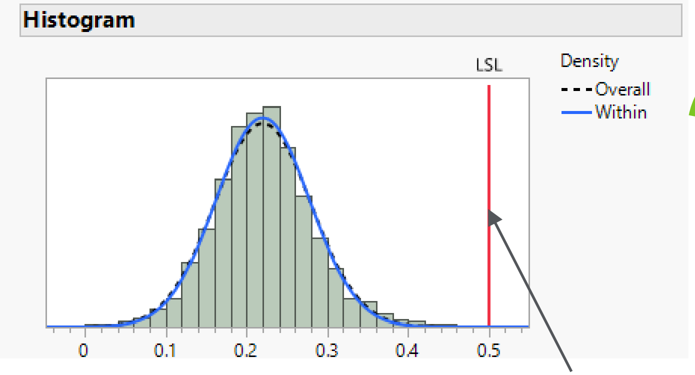
Overall Sigma Capability

Index	Estimate	Lower 95%	Upper 95%
Ppk	-0.125	-0.132	-0.118
Ppu	-0.125	-0.132	-0.118

Nonconformance

Portion	Observed %	Expected Within %	Expected Overall %
Above USL	63.6800	64.7835	64.6085
Total Outside	63.6800	64.7835	64.6085

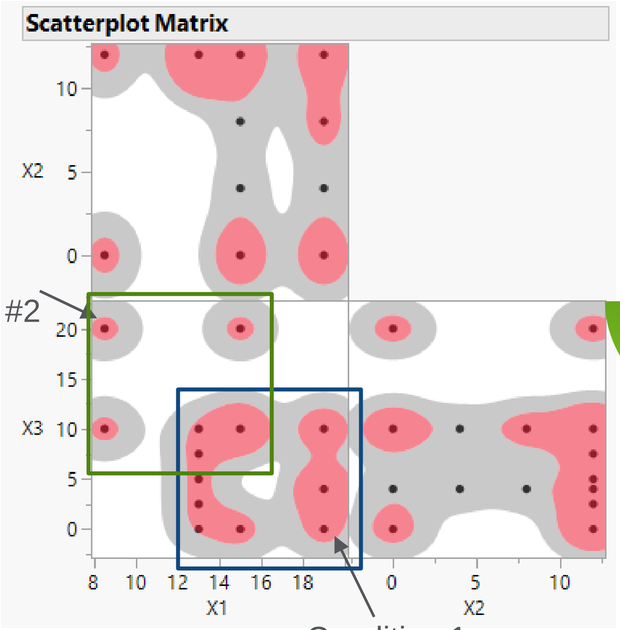
Baseline condition @ baseline model – design evaluation



Requirement

Process tuning

Condition 2
Hypothesis #2

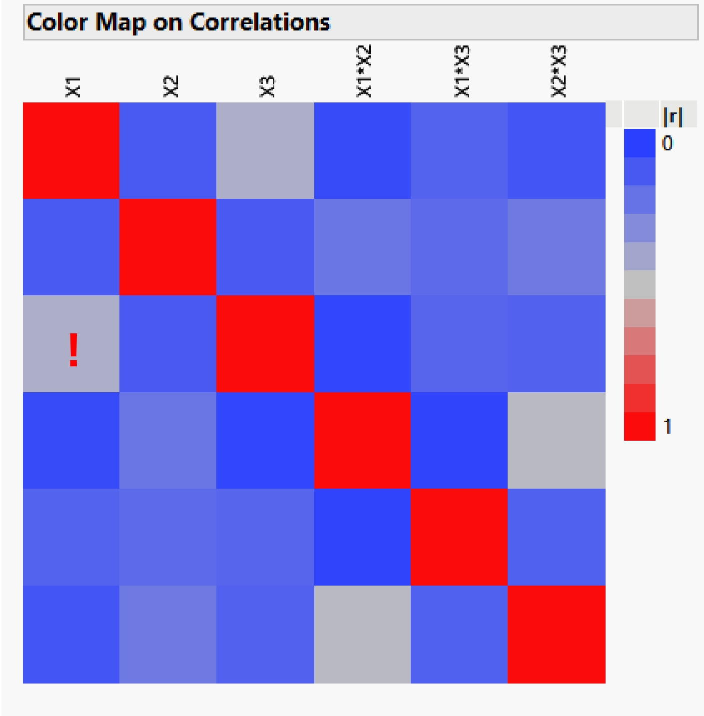


Condition 1
Hypothesis #1

Design evaluation

Confounding Analysis:

- Resolution II: $X_1 + X_3$ @ 0.4352
- Resolution III: low confounding risk



Baseline capability:

- Baseline process (condition 1) cannot meet the CTQ1 requirement
- Need to determine if the hardware has the capability to meet requirement for CTQ1
- Subject matter expert (SME) advised shift process condition 1 to process condition 2 based on hypothesis #2

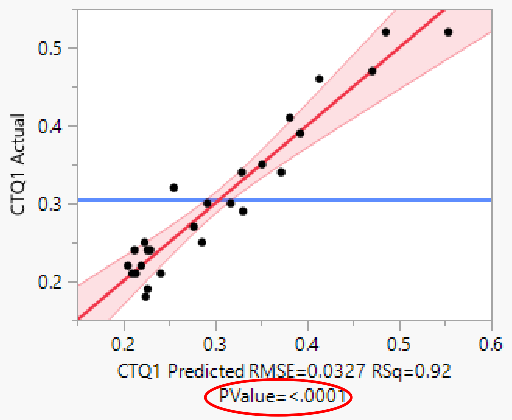
Scatterplot Analysis:

- Data collected not in orthogonal structure
- 2 step evolution design
- Widen the process range to meet spec for CTQ1
- Weak prediction capability in white area
- Good prediction for condition 1 & 2

Baseline condition @ baseline model – RSM

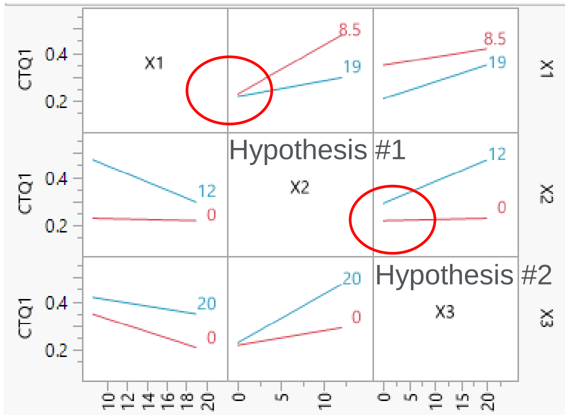
CTQ1

Actual by Predicted Plot



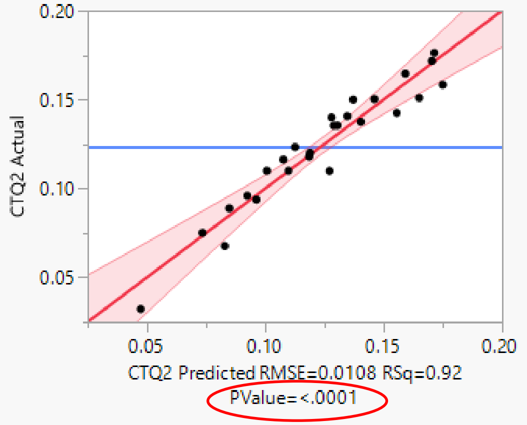
Summary of Fit

RSquare	0.921232
RSquare Adj	0.896357
Root Mean Square Error	0.032657
Mean of Response	0.305385
Observations (or Sum Wgts)	26



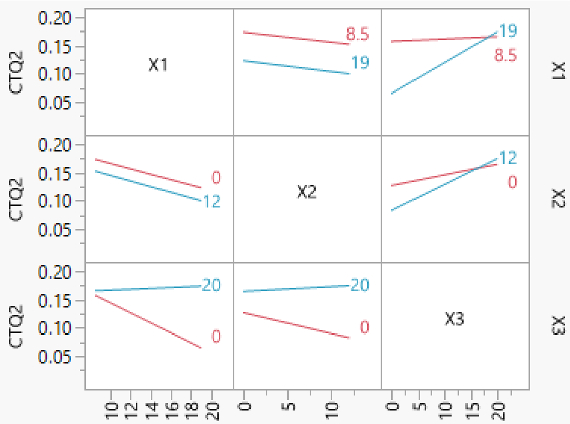
CTQ2

Actual by Predicted Plot



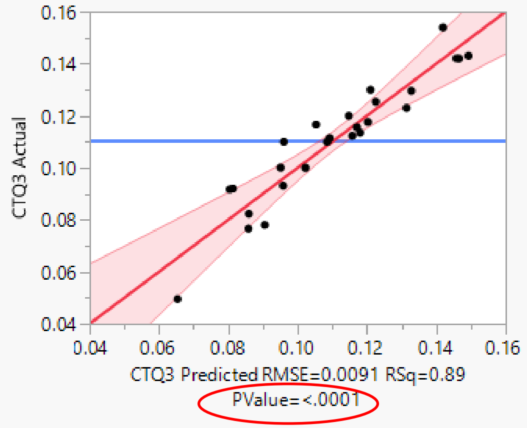
Summary of Fit

RSquare	0.923404
RSquare Adj	0.899215
Root Mean Square Error	0.010787
Mean of Response	0.123657
Observations (or Sum Wgts)	26



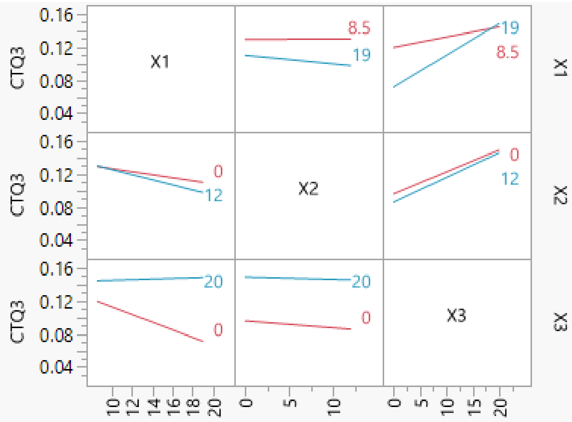
CTQ3

Actual by Predicted Plot



Summary of Fit

RSquare	0.889566
RSquare Adj	0.854692
Root Mean Square Error	0.009092
Mean of Response	0.110749
Observations (or Sum Wgts)	26



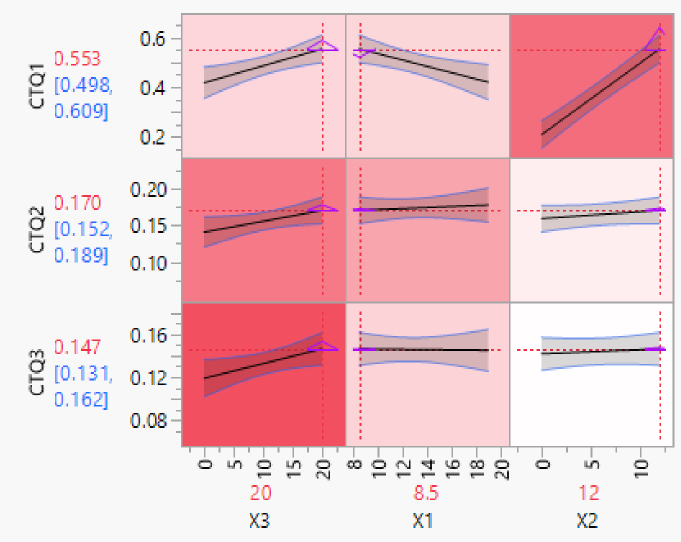
Effect Summary

Effect Summary

Source	LogWorth	PValue
X2	7.811	0.00000
X3	7.647	0.00000
X1	6.033	0.00000
X1*X3	3.733	0.00019
X1*X2	2.640	0.00229
X2*X3	2.613	0.00244

Improved CTQ1?

Prediction Profiler

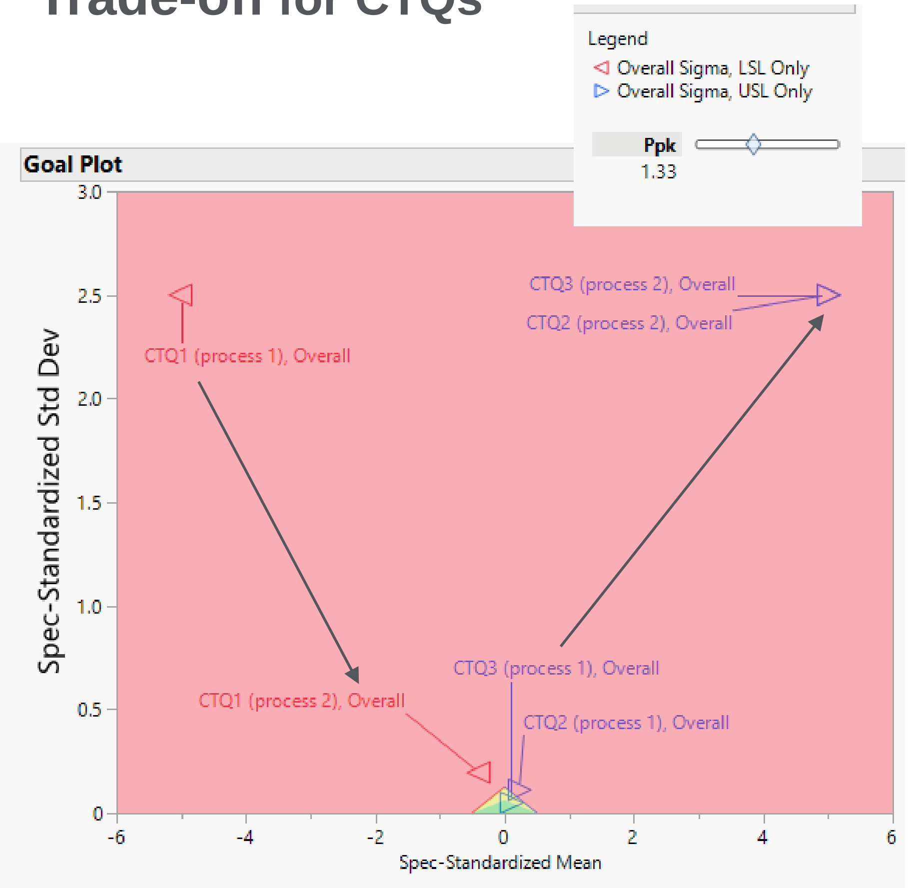


- 95% confidence interval of CTQ1 is (49.8%~60.9%)

BUT…..

Optimized solution: maximize desirability for (baseline model; N.A)

Trade-off for CTQs

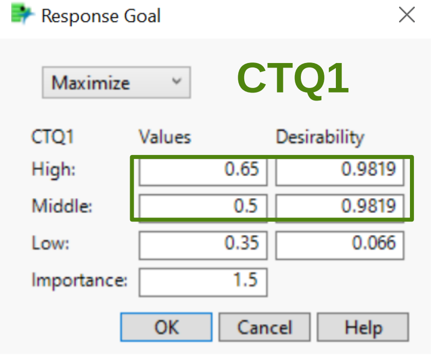


Process condition 1→process condition 2:

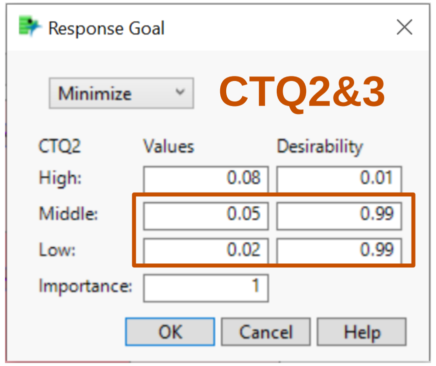
- Improve CTQ1
- Compensate CTQ 2&3

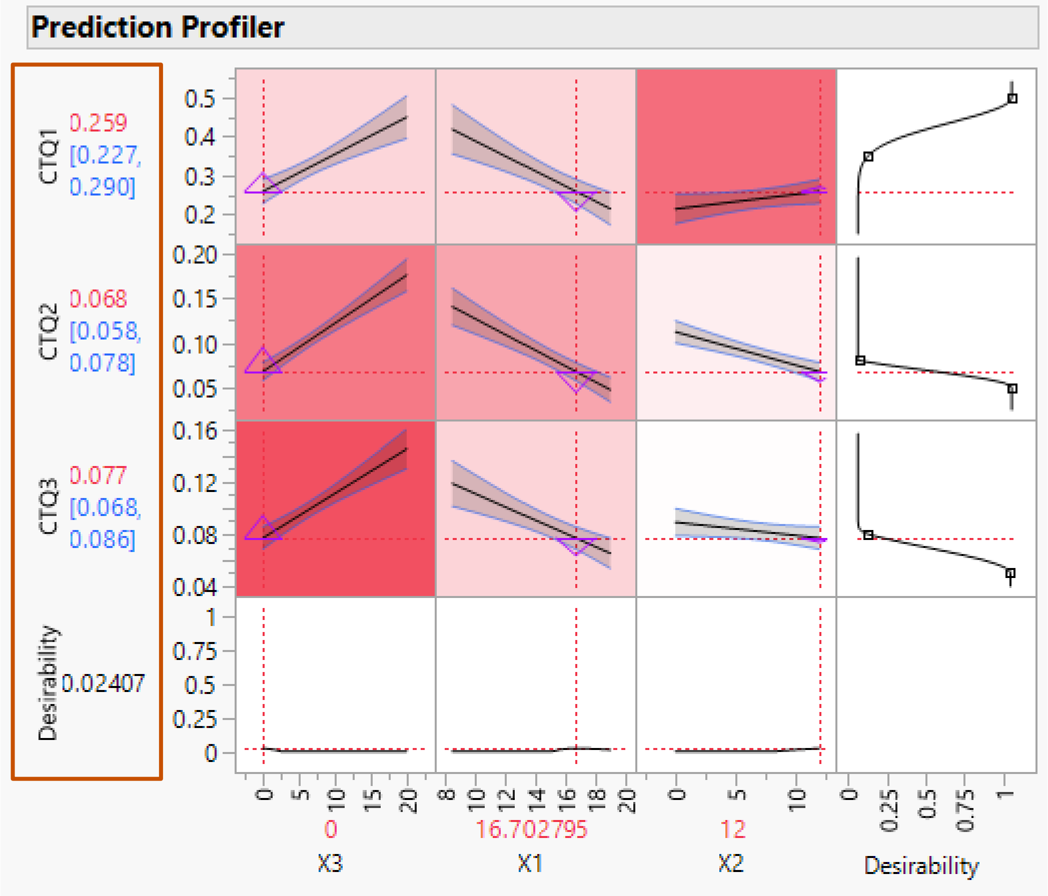
Find optimized solution via desirability function

For CTQ1:
Maximum plateau
(any value >= target is equally preferred)



For CTQ2&3:
Minimum plateau
(any value <= target is equally preferred)

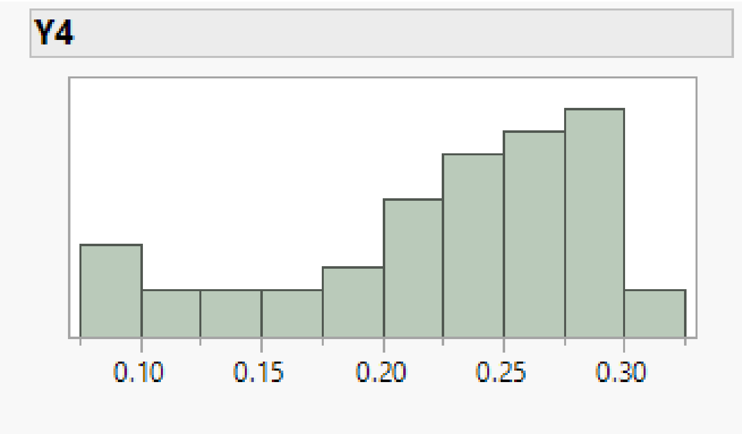




☹ 0.02 desirable
☹ no CTQ meet success criteria
☹ Hardware limitations

APPLIED MATERIALS

Y_4 & X_4



SME decided to introduce Y_4 , a measurable

- Reflects process intrinsic property
- Affects CTQ2 &CTQ3
- Y_4>0, +ve process
- Y_4<0, -ve process
- Y_4~0, neutral process → smaller CTQ2 &CTQ3

Smaller Y_4: smaller CTQ2 & CTQ3

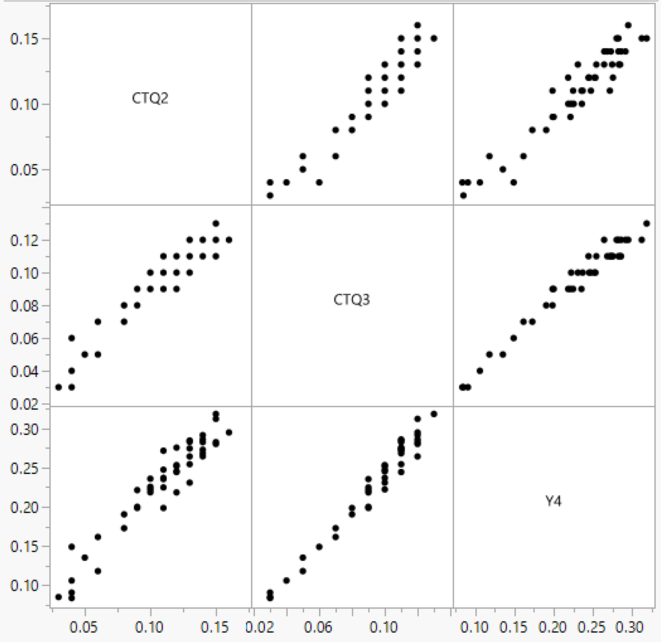
Multivariate

Correlations

	CTQ2	CTQ3	Y4
CTQ2	1.0000	0.9602	0.9619
CTQ3	0.9602	1.0000	0.9824
Y4	0.9619	0.9824	1.0000

The correlations are estimated by Row-wise method.

Scatterplot Matrix

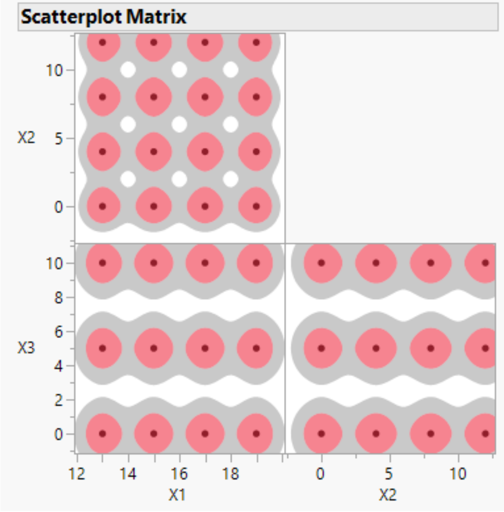


Next: add in X_4 impact Y_4

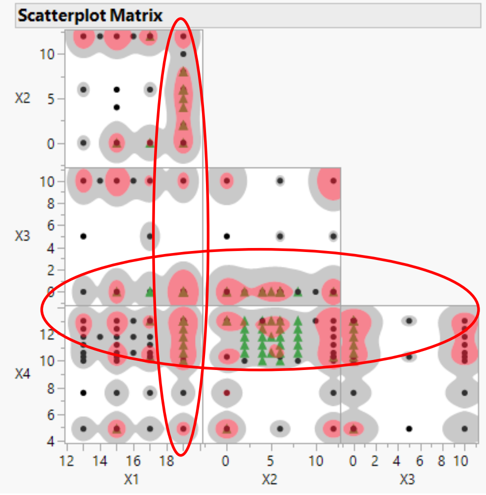
(Hypothesis #3 & Hypothesis #4)

Validate X_4 impact on CTQ2&3

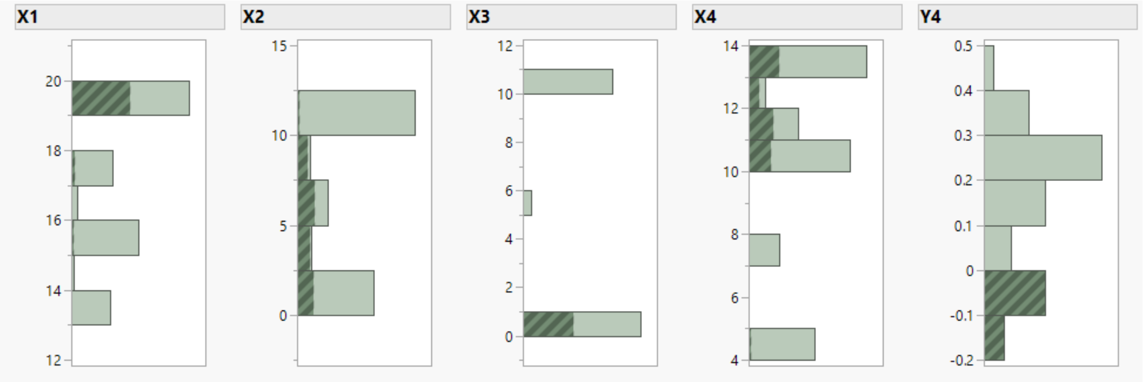
Without X_4

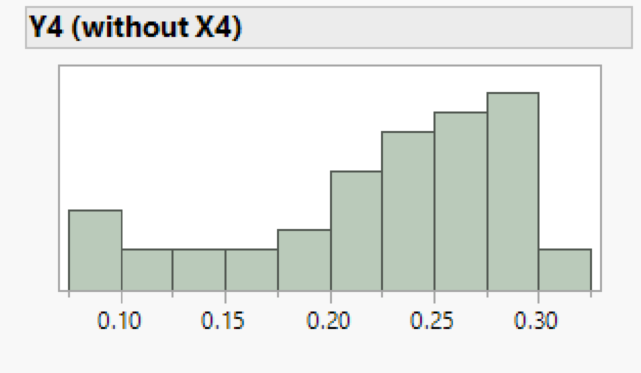


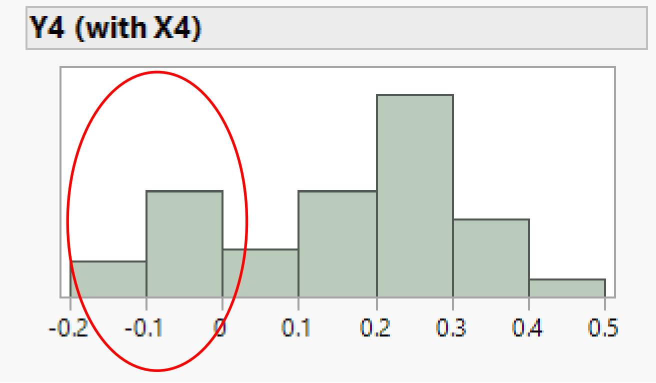
With X_4



Simple screen of conditions for Y_4<0:
-ve process







- **X_4 has impact on Y_4 → can impact CTQ 2&3**
- **Wide range of Y_4, potential solution with two step process**

Tuning range (orthogonal)

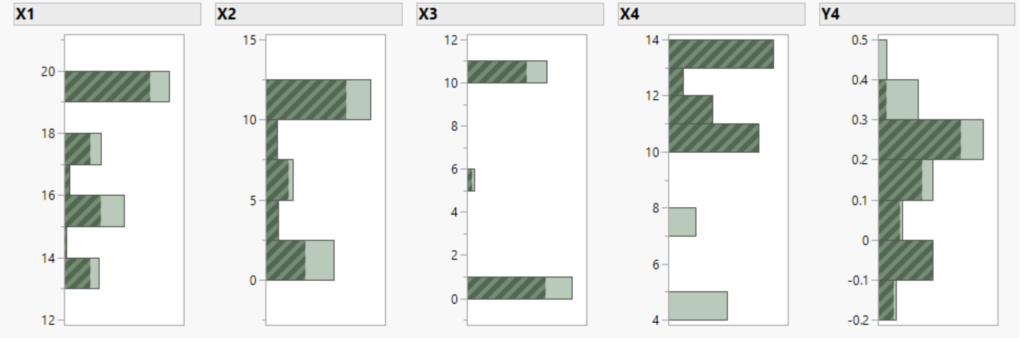
- X1: 13~19
- X2: 0~12
- X3: 0~10

Tuning range

- X1: 13~19
- X2: 0~12
- X3: 0~10
- X_4: 5~13

Analyze & improve model: design evaluation (CTQ1, 2 &3)

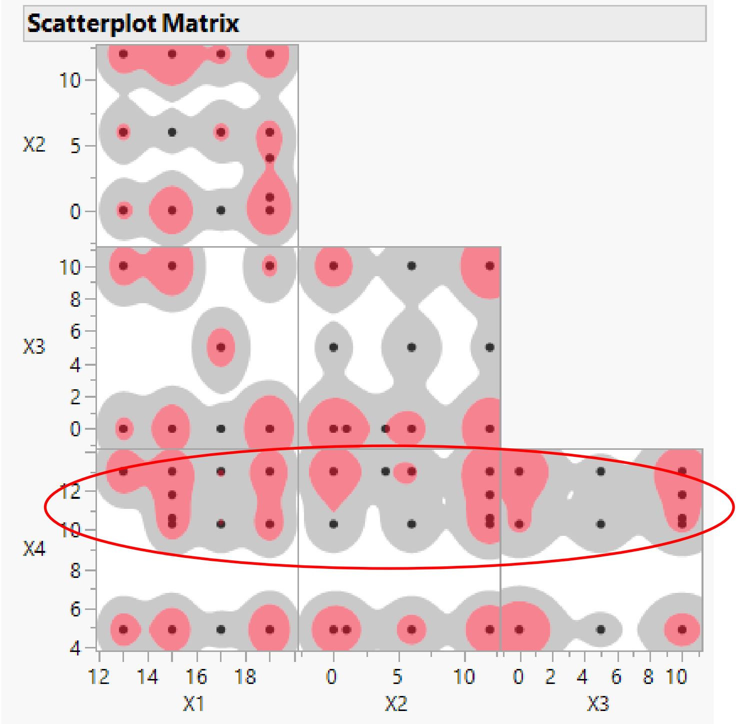
Prescreening



Prior data collection

- Validated X_4
- Prescreen conditions of interest (higher value of X_4)
- Provide most Y_4 conditions
- X_4 might have interactions with other Xs

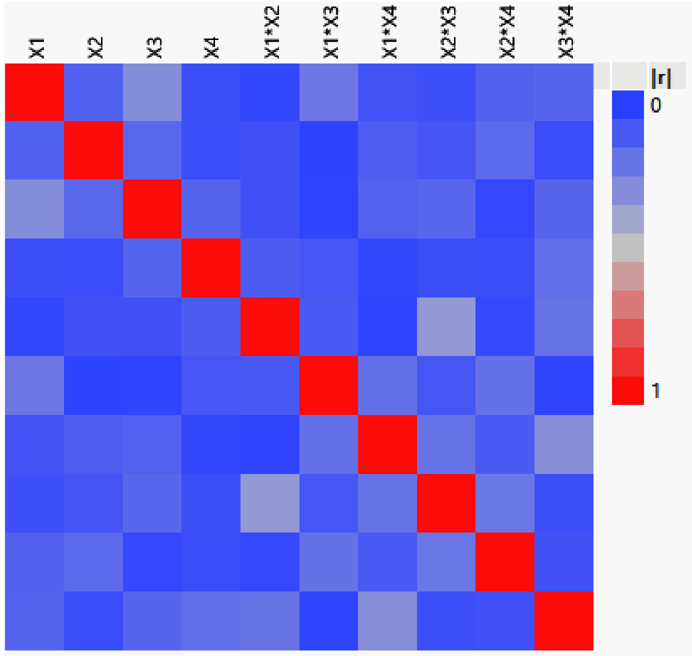
Data collection



Scatterplot Analysis:

- Wide range (with X_4)
- More data collected at conditions of interest
- Not most orthogonal structure

Design evaluation

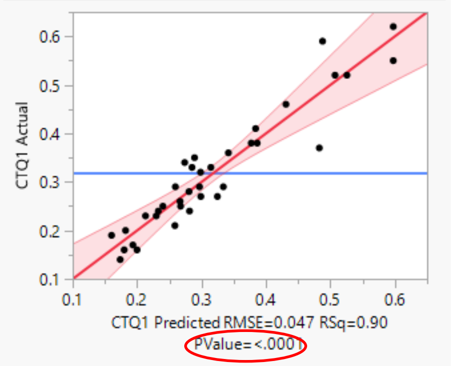


Confounding Analysis:

- Low confounding risk
- Data structure good for modelling

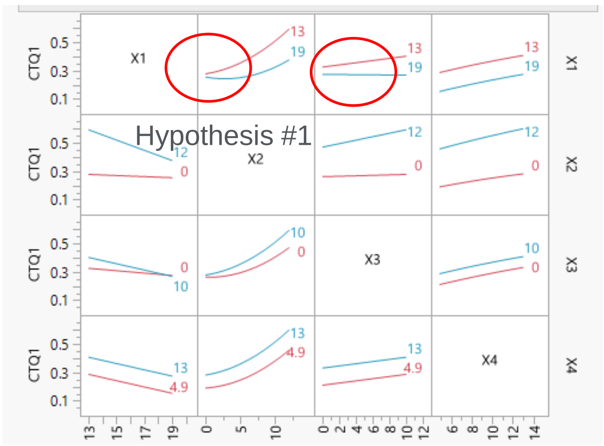
Analyze & improve model: model evaluation (CTQ1, 2 &3)

CTQ1



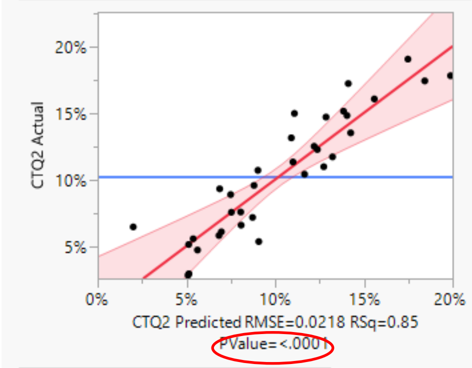
Summary of Fit

RSquare	0.897076
RSquare Adj	0.855906
Root Mean Square Error	0.047035
Mean of Response	0.318056
Observations (or Sum Wgts)	36



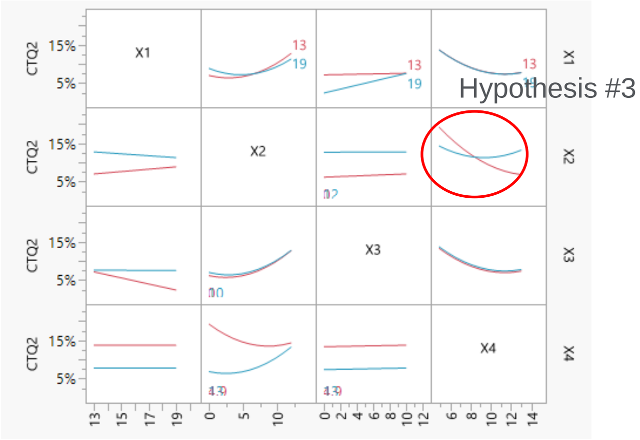
Hypothesis #2

CTQ2

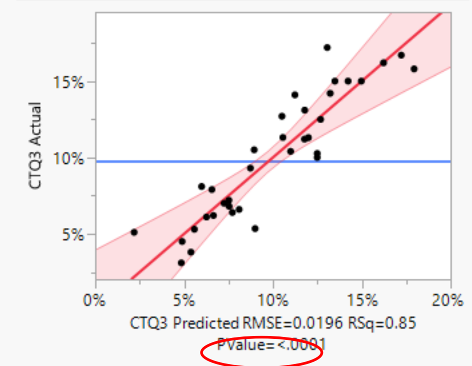


Summary of Fit

RSquare	0.845758
RSquare Adj	0.784062
Root Mean Square Error	0.021763
Mean of Response	0.102236
Observations (or Sum Wgts)	36

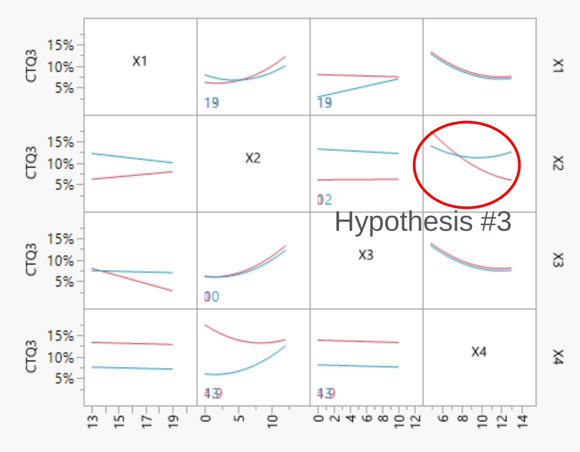


CTQ3



Summary of Fit

RSquare	0.851252
RSquare Adj	0.791753
Root Mean Square Error	0.019636
Mean of Response	0.098031
Observations (or Sum Wgts)	36



Effect Summary

Effect Summary

Source	LogWorth	PValue
X2	7.562	0.00000
X2*X4	5.074	0.00001
X4	4.440	0.00004 ^
X1*X2	2.952	0.00112
X1	2.899	0.00126 ^
X3	2.705	0.00197
X2*X2	2.277	0.00528
X2*X3	1.705	0.01972
X1*X3	1.627	0.02359
X4*X4	1.569	0.02696

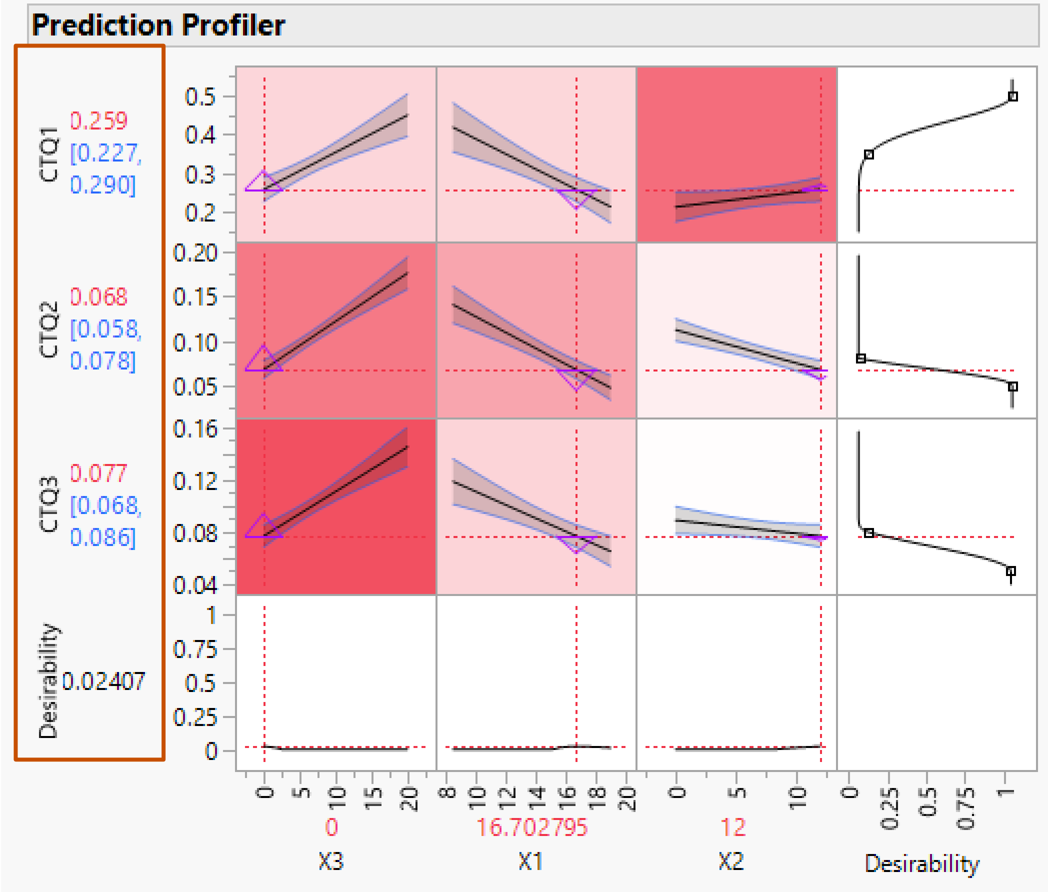
- Only factor with Pvalue<0.05 included in model
- Rsquare > 80%; Rsquare-Rsqaure Adj < 10%, Pvalue =< .0001; adequate models
- Hypothesis #1~#4 validated with interaction profilers

Optimized solution?

APPLIED MATERIALS

No optimized solution via desirability function, **BUT**

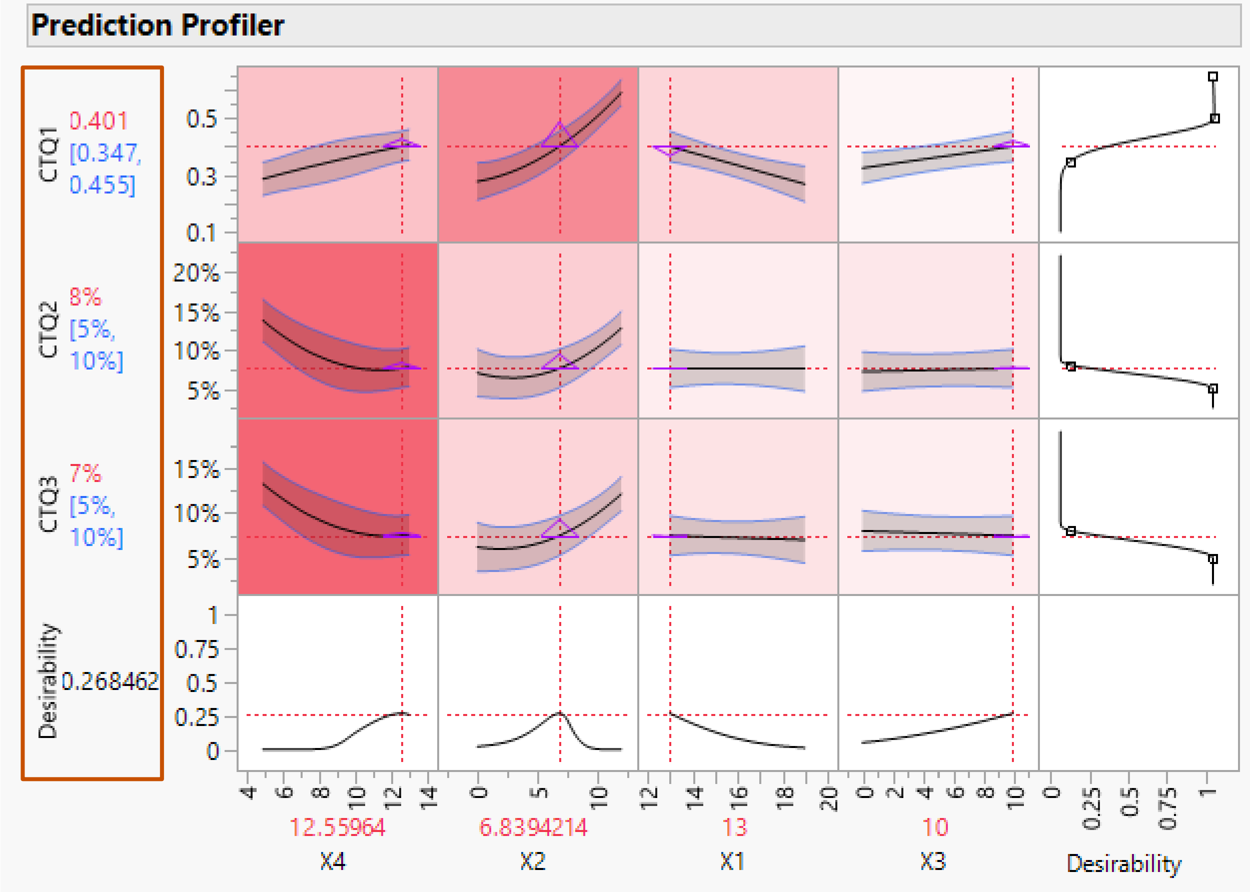
Baseline hardware (without X_4)



😞 0.02 desirable

😞 no CTQ meet success criteria

Improved hardware (with X_4)

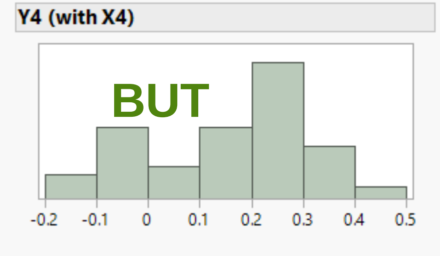


☺ Improved desirability

😞 But still low (0.27)

☺ All CTQ improved

😞 But not all meet requirement in one step



Potential solution: two step process

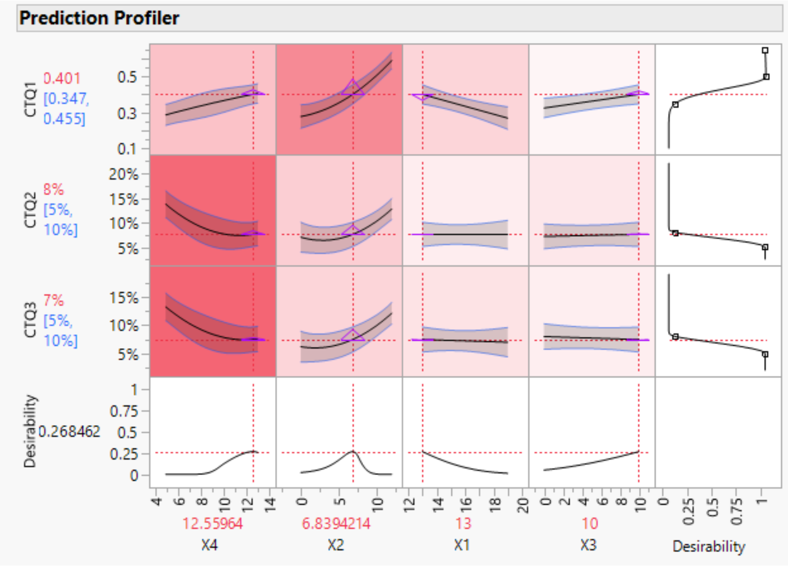
One step process

Experiment Unit

@ maximized desirability

- X_1
- X_2
- X_3
- X_4

Experiment Unit



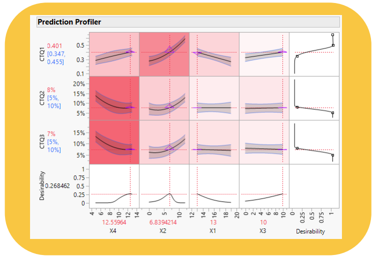
A known model

Two step process

Experiment Unit

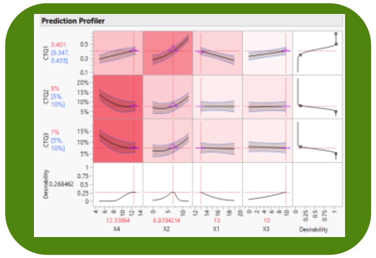
process condition 1

- X_1 1
- X_2 1
- X_3 1
- X_4 1
- Duration (1&2)



process condition 2

- X_1 2
- X_2 2
- X_3 2
- X_4 2
- Duration (1&2)



?

A new model

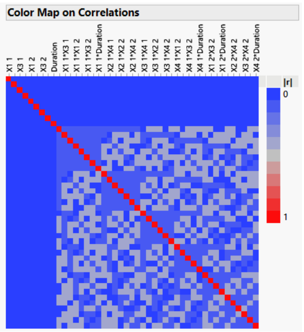
9 variables in total

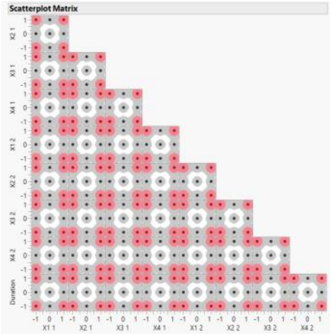
Two step process: strategies

Strategy 1: 9 variables with DSD modelling

Design

Run	X1 1	X2 1	X3 1	X4 1	X1 2	X2 2	X3 2	X4 2	Duration
1	0	1	1	1	1	1	1	1	1
2	0	-1	-1	-1	-1	-1	-1	-1	-1
3	1	0	1	-1	1	1	1	-1	-1
4	-1	0	-1	1	-1	-1	-1	1	1
5	1	-1	0	1	-1	1	1	1	-1
6	-1	1	0	-1	1	-1	-1	-1	1
7	1	1	-1	0	1	-1	1	1	1
8	-1	-1	1	0	-1	1	-1	-1	-1
9	1	-1	1	-1	0	1	-1	1	1
10	-1	1	-1	1	0	-1	1	-1	-1
11	1	-1	-1	1	-1	0	1	-1	1
12	-1	1	1	-1	1	0	-1	1	-1
13	1	-1	-1	-1	1	-1	0	1	-1
14	-1	1	1	1	-1	1	0	-1	1
15	1	1	-1	-1	-1	1	-1	0	1
16	-1	-1	1	1	1	-1	1	0	-1
17	1	1	1	-1	-1	-1	1	-1	0
18	-1	-1	-1	1	1	1	-1	1	0
19	1	1	1	1	-1	-1	-1	1	-1
20	-1	-1	-1	-1	1	1	1	-1	1
21	1	-1	1	1	1	-1	-1	-1	1
22	-1	1	-1	-1	-1	1	1	1	-1
23	1	1	-1	1	1	1	-1	-1	-1
24	-1	-1	1	-1	-1	-1	1	1	1
25	0	0	0	0	0	0	0	0	0



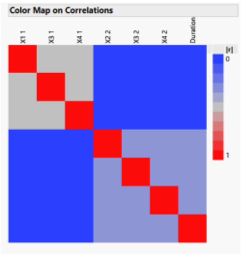


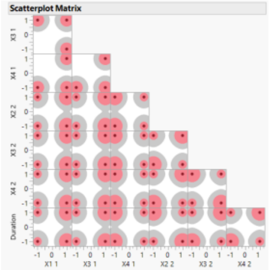
- 25 runs at least for first trial
- Good orthogonal structure
- RSM model (9 variables) constructed
- High cost

Strategy 2: Group orthogonal super-saturated (GOSS) design

Design

Run	Intercept	X1 1	X3 1	X4 1	X2 2	X3 2	X4 2	Duration
1	1	1	1	1	1	1	1	1
2	1	-1	1	-1	1	-1	1	-1
3	1	1	-1	-1	1	1	-1	-1
4	1	1	1	1	-1	-1	-1	-1
5	1	-1	1	-1	-1	1	-1	1
6	1	1	-1	-1	-1	-1	1	1





- 6 runs for 7 variables (super-saturated) (screen out 2 first: X_2 of step 1 and X_1 of step 2)
- Two independent blocks for each process step
- No interaction between factors cross blocks
- Orthogonal data structure in each block
- Main effect considered only
- Low cost
- May need further DOE design

DSD

- 17 runs
- High cost
- Interaction added

Augment DOE

- + 8 runs typically
- Medium cost
- Interaction added

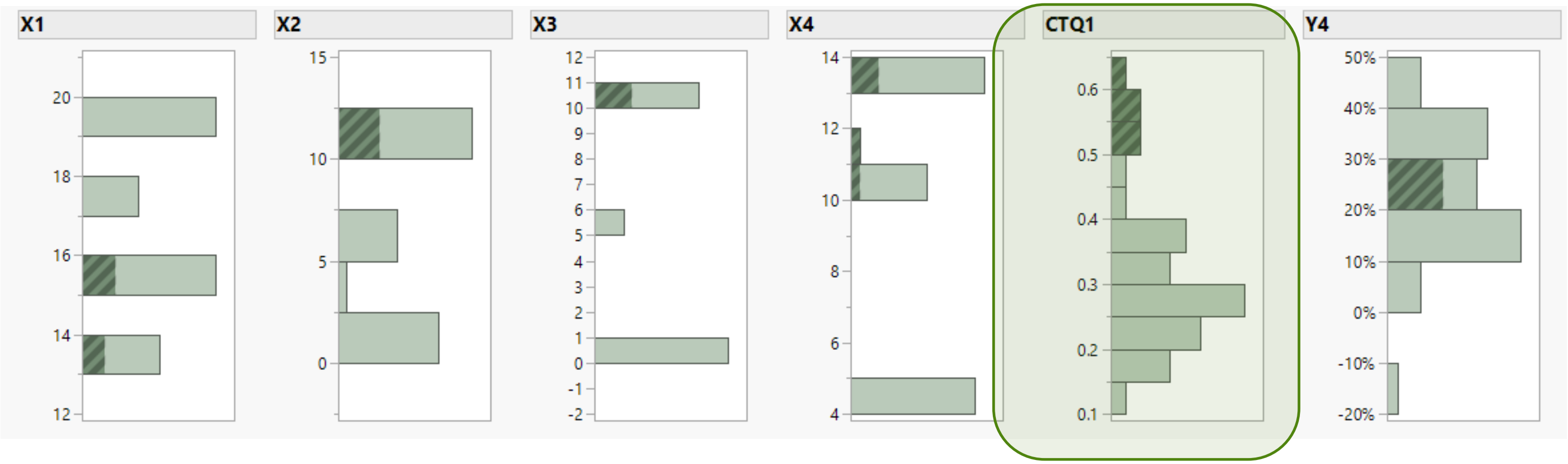
OFAT

- Valid without interaction
- Low cost
- One main effect only

Proceed with strategy 2: cost saving

Two-step process strategy: narrow down parameters

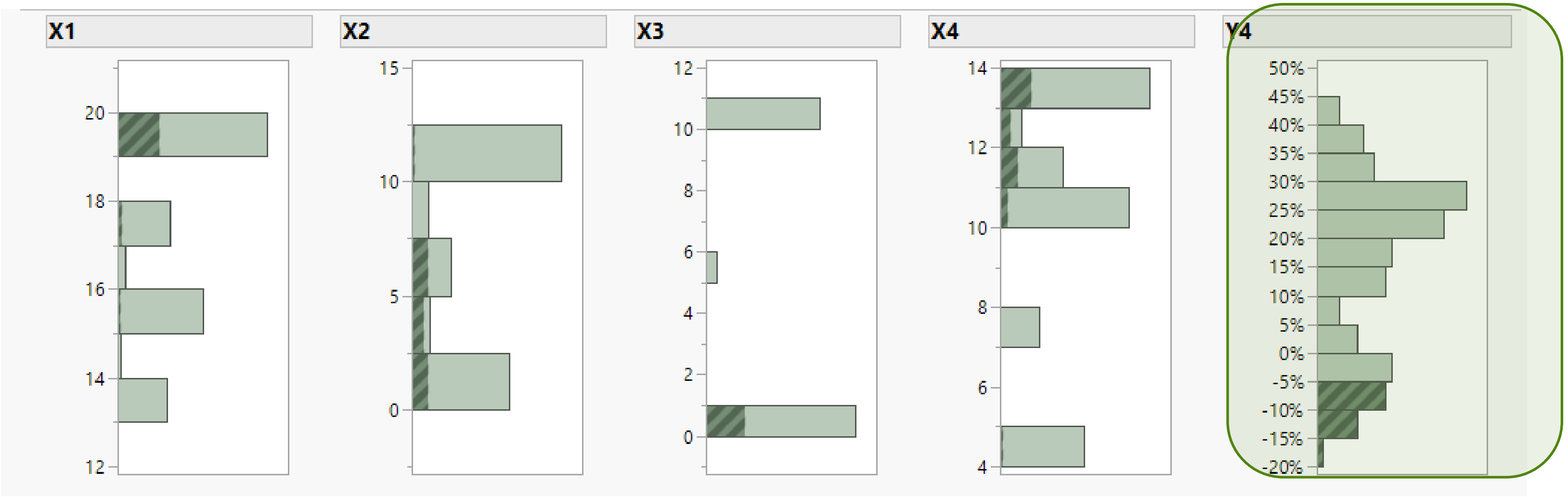
Step 1: CTQ1 > 0.5 (good for CTQ1)



Determined range for X_1, X_3, X_4; X_2 fixed

+ve process

Step 2: Y_4< -5% (sum net process, good for CTQ2 and CTQ3)



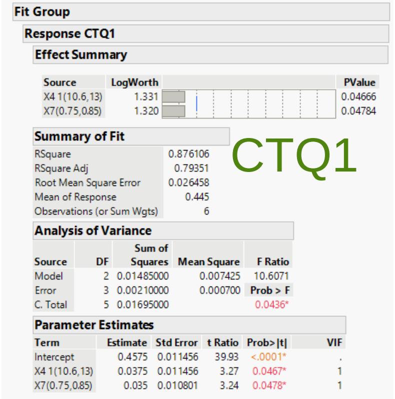
Determined range for X_2, X_3, X_4; X_1 fixed

-ve process

* Known benefit process most from past learning

Modeling via stepwise after GOSS

Stepwise fit with main effect only



Fit Group

Response CTQ1

Effect Summary

Source	LogWorth	PValue
X4 1(10.6,13)	1.331	0.04666
X7(0.75,0.85)	1.320	0.04784

Summary of Fit

RSquare	0.876106
RSquare Adj	0.79351
Root Mean Square Error	0.026458
Mean of Response	0.445
Observations (or Sum Wgts)	6

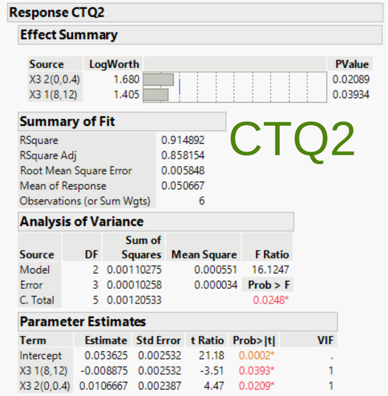
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.01485000	0.007425	10.6071
Error	3	0.00210000	0.000700	Prob > F
C. Total	5	0.01695000		0.0436*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	0.4575	0.011456	39.93	<.0001*	.
X4 1(10.6,13)	0.0375	0.011456	3.27	0.0467*	1
X7(0.75,0.85)	0.035	0.010801	3.24	0.0478*	1

CTQ1



Response CTQ2

Effect Summary

Source	LogWorth	PValue
X3 2(0,0.4)	1.680	0.02089
X3 1(8,12)	1.405	0.03934

Summary of Fit

RSquare	0.914892
RSquare Adj	0.858154
Root Mean Square Error	0.005848
Mean of Response	0.050667
Observations (or Sum Wgts)	6

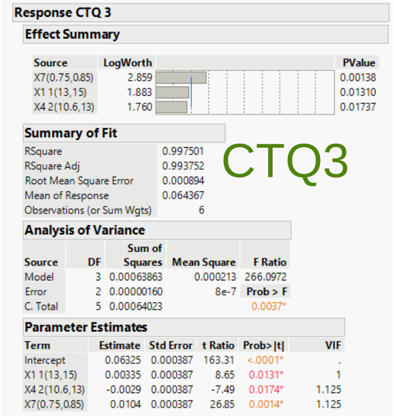
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.00110275	0.000551	16.1247
Error	3	0.00010258	0.000034	Prob > F
C. Total	5	0.00120533		0.0248*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	0.053625	0.002532	21.18	0.0002*	.
X3 1(8,12)	-0.008875	0.002532	-3.51	0.0393*	1
X3 2(0,0.4)	0.0106667	0.002387	4.47	0.0209*	1

CTQ2



Response CTQ 3

Effect Summary

Source	LogWorth	PValue
X7(0.75,0.85)	2.859	0.00138
X1 1(13,15)	1.883	0.01310
X4 2(10.6,13)	1.760	0.01737

Summary of Fit

RSquare	0.997501
RSquare Adj	0.993752
Root Mean Square Error	0.000894
Mean of Response	0.064367
Observations (or Sum Wgts)	6

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.00063863	0.000213	266.0972
Error	2	0.00000160	8e-7	Prob > F
C. Total	5	0.00064023		0.0037*

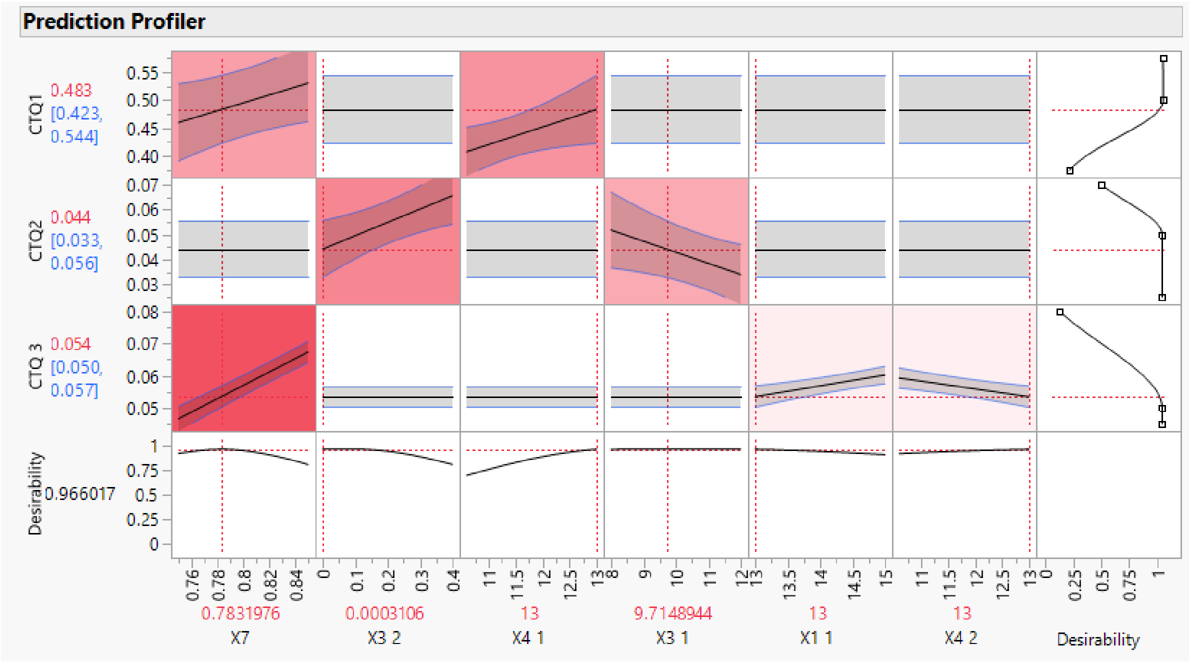
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	0.06325	0.000387	163.31	<.0001*	.
X1 1(13,15)	0.00335	0.000387	8.65	0.0131*	1
X4 2(10.6,13)	-0.0029	0.000387	-7.49	0.0174*	1.125
X7(0.75,0.85)	0.0104	0.000387	26.85	0.0014*	1.125

CTQ3

- Each CTQ has validated model (P<0.05)
- Rsquare Adj. ~0.8
- VIF<5

Optimized solution via desirability



- Provide with optimized solution with desirability > 0.96 (>>0.27>>0.02)
- Lock process parameter (high desirability)
- Next step: OFAT change duration for steps to find optimized

Summary

- Different JMP tools involved in data analysis throughout DMAIC project
  - Baseline capability analysis: Monte-Carlo simulation, Goal Plot
  - Root cause analysis: Multivariate Method, Graphic Analysis
  - DOE: Augment DOE, GOSS, Design Diagnostic
  - Model and prediction: Fitting, Prediction Profile, Interaction Profile
  - Screen condition of interest: Interactive Graph
  - Decision making: Desirability Function

Acknowledgement

- Thanks Charles C Chen's mentor

APPLIED MATERIALS®

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