Know the SCOR for Multifactor Strategy of Experimentation:

Screening, Characterization, Optimization and Ruggedness Testing

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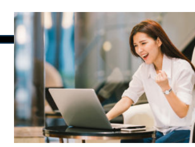
Maximizing this educational opportunity



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- Attendees on mute
- Chat not opened until afterwards
- Address questions to mark@statease.com
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The WIIFM (What's in it for me)

- By example, lay out a strategy for DOE that provides maximum efficiency and effectiveness for development of a robust process.
- Map out a sure path for converging on the 'sweet spot'—the most desirable combination of process parameters and product attributes.

Whether you are new or experienced at doing DOE, this talk is for you and your organization's bottom line!

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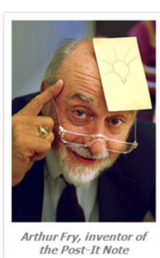
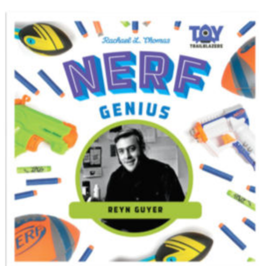
Before SCOR: A Great Invention!


Arthur Fry, inventor of the Post-It Note



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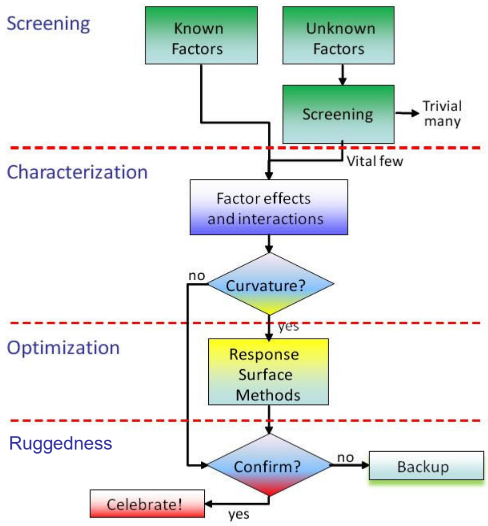
Strategy of Experimentation



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Welding Case
Demonstrates SCOR from start to finish*

Welds are falling short of 50,000 psi tensile-strength. The engineering team identifies 11 factors, 9 of which are unknown—these must be screened. They consider three designs:

1. Study only the first 7 unknown factors (foregoing 2 that are most sketchy) in an 8-run standard fractional factorial. *Rejected due to poor resolution and missing 2 factors.*
2. Screen all 9 factors in the classic 32-run standard fraction. *Better resolution and all inclusive, but too many runs!*
3. Choose a modern minimum-run* screening design. *(20 including 2 extras to allow for a few things to go wrong.)*

Press the raise-hand button if you are with me on #3.

*Know the SCOR for Multifactor Strategy of Experimentation: Screening, Characterization, Optimization and Ruggedness Testing, *The ITEA Journal of Test and Evaluation* 2019; 40: 56-61

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Minimum-Run Designs (up to 50 factors)

Considerable Savings Over Standard Fractions

Characterization

Factors	Standard	MR5*
6	32	22
7	64	30
8	64	38
9	128	46
10	128	56
11	128	68
12	256	80
13	256	92
14	256	106

Screening

Factors	Standard	MR4**
9	32	18
10	32	20
11	32	22
12	32	24
13	32	26
14	32	28
15	32	30
16	32	32
17	64	34

* Oehlert & Whitcomb, "Small, Efficient, Equireplicated Resolution V Fractions of 2^k designs …", Fall Technical Conference, 2002: www.statease.com/pubs/small5.pdf

** Anderson & Whitcomb, "Screening Process Factors In the Presence of Interactions," Annual Quality Congress, American Society of Quality, Toronto, 2004: www.statease.com/pubs/aqc2004.pdf

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Welding Phase 1: MR4* Design on 9 Factors

*Plus 2 to provide for botched runs

A. Angle, degrees: 60 - 80
B. Substrate thickness, millimeters (mm): 8 - 12
C. Opening, mm: 1.5 - 3
D. Rod diameter, mm: 4 - 8
E. Rate of travel, mm/second: 0.5 - 2
F. Drying of rods, hours: 2 - 24
G. Electrode extension, mm: 6 - 15
H. Preheating Temperature, degrees F: 250 - 350
J. Edge prepped: No – Yes

Weld-Screen
Rebuild noting power
Analyze

#	A	B	C	D	E	F	G	H	J	Tensile
1	80	8	3	8	0.5	24	6	350	No	43880
2	80	8	1.5	8	0.5	24	15	250	No	46100
3	60	12	1.5	8	0.5	24	6	250	Yes	46770
4	80	12	3	8	0.5	2	15	250	Yes	51290
~	~	~	~	~	~	~	~	~	~	~
20	60	8	3	4	2.0	24	15	250	No	45040

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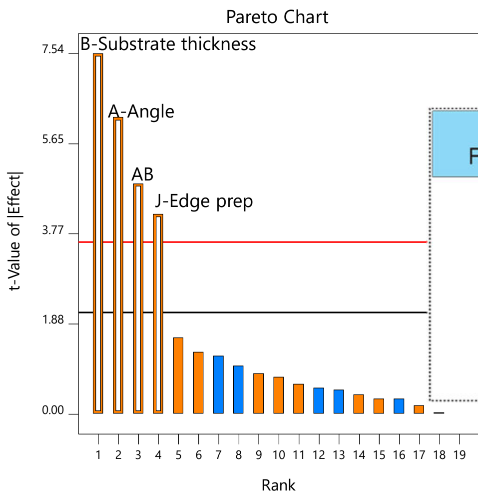
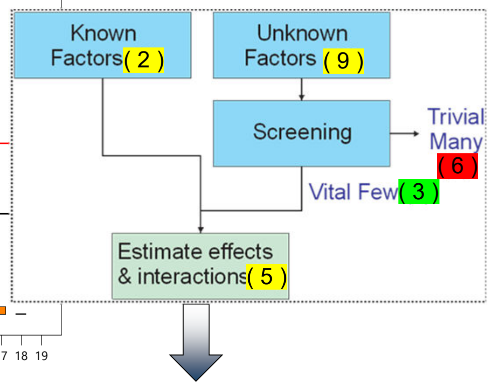
Welding Phase 1 (Screening): Results



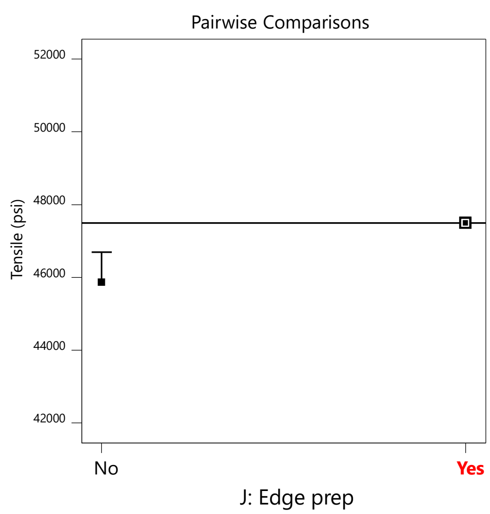
Only 3 of the 9 factors survive.



Welding Phase 2: Characterization Design

Experiment design (part 1 of 2)

Factor J—the edge prep—exhibited a main effect only and "Yes" as expected, so do that: Fix the factor going forward.



Welding Phase 2: Characterization Design
Experiment design (part 2 of 2)

That leaves 4 factors to be studied:

- A. Angle, degrees: 60 – 80
  Previously unknown—survived screening (one of vital few)
- B. Substrate Thickness, mm: 8 – 12 *Ditto*
- C. Current, amps: 125 – 160
  One of two known factors that bypassed screening
- D. Metal Substrate, stainless steel: SS35 – SS41 *Ditto*

Characterizing the two-factor interactions requires the full, 16-run, two-level factorial (2^4)—a fractional will be too low in resolution, aliasing 2FIs.

To test for curvature and provide measures of pure error, the experimenters add 3 center points of the numeric factors A, B, and C at each of the two categories of stainless steel (D).

Welding Phase 2: Characterization Design
Results

As expected, all 4 factors emerged as main effects and/or involved in 2FIs. However, curvature came out significant (left) and appreciable (right). This requires the next step: move up to Response Surface Methods (RSM).

Curvature Check | Analysis of Variance

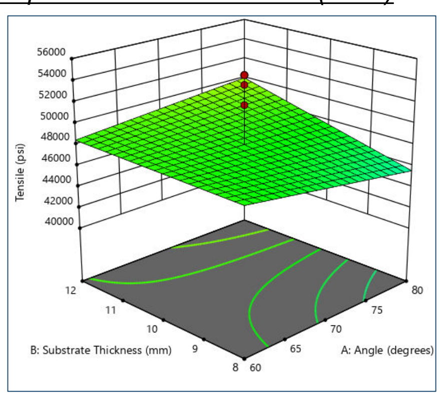
Curvature Check

You have center points in your design, with a factorial model. These points are used to test whether there is curvature in the data. If curvature is detected, a factorial model may not be appropriate.

Term	Adjusted F-value	Model p-value	
Model	17.64	< 0.0001	significant
Curvature	64.48	< 0.0001	significant
Lack of Fit	0.9706	0.5620	

Curvature Term

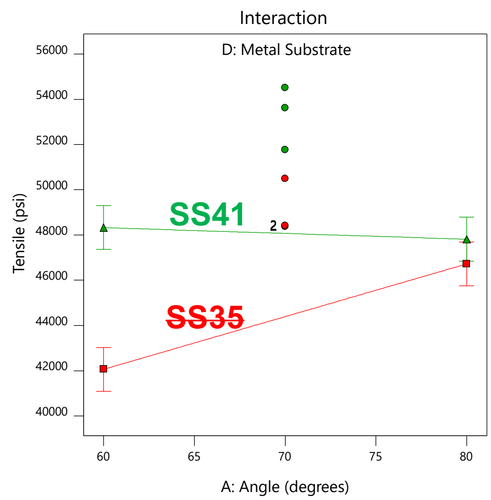
Curvature appears **significant**. Augment to a **Response Surface** design if you want to explain what is causing the curvature or if curvature is in a desirable direction for your goal. Proceeding with the analysis with the curvature term included is equivalent to ignoring the data from the center point runs.



Weld-Characterize: Rebuild noting power for 1500/900 (revise), analyze

Welding Phase 2: Characterization Design

Results—Postscript



To keep things simple for the next stage, the engineers eliminate SS35 from further consideration due to its inferiority in general (other than high angle) and at the center of the space (red dots below green ones).

Only SS41 will be carried forward.

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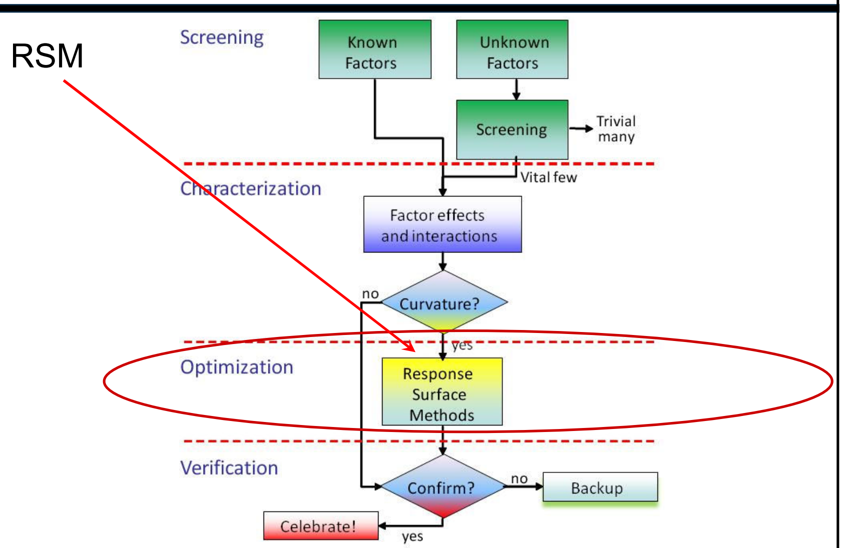
Strategy of Experimentation



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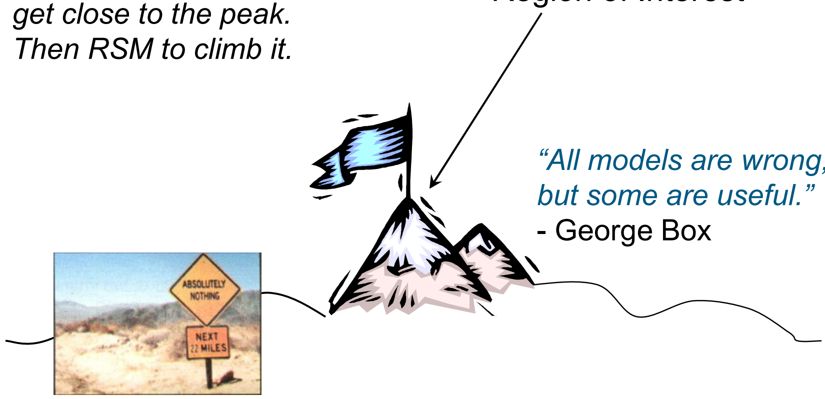
RSM: When to Apply It

Use factorial design to get close to the peak. Then RSM to climb it.



"All models are wrong, but some are useful."
- George Box

← Region of Operability →

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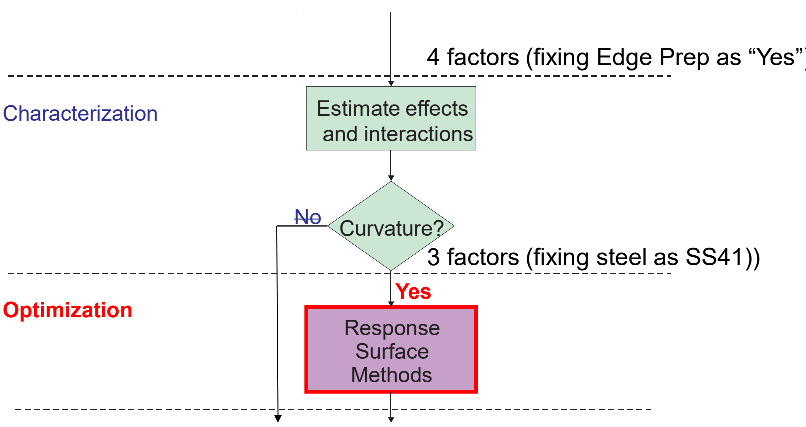
Welding Phase 3: Optimization



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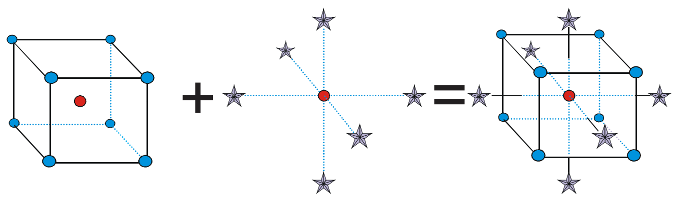
Welding Phase 3: RSM Design

The engineers build a central-composite design by augmenting the prior two-level factorial with a new block of axial points that go outside of the cube to provide leverage.



This sequential strategy saves a lot of time!

Sensible?

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Welding Phase 3: RSM Results *(Good!)*

Run	Blk	Location	A	B	C	Tensile
1	1	Factorial	60.0	8.0	125.0	47910
2	1	Factorial	80.0	8.0	125.0	44380
3	1	Factorial	60.0	12.0	125.0	48600
4	1	Factorial	80.0	12.0	125.0	47370
5	1	Factorial	60.0	8.0	160.0	47430
6	1	Factorial	80.0	8.0	160.0	46540
7	1	Factorial	60.0	12.0	160.0	49370
8	1	Factorial	80.0	12.0	160.0	**52970**
9	1	Center	70.0	10.0	142.5	**51770**
10	1	Center	70.0	10.0	142.5	**53620**
11	1	Center	70.0	10.0	142.5	**54510**
12	2	Axial	53.2	10.0	142.5	48850
13	2	Axial	86.8	10.0	142.5	48890
14	2	Axial	70.0	6.6	142.5	46600
15	2	Axial	70.0	13.4	142.5	**50810**
16	2	Axial	70.0	10.0	113.1	**50460**
17	2	Axial	70.0	10.0	171.9	**53200**
18	2	Center	70.0	10.0	142.5	**53300**
19	2	Center	70.0	10.0	142.5	**53300**

Weld-Optimize
Rebuild
Analyze
Optimize
Confirm (n=6)

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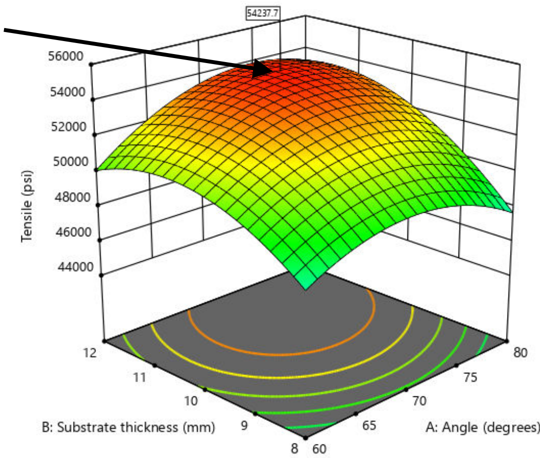
Welding Phase 3: RSM Results

Numerical search finds desirable weld at 73 deg, 11 mm & 160 amps. Mission accomplished, but…

- *Must be confirmed at field conditions.*



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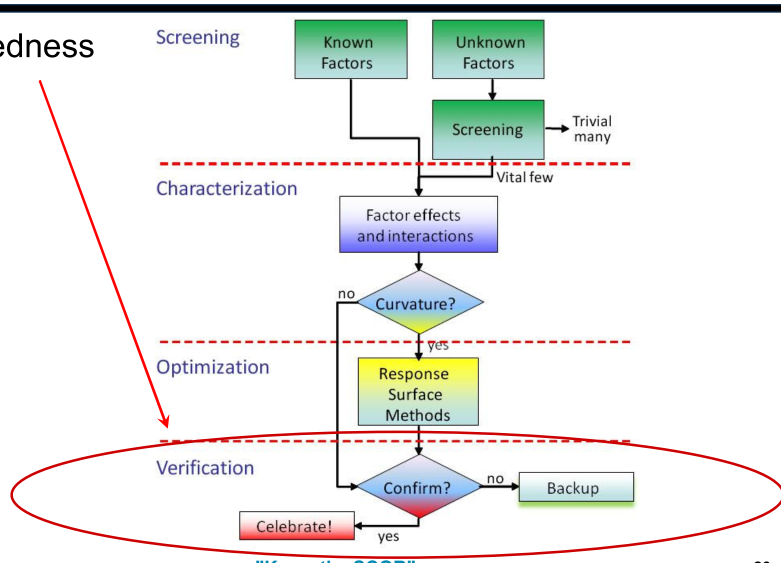
Strategy of Experimentation

Ruggedness



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Ruggedness Testing

Ruggedness testing is a *"special application of a statistically designed experiment"* that examines a *"large number of possible factors"* to determine which *"might have the greatest effect on the outcome"* of a test method. *"Two levels for each factor are chosen to use moderate separations between the high and low settings."* (ASTM*)

*(E1169 – 14: Standard Practice for Conducting Ruggedness Tests, 5.1-5.2.)

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Good choice for ruggedness testing:
Plackett-Burman Design

While testing proximity fuses on bombs during WWII, Plackett and Burman (1946) developed designs with the number of runs (N) being a multiple of 4 (vs the classical 2^{k-p} powers of two). PB's work well for pass-or-fail ruggedness testing being resolution III. They had best be run "saturated" with k factors, i.e, k = N – 1 (or filled out with "dummies").

If the ruggedness test reveals possibly important effects, then the PB design can be simply folded over, i.e., a second block of runs done with all levels opposite of the first. This produces a design that resolves the main effects clear of two-factor interactions (i.e., Res IV).

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Welding Phase 3: Ruggedness

All that remains for achieving SCOR is to see if the welding process will be robust to production conditions by running a ruggedness test.

The engineering team identifies 11 factors of concern—ambient conditions and the like. They set ranges from low (minus) to high (plus) that span the majority (95 percent or so) of the normal variation based on historical records.

A 12-run Plackett-Burman design conveniently provides adequate power to detect changes in tensile strength of any importance.

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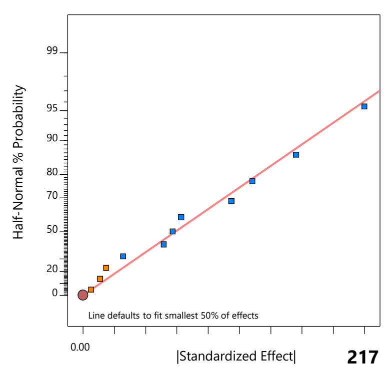
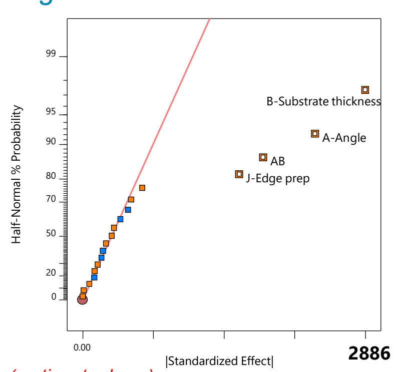
Welding Phase 3: Ruggedness

Test Results—Process Passes Field Tests!

The half-normal plot (left) shows nothing significant and the range unimportant compared to the 10x larger results for the screening (right). Time for the welding engineers to celebrate!

Do you agree?





Weld-Ruggedness (no time to demo)

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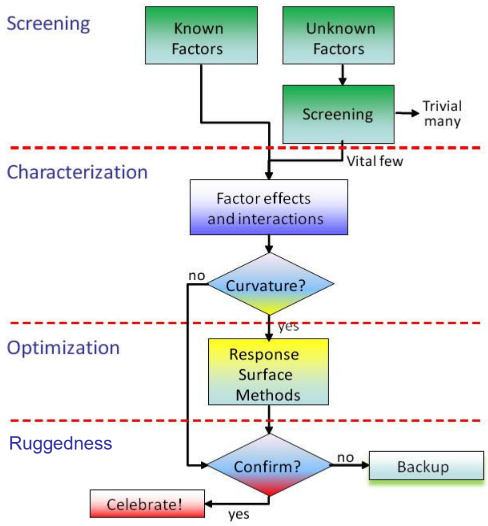
Strategy of Experimentation
It's good to know the SCOR!



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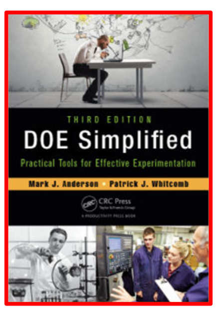
References*

3rd edition 2015



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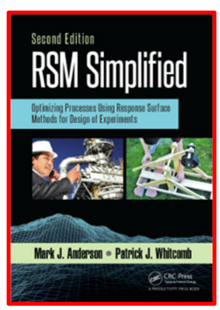

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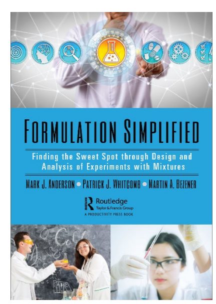

** Taylor & Francis/CRC/ Productivity Press New York, NY.*

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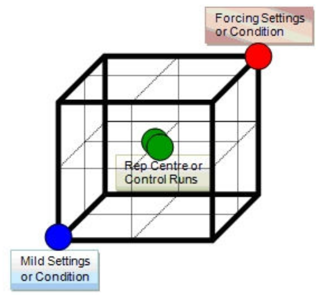
Developments on Setting Factor Levels
Scoping Designs

Heads up! Before deploying the SCOR strategy of experimentation, it pays to do some range-finding—most simply via OFAT (one-factor-at-time). However, per statistician Paul Nelson*, consider applying a multifactor approach called a "scoping design", which lays out explores extreme settings as pictured.



"About 80 percent of your success in conducting a designed experiment results directly from how well you do the pre-experimental planning."

-Douglas Montgomery

* www.prismtc.co.uk/docs/scoping-designs

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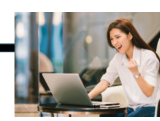
Conclusion
Benefits from Knowing the SCOR



- ✓ Provides a tried-and-true path to process improvement via an iterative series of statistically designed experiments.
- ✓ Cannot fail to be productive* whether it meets objectives or not**.
  **If powered properly by sufficient runs (sample size).*
  ***By process of elimination.*
- ✓ Breaks R&D into small steps, allowing experimenters to react to results along the way, thus reducing wasteful runs. For example, testing all 11 welding factors in a on RSM design would have required 96 runs for a CCD (or 88 runs for a minimal optimal design) vs only 50* runs for sequential SCOR.
  **20 screening, 22 characterize,8 optimization (augment).*
  In any case, confirmation runs and ruggedness tests would have been done.

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The WIFFM

- By example, lay out a strategy for DOE that provides maximum efficiency and effectiveness for development of a robust process.
- Map out a sure path for converging on the 'sweet spot'—the most desirable combination of process parameters and product attributes.

Whether you are new or experienced at doing DOE, this talk is for you and your organization's bottom line!

Do you agree?

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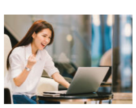

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Bye. Email questions.