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Milestones to Modern DOE for Rapid Manufacturing Improvement

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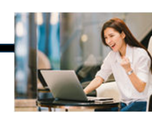
Maximizing this educational opportunity



Welcome everyone! To make the most from this webinar:

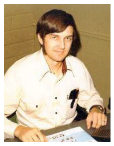
- Attendees on mute
- Send questions to mark@statease.com

PS: Presentation slides* posted to www.statease.com/webinars/
from there link to the YouTube video.

Please press the raise-hand button if you are with me.

Talking Points

Based on 50+ years of DOE experience

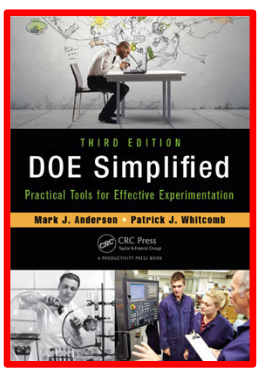


- ❖ The evolution of DOE going back to early 1900's
- ❖ Simple comparative studies—t and F testing
- ❖ Industrial multifactor DOE success stories:
  - ➢ Two-level design—Bearing life*
    - **Illustrates downsides of one-factor-at-a-time (OFAT)*
  - ➢ Response surface methods—Electrodischarge milling*
    - **Demo of state-of-the-art DOE software from Stat-Ease*

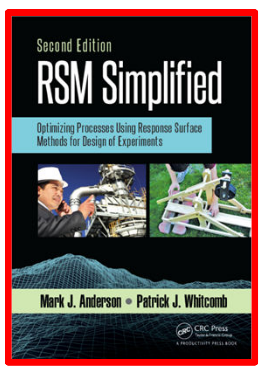
My Payback: Practical Paperbacks*

KISMIF: Keeping it simple and making it fun!

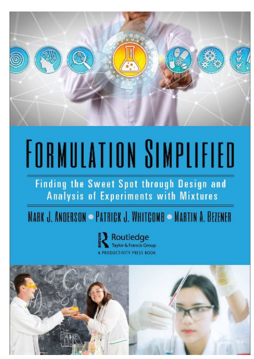
3rd edition



2nd edition



1st edition

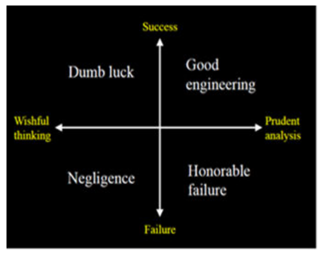


Focus of this talk will be process DOE (not mixture)

Before Statistics and Multifactor Testing
How industrial experimenters succeeded

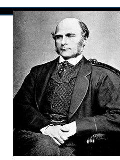
1. <u>Scientific method</u>: Commonly attributed to Francis Bacon in the 17th century, stemming from Aristotle in mid-300s BC.
2. <u>Persistence</u>: Edison's 1% inspiration and 99% perspiration.
3. <u>Good engineering</u>: Edison's protégé Charles Steinmetz once charged $1000 to GE for knowing which part to investigate on an electrical device, $1 for the chalk mark and $999 for knowing where to put it.

4. "Dumb luck"!



Source: "Beyond Probability, A pragmatic approach to uncertainty quantification in engineering," Scott Ferson, NASA Statistical Engineering Symposium, Williamsburg, Virginia, 4 May, 2011

The Beginning of Statistical Methods
Regression of happenstance data (1/2)



Regression analysis, invented in the late 19^{th} century by Francis Galton (pictured),* connects the responses (Y's) to the input factors (X's) via mathematical models of the form: $\hat{\mathbf{Y}} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \;.... + \beta_k X_k + \varepsilon$

where k is the number of factors and ε represents error.

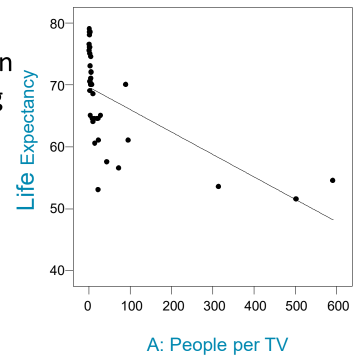
*"Regression towards mediocrity in hereditary stature," *The Journal of the Anthropological Institute of Great Britain and Ireland* (1886), 15: 246–263

> *"Engineers are quite comfortable these days - in fact, <u>far too comfortable</u> – with results from the blackest of black boxes: neural nets, genetic algorithms, data mining, and the like." [e.g., machine learning and, AI]*
>
> \- Russell Lenth (Professor of Statistics, University of Iowa)

The Beginning of Statistical Methods
Regression of happenstance data (2/2)

A Cal Poly stats prof observed* that life expectancy in various countries varies with the number of people per television (TV). This solves our problems replacing obsolete devices: Ship them to developing nations so these poor TV-deprived people can live longer! ;)

*Allan Rossman, "Televisions, Physicians, and Life Expectancy." *Journal of Statistics Education* 2, no. 2 (1994).



The Beginning of Statistical Methods
Simple comparative experiments

More than a century ago, William Sealy Gossett, a chemist at Guiness Brewery, developed a statistical method called the "t-test" to determine when the soft-resin content (desirable for stout) in hop flowers differed significantly from the brewery's standard.*

This is a simple comparative experiment on one factor at a time (OFAT). It is still widely used of sensory and other evaluations.

*(Published in 1908 under the pseudonym "Student".)

"He possessed a wickedly fertile imagination and more energy and focus than a St. Bernard in a snowstorm."
– Stephen Ziliak

A Very Small Dose of Stat Detail
One-factor comparison via t-tests

Legal judgment: Innocent until proven guilty.

Hypothesis test: Same until proven different.

H_0("null"): $\mu_1 = \mu_2$ (samples from same population)

H_1("alternative"): $\mu_1 \neq \mu_2$ (samples from different populations)

$$t = \frac{\bar{Y}_1 - \bar{Y}_2}{s_{\bar{Y}_1 - \bar{Y}_2}}$$

$$t = \frac{\text{difference between averages}}{\text{standard deviation of difference}}$$

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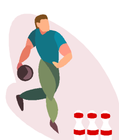
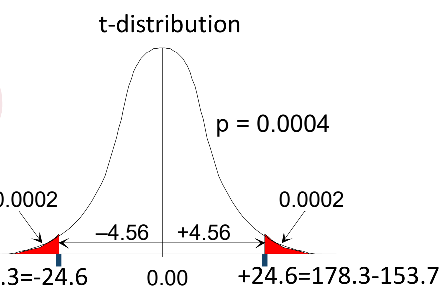
Comparisons via t-Test
Case study: Stat-Ease bowling contest





Run	Pat	Mark
1	160	165
2	150	180
3	140	170
4	167	185
5	157	195
6	148	175
Avg	153.7	178.3

t = 4.56 standard deviations between means, so by two-tailed test (Pat-Mark or Mark-Pat) p = 0.0004, thus with >99.9% confidence Mark is the better bowler. ☺

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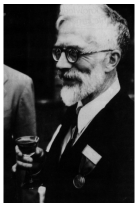
Fisher: Inventor of Modern-Day Statistics
and multilevel, multifactor experiment designs

"Personally, the writer prefers to set a low standard of significance at the 5 per cent point and ignore entirely all results which fail to reach this level. A scientific fact should be regarded as experimentally established only if a properly designed experiment rarely fails to give this level of significance."



-Sir Ronald Fisher
"The Arrangement of Field Experiments,"
The Journal of the Ministry of Agriculture, 1926, 33, 504.

Little known fact:
When Fisher invented DOE at Rothamsted Experimental Station in England, computations were done by 'calculators' – mathematical adepts, mainly female.

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Example of Fisher's pioneering work:
A randomized, replicated, blocked DOE (1/3)

In a landmark field trial on barley in Minnesota, agronomists guided by Fisher grew 5 varieties (M, S, V, T, P) at 5 ag stations in 1931 and 1932.
Which variety stands out? (Hint: See Graphs!)

Location	Year	M	S	V	T	P
1	1	81	105	120	110	98
	2	81	82	80	87	84
2	1	147	145	151	192	146
	2	100	116	112	148	108
3	1	82	77	78	131	90
	2	103	105	117	140	130
4	1	120	121	124	141	125
	2	99	62	96	126	76
5	1	99	89	69	89	104
	2	66	50	97	62	80
6	1	87	77	79	102	96
	2	68	67	67	92	94

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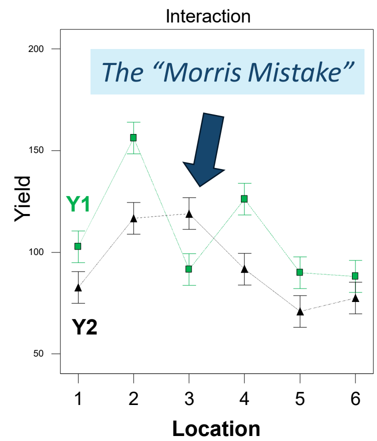
Example of Fisher's pioneering work:
A randomized, replicated, blocked DOE (2/3)

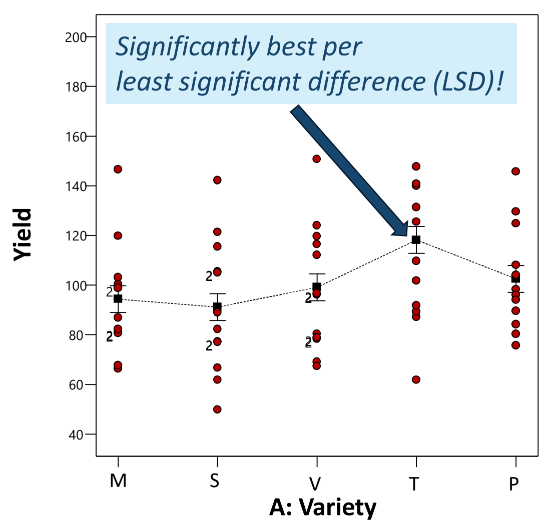
In a book called *Visualizing Data* (Hobart Press, 1993) William S. Cleveland suggests that the experimenters* reversed the numbers year-by-year in their report for location 3 (Morris, MN). It is hard to see in the raw data, but obvious when graphed with varieties averaged. The 'take home' message:
One picture = 1000 numbers!



*(Immer, et al, *Journal of Agronomy*, 26, 403-419, 1934).

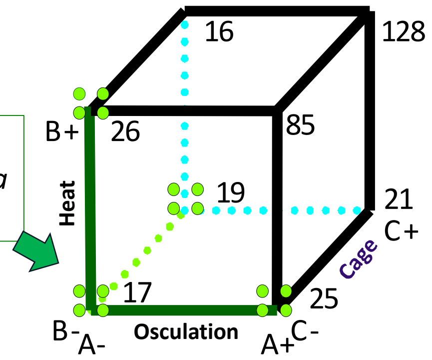
Example of Fisher's pioneering work:
A randomized, replicated, blocked DOE (3/3)

Key to Varieties:
- M: Manchuria
- S: Svansota
- V: Velvet
- T: Trebi
- P: Peatland



Two-Level Multi-Factorial (VS OFAT)
*Life from accelerated bearing test**

Start point for One Factor at a Time **(OFAT)**

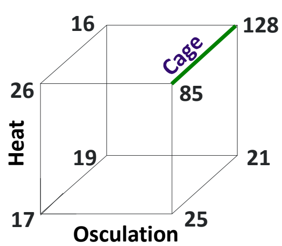


Relative efficiency = 16/8

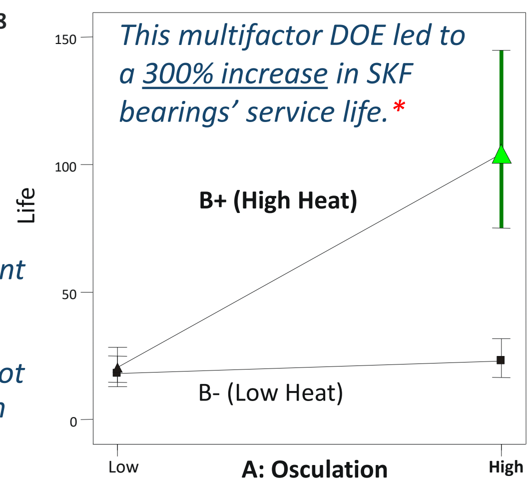
2 to 1!

*Hellstrand, C., "The necessity of modern quality improvement and some experience with its implementation in the manufacture of rolling bearings", *Philosophical Transactions of the Royal Society of London A* 327, 529-537, 1989.

Interaction Plot
The happy ending!



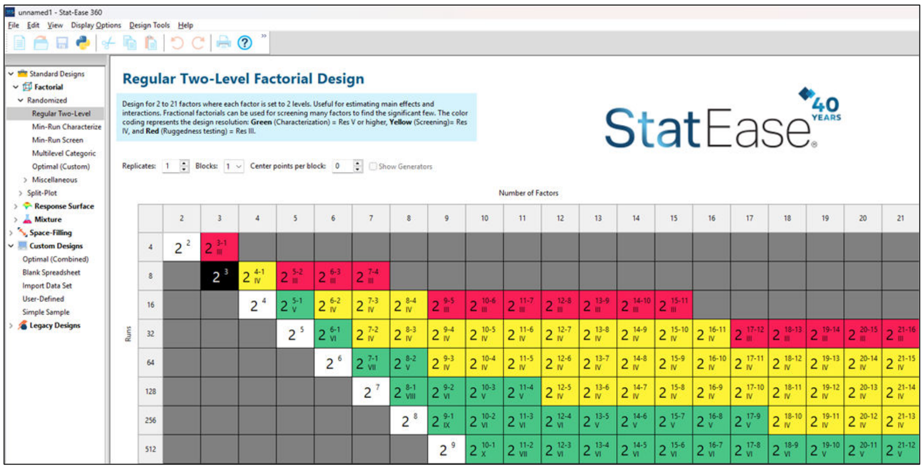
PS: The least significant difference (LSD) bar widens at high-life setting. Thus, Cage not significant. But worth changing to plastic!



* "Breaking the Boundaries," *Design Engineering*, Feb 2000, pp 37-38.

Standard Two-Level Designs (2^{k-p})

Refined from Fisher, 1935, "The Design of Experiments"



Minimum-Run Designs (up to 50 factors)

Considerable savings over standard fractions

Characterization

Factors	Std Res V	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

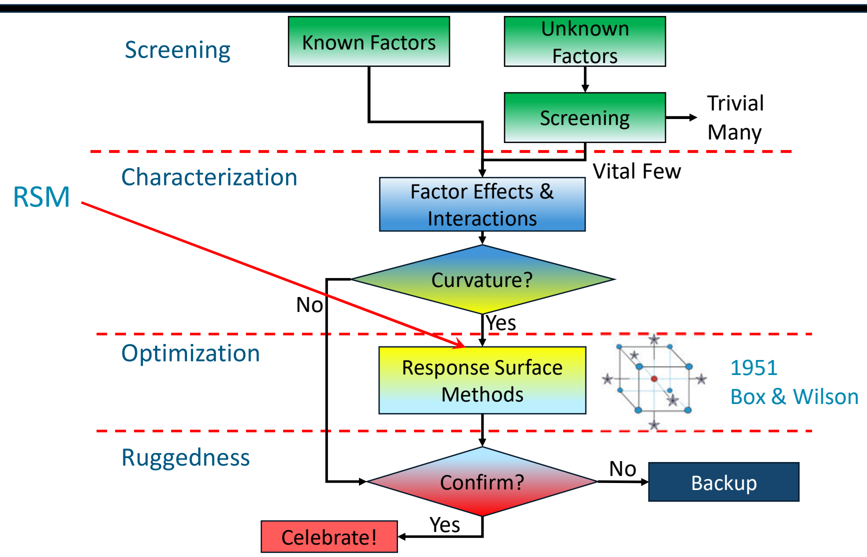
Factors	Std Res IV	MR4**
9	32	18
10	32	20
11	32	22
12	32	24
13	32	26
14	32	28
15	32	24
16	32	26
17	64	28

* Oehlert & Whitcomb, "Small, Efficient, Equireplicated Resolution V Fractions of 2^k designs …", Fall Technical Conference, 2002.

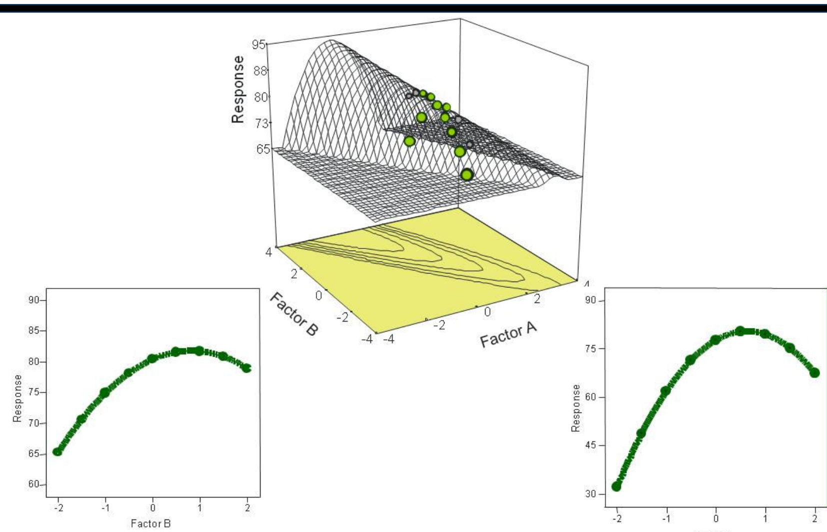
** Anderson & Whitcomb, "Screening Process Factors In the Presence of Interactions," Annual Quality Congress, American Society of Quality, Toronto, 2004.

Strategy of Experimentation—1950s to Now

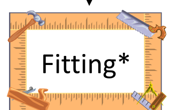
Process development—Imperial Chem, DuPont, G Mills…



Multifactor RSM vs OFAT



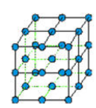
RSM: Flowchart

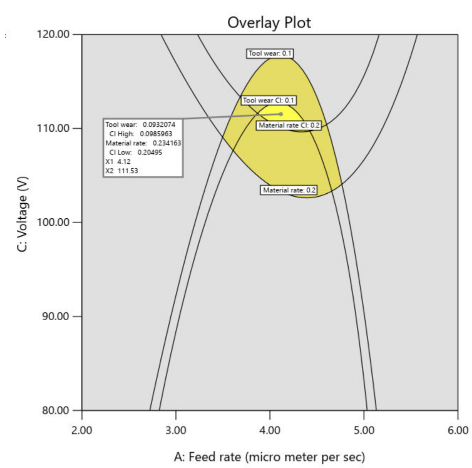
Subject Matter Knowledge
(Plus, Factorial Screening)
↓
Vital Few Factors (x's)
↓
Process → Measured Response(s) (y(s))
↓


↓
Polynomial Model
↓
Response Surface

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

Multiple Response Optimization
Robust Electrodischarge milling (EDM)





Goals: At highest feed rate and lowest voltage, minimize tool wear ideally to 0.05 but no more than 0.1; and maximize material rate to 0.2 or more, ideally to 0.4. Search for a robust sweet spot.

V25.0

Milling
Rebuild, re-open.
Skip diagnostics tool wear.
Show Perturbation. 2D, 3D.
Do diagnostics for material rate.
Show Perturbation. 2D, 3D.
Optimize—note goals on factors.
Overlay A vs C with CI's.

"Numerical optimization via desirability investigation of machining parameters for the multiple-response optimization of micro electrodischarge milling," Mehfuz & Ali, *International Journal of Advanced Manufacturing Technology* (2009) 43:264–275

Conclusion

➢Trim out the OFAT!

By making use of multifactor design of experiments (DOE) starting with simple two-level factorials and graduating to response surface methods (RSM) for processes, you will greatly accelerate product development and process optimization. We've come a long way!

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Stat-Ease Training: *Sharpen Up Your DOE Skills*

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Via lessons learned from
"Milestones to Modern DOE for Rapid Manufacturing Improvement"

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Please email questions!

Let's connect!