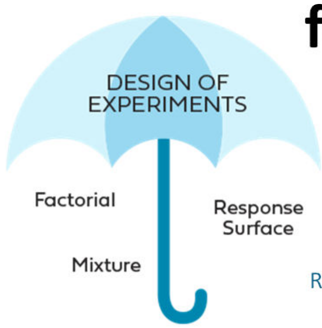
StatEase
statistics made easy
Make the most from every experiment!

DOE Crash Course for Experimenters



Richard Williams, BSChE, MSM, Six Sigma MBB
stathelp@statease.com

February 2024

Making the most of this learning opportunity

Hide the Control Panel
Mute your line

To prevent audio disruptions, all attendees will be muted.

Questions can be posted in the Question area, and I'll make every effort to address them during our brief one-hour webinar.

Questions may also be sent to stathelp@statease.com. Please provide your company name and, if you are using Design-Expert, the serial number (found under Help, About).

Note: The slides and a previous recording of this webinar is posted on the Webinars page of the Stat-Ease website for your review.

Stat-Ease, Inc.

Design of Experiments Software and Training
www.statease.com

StatEase 360
DESIGN EXPERT

STAT-EASE ACADEMY

YouTube Statistics Made Easy by Stat-Ease
@StatisticsMadeEasybyStatEase

Crash Course in DOE 3

Stat-Ease Training:
Sharpen Up Your DOE Skills

Modern DOE for Process Optimization

Mixture Design for Optimal Formulations

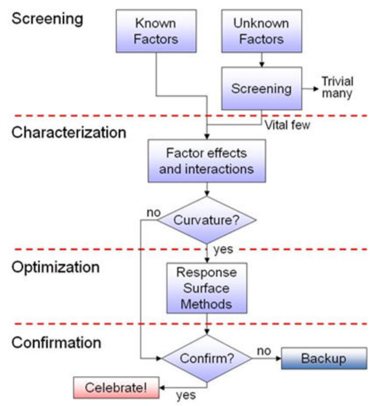
Individuals	Teams (6+ people)
Improve your DOE skills	Choose your date & time
Topics applicable to both novice and advanced practitioners	Add company case studies

Email list sign up:
www.statease.com/publications/signup/

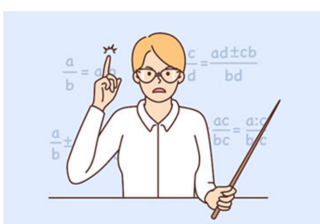
Crash Course in DOE 4

Agenda

- **What is DOE?**
- Two-level Factorial Designs
- Case Study – Filtration Rate
- Wrap Up

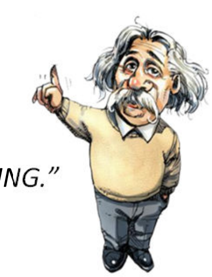


Traditional Experimentation (OFAT)



"You can't learn ANYTHING if you change more than one thing at a time."

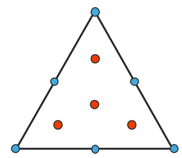
"Correct! Instead, you'll learn ALMOST EVERYTHING."

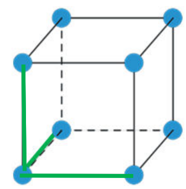


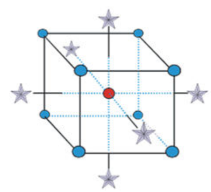
Designed Experimentation

Organize and create a multi-factor statistical test plan that will provide information about many things all at once!
Maximum information → minimum runs!

Std	A	B	C
1	–	–	–
2	+	–	–
3	–	+	–
4	+	+	–

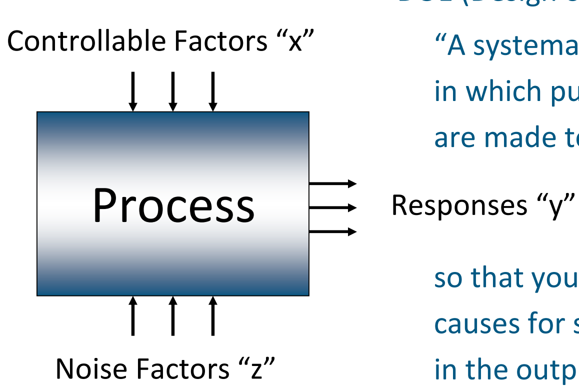






Crash Course in DOE 7

Design of Experiments



DOE (Design of Experiments) is:

"A systematic series of tests, in which purposeful changes are made to input factors, so that you may identify causes for significant changes in the output responses."

Crash Course in DOE 8

DOE Process Vocabulary

Controllable factors (X)– input variables that can be changed during the experiment (may be numeric or categoric)
(time, temperature, vendor)

Responses (Y) – measurable (numeric) outputs of the process *(yield, tensile strength, efficacy of drug)*

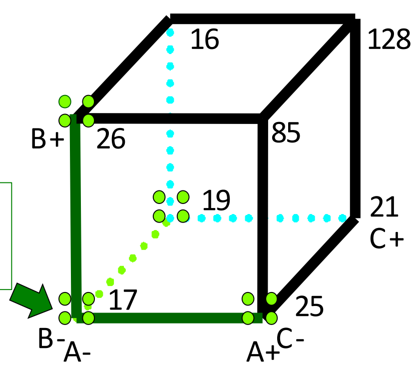
Uncontrollable factors (Z) – variables that may fluctuate during the experiment – including the measurement system
(humidity, ambient temperature, chemical degradation)

Z goes by different names*: Noise, Error, Residual*

The Experimenter's Role – Identify factors (**X**'s), whose impact on the responses (**Y**'s) exceeds what would be expected given the noise (**Z**) in the system

Multi-Factorial (VS OFAT)
(bearing life from accelerated test)

Start point for One Factor at a Time (OFAT)



Relative efficiency = 16/8

⇨ 2 to 1!

"To make knowledge work productive will be the great management task of this century."
-- Peter Drucker

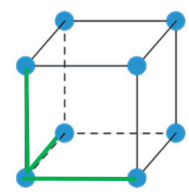
DOE versus OFAT Summary

Traditional Approach to Experimentation

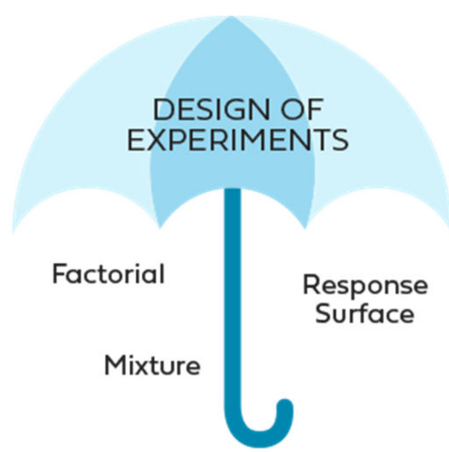
- Study one factor at a time (OFAT), holding all other factors constant
- Simple process, but doesn't account for interactions
- It is inefficient (serial processing)

Factorial Design

- Study multiple factors changing at once (parallel processing)
- Accounts for interactions between variables
- Maximizes information with minimum runs



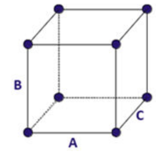
Types of Designed Experiments (DOE)



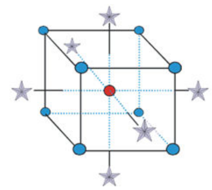
For an overview, see my webinar - *New-User Intro to Design-Expert Software*

Types of DOE's

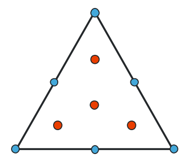
Factorial – Learn about main effects and interactions for either a screening or characterization study. Two levels for each factor minimizes work and maximizes information.



Response surface – Build quadratic (or higher-order) polynomials to model non-linear factor-response relationships. Three+ levels for factors requires more runs but provides more information.



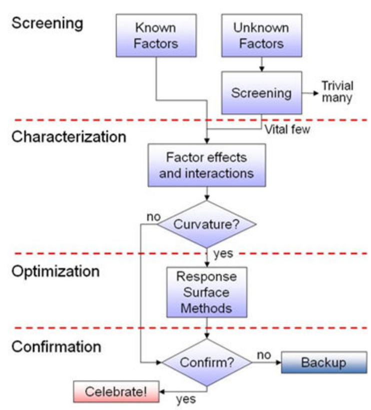
Mixture* – Model formulations where the responses are dependent on the proportions of the mixture components. Required to properly model the dependencies between the components.



**Recorded Webinar – Crash Course in Mixture DOE*

Agenda

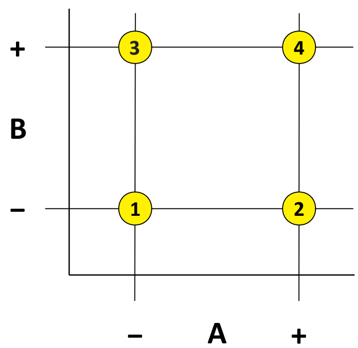
- What is DOE?
- **Two-level Factorial Designs**
- Case Study – Filtration Rate
- Wrap Up



Two-Level Full Factorial Design

Run all high/low combinations of 2 (or more) factors

Use statistics to identify the critical factors

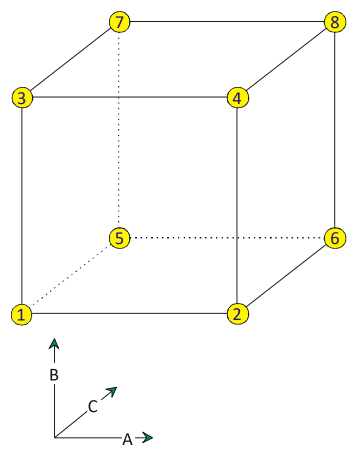


2^2 Full Factorial

$$\text{Effect}(\Delta y) = \frac{\sum y_+}{n_+} - \frac{\sum y_-}{n_-}$$

What could be simpler?

Design Construction
2^3 Full Factorial



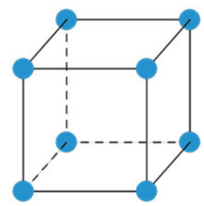
Std	A	B	C	AB	AC	BC	ABC	
1	–	–	–	+	+	+	–	y_1
2	+	–	–	–	–	+	+	y_2
3	–	+	–	–	+	–	+	y_3
4	+	+	–	+	–	–	–	y_4
5	–	–	+	+	–	–	+	y_5
6	+	–	+	–	+	–	–	y_6
7	–	+	+	–	–	+	–	y_7
8	+	+	+	+	+	+	+	y_8

8 runs → 7 independent effects + average

3 Main effects, 4 interaction effects

2^k Factorial Design
Advantages

- Simple structure.
- Minimal runs required. *Can run fractional designs.*
- Have hidden replication. *More power than OFAT.*
- Tests more combinations than OFAT experiments.
- Reveal interactions. *Key to new discoveries!*
- Easy to analyze.
- Interpretation is not difficult. *Graphs make it easy.*
- Form base for more complex designs.
  Second order response surface method (RSM) design.



Two-Level Factorials in Stat-Ease software

Color-coded DX/SE360 selection grid for two-level designs:

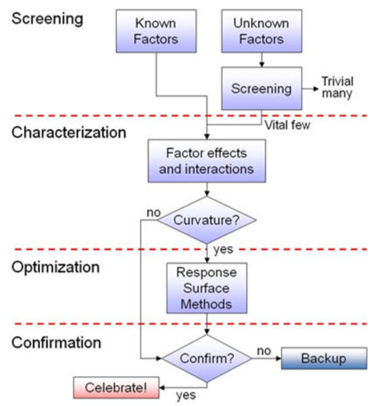
- **Green** (Go) – main effects and two-factor interactions (2FI)
- **Yellow** (Caution) – clean main effects, not biased by hidden 2FI
- **Red** (Stop) – no clean effects, biased if hidden 2FI exist

Number of Factors

Runs	2	3	4	5	6	7	8	9	10	11	12	13	14
4	2^2	2^{3-1}_{III}											
8		2^3	2^{4-1}_{IV}	2^{5-2}_{III}	2^{6-3}_{III}	2^{7-4}_{III}							
16			2^4	2^{5-1}_{V}	2^{6-2}_{IV}	2^{7-3}_{IV}	2^{8-4}_{IV}	2^{9-5}_{III}	2^{10-6}_{III}	2^{11-7}_{III}	2^{12-8}_{III}	2^{13-9}_{III}	2^{14-10}_{III}
32				2^5	2^{6-1}_{VI}	2^{7-2}_{IV}	2^{8-3}_{IV}	2^{9-4}_{IV}	2^{10-5}_{IV}	2^{11-6}_{IV}	2^{12-7}_{IV}	2^{13-8}_{IV}	2^{14-9}_{IV}
64					2^6	2^{7-1}_{VII}	2^{8-2}_{V}	2^{9-3}_{IV}	2^{10-4}_{IV}	2^{11-5}_{IV}	2^{12-6}_{IV}	2^{13-7}_{IV}	2^{14-8}_{IV}
128						2^7	2^{8-1}_{VIII}	2^{9-2}_{VI}	2^{10-3}_{V}	2^{11-4}_{V}	2^{12-5}_{IV}	2^{13-6}_{IV}	2^{14-7}_{IV}
256							2^8	2^{9-1}_{IX}	2^{10-2}_{VI}	2^{11-3}_{VI}	2^{12-4}_{VI}	2^{13-5}_{V}	2^{14-6}_{V}

Agenda

- What is DOE?
- Two-level Factorial Designs
- **Case Study – Filtration Rate**
- Wrap Up



Filtration Rate

DX Help, Tutorials: Two-Level Factorial – Filtration Rate

This case study comes from DOE guru Doug Montgomery.* It stems from a troubleshooting job he did for a manufacturer of waferboard that went into mobile homes.

Excess formaldehyde in the glue causes an odor problem (not to mention a potential health hazard). During the filtering of the glue, formaldehyde must be added to maintain production rate.

Something must be done!

Goal: Find process conditions that reduce the concentration of formaldehyde while maintaining a high filtration rate.

Filtration Rate

Build the Design *(page 1 of 2)*

1. Choose **4** factors in **16** runs, a 2^4 full factorial.
2. Enter the factor names and levels:

	Name	Units	Type	Low	High
A [Numeric]	Temperature	Deg C	Numeric	24	35
B [Numeric]	Pressure	Psig	Numeric	10	15
C [Numeric]	Concentration	Percent	Numeric	2	4
D [Numeric]	Stir Rate	Rpm	Numeric	15	30

Filtration Rate

Build the Design *(page 2 of 2)*

3. Enter the response name, units, Δ (delta), and σ (sigma). Then the program calculates the Δ/σ of 2.

Name	Units	Diff. to detect Delta ("Signal")	Est. Std. Dev. Sigma ("Noise")	Delta/Sigma (Signal/Noise Ratio)
Filtration Rate	gallons/hr	10	5	2

Continue to the power report>>

Name	Units	Delta (Signal)	Sigma (Noise)	Signal/Noise	Power for A	Power for B	Power for C
Filtration Rate	gallons/hr	10	5	2	**95.3%**	**95.3%**	**95.3%**

Finish

Filtration Rate

Analyze Results – *Help, Tutorial Data – Filtration Rate*

	Random	Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	**Run**	**A:Temperature**	**B:Pressure**	**C:Concentration**	**D:Stir Rate**	**Filtration Rate**
		deg C	psig	percent	rpm	gallons/hr
11	1	24	15	2	30	45
9	2	24	10	2	30	43
12	3	35	15	2	30	104
13	4	24	10	4	30	75
15	5	24	15	4	30	70
14	6	35	10	4	30	86
2	7	35	10	2	15	71
3	8	24	15	2	15	48
7	9	24	15	4	15	80
10	10	35	10	2	30	100
8	11	35	15	4	15	65
1	12	24	10	2	15	45
4	13	35	15	2	15	65
6	14	35	10	4	15	60
16	15	35	15	4	30	96
5	16	24	10	4	15	68

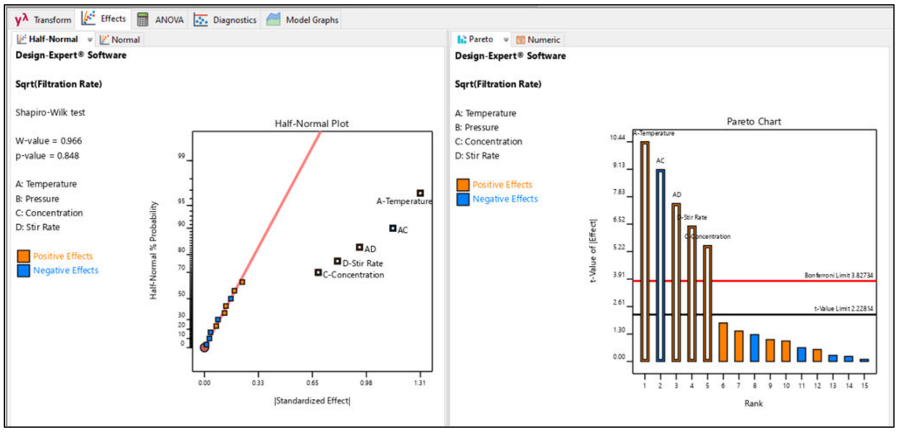
Filtration Rate

Analyze Results

Analysis Guide

1. Effects – use the half-normal plot and Pareto chart to choose the significant effects – only those that “jump off” the line.
2. ANOVA – review the p-values for significance (<0.05) and other statistical measures as appropriate
3. Diagnostics – confirm that there is no “signal” left in the residuals
4. Model Graphs – draw pictures IF you have a significant model with good diagnostics

Filtration Rate
Effects - Half Normal Plot & Pareto



Select <u>only</u> largest effects (jump off the line to the right).

Filtration Rate
ANOVA – look for significant p-values

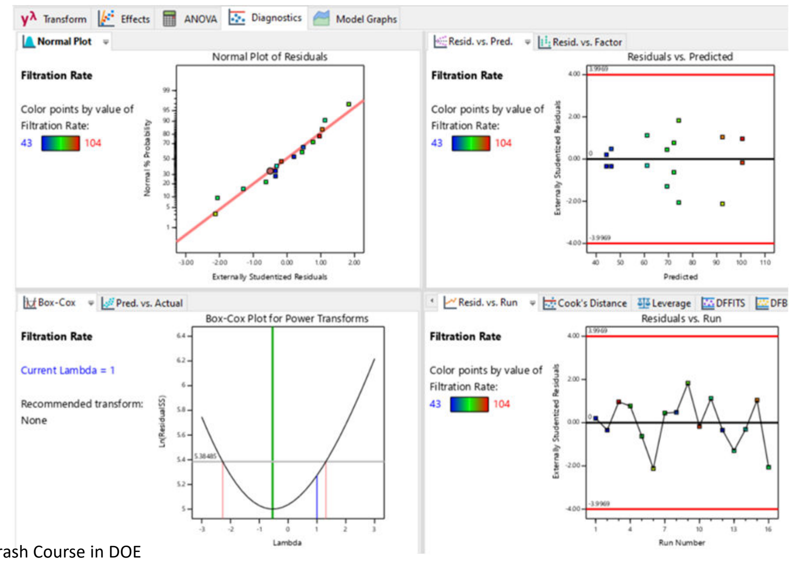
ANOVA for selected factorial model

Response 1: Filtration Rate

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5535.81	5	1107.16	56.74	< 0.0001	significant
A-Temperature	1870.56	1	1870.56	95.86	< 0.0001	
C-Concentration	390.06	1	390.06	19.99	0.0012	
D-Stir Rate	855.56	1	855.56	43.85	< 0.0001	
AC	1314.06	1	1314.06	67.34	< 0.0001	
AD	1105.56	1	1105.56	56.66	< 0.0001	
Residual	195.13	10	19.51			
Cor Total	5730.94	15				

Model should only include significant effects, plus those needed to maintain hierarchy.

Filtration Rate
Diagnostics – used to Validate ANOVA, detect outliers



DOE Graph Vocabulary

Main Effect – the amount of linear change in the response when the factor is changed from its low to high setting

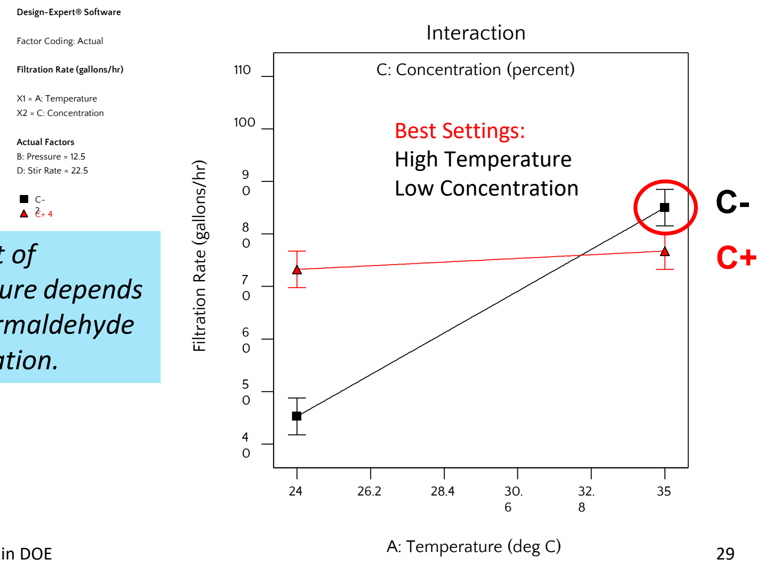
Interaction – a special relationship where the response value at one factor setting is dependent on another factor setting

Contour – a contour plot is like a topographical map that shows the values of the response as “contour lines”

3D Surface – provides a 3D view of the contour plot showing 2 factors and the response

Filtration Rate

Model Graphs – Interaction Plot (AC – Temp x Conc)

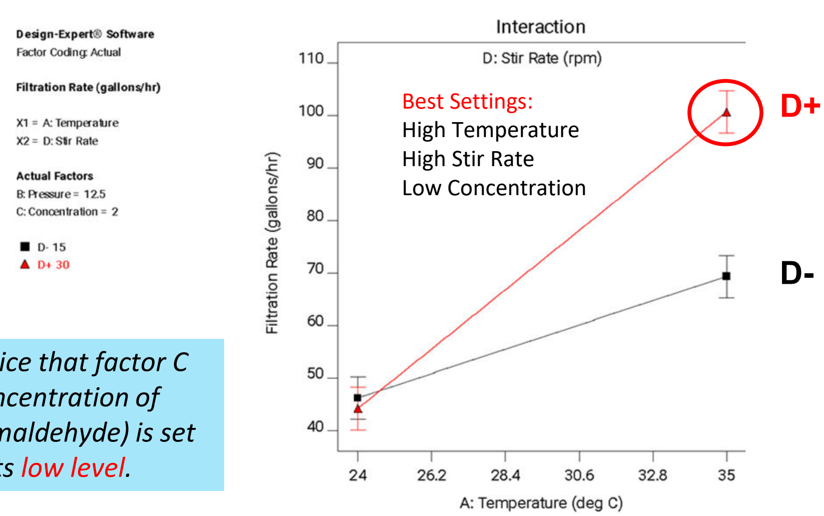


The effect of temperature depends on the formaldehyde concentration.

Crash Course in DOE 29

Filtration Rate

Model Graphs – Interaction Plot (AD – Temp x Stir Rate)



Notice that factor C (concentration of formaldehyde) is set to its low level.

Crash Course in DOE 30

Filtration Rate
Key Discovery

OFAT – *Rejected Temperature* as a factor to consider because at the original 4% concentration, there was NO temperature effect!

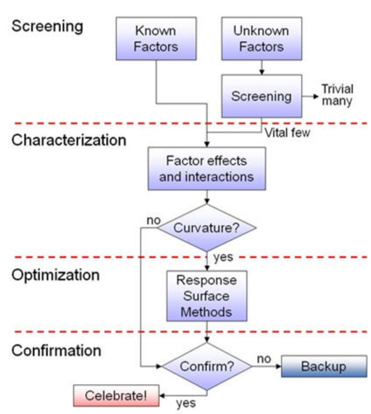
Factorial DOE – Discovers that Temperature has a significant interaction with both Concentration and Stir Rate. A new maximum Filtration Rate can be achieved with:

- Low Formaldehyde Concentration
- High Temperature
- High Stir Rate

DOE Success!!

Agenda

- What is DOE?
- Two-level Factorial Designs
- Case Study – Filtration Rate
- **Wrap Up**



Wrap Up

- **Trim out the OFAT!**
  Accelerate product development and process optimization with
  - Factorial design for detecting effects
  - Response surface design for optimization
  - Mixture design for formulations
- **Stat-Ease® 360 and Design-Expert® software make DOE easy, yet powerful.**
  Dedicated DOE programs—far better than a general stats package. Intuitive with user-friendly guidance.

STAT-EASE 360 DESIGNEXPERT

Learn DOE on Stat-Ease website or YouTube

Stat-Ease Webinars: www.statease.com/webinars/

New-User Intro to Design-Expert Software – on demand

Learn about factorial design, the core tool for DOE, followed by a peek at response surface methods (RSM) for process optimization and last, but not least, a look into mixture design for optimal formulation.

Know the SCOR for Multifactor Experimentation – on demand

Follow this case study that lays out a strategy for design of experiments (DOE) that provides maximum efficiency and effectiveness for development of a robust process.

Self-study options for learning more

YouTube Channel: www.youtube.com/c/StatisticsMadeEasybyStatEase

New to DOE? Resources for Experimenters

A collection of webinars on basic to intermediate-level topics.

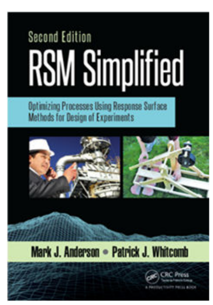
Stat-Ease Academy: www.statease.com/training/academy/

Self-paced online courses covering the basics of factorial and fractional-factorial designs.

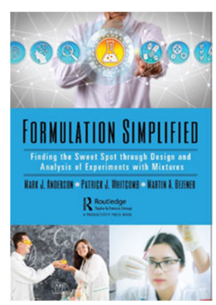
Awesome Texts – available online*

3rd edition 2015

2nd edition 2016



1st edition 2018



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

StatEase
statistics made easy

Make the most from every experiment!℠

DOE Questions? Email Stathelp@statease.com

Sales Questions? Email Sales@statease.com