Should Introductory Statistics Classes Include Multifactor Statistical Design of Experiments (DoE)?

## USCOTS 2021 Tuesday, June 29th 3:00-3:45pm ET

## David Fluharty

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# Should Introductory Statistics Classes Include DoE?

• Discussion in a Beyond Session at USCOTS 2021 Tuesday, June 29th 3:00-3:45pm ET

 To Continue the Discussion and Possibly Form an "Early DoE" Community, Please Email me at fluharty.earlydoe@gmail.com

# Dave Fluharty

- Adjunct Professor of Statistics and Economics, Ivy Tech Community College—Columbus Indiana
- In 2020 completed 4 decades in motor vehicle industry working in statistics, forecasting, finance, economics, reliability, and training
- PhD, Educational Evaluation and Research, Wayne State University
- MA, International Relations, University of Chicago
- MBA, Business Economics and Finance, Booth School of Business, University of Chicago

## Use Slide Show Mode

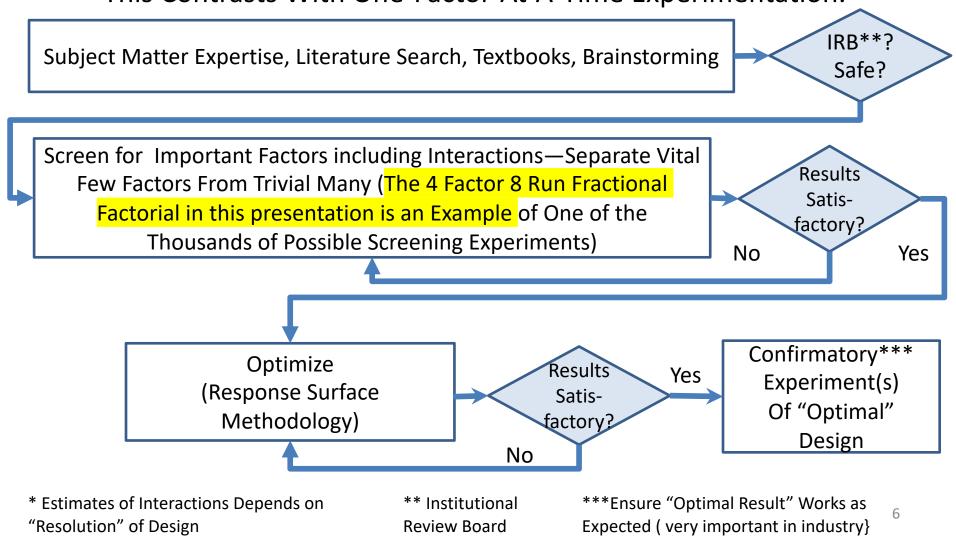
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A Proposal for Inclusion on Multifactor Statistical Design of		
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3 Proposi Subalite tor incluion in the read revision of the Statement of A conserved and restruction in Statistics Resardion (04.00) Report of Part Contenue		
<ul> <li>Before graduation, every high school student should at least see a demonstration—and preferably participate in the planning, execution, and analysis—of a simplified</li> </ul>		
execution, and analysis - of a simplified Multifactor series of Statistically Design of Experiment [DoG]. * For example, the B-run experiment described		
<ul> <li>For example, the Brun experiment described in the PowerPointmight be done in astitute as one or two class periods.</li> </ul>		
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DoE In High Schools		
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Many of us where taught that the best way to do     scientific experimentation is to change one and		
<ul> <li>Many of us where taught that the best way to do scientific experimentation is to change one and only one thing at a form while holding everything site content.</li> <li>Exerctions called DTAT (give Exerce at &amp; Tm)</li> </ul>		4:43 PM
<ul> <li>Over the set century the statistical science has developed a more efficient and insightful because).</li> </ul>		
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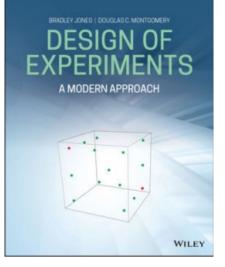
# Abraham Lincoln and the Invention of Invention

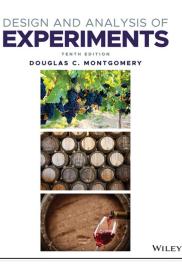
• Man is not the only animal who labors; but he is the only one who *improves* his workmanship. This improvement, he effects by *Discoveries*, and Inventions... Now, it was the destined work of Adam's race to develop, by discoveries, inventions, and improvements, the hidden treasures of this mine. But Adam had nothing to turn his attention to the work. If he should do anything in the way of invention, he had first to invent the art of invention -- the instance at least, if not the *habit* of observation and reflection.

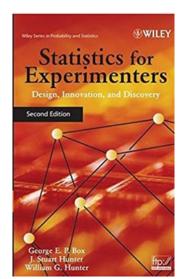
Abraham Lincoln, "Lecture on Discoveries and Inventions," Various Illinois Locations, 1858 – 1859 DoE Is an Art and Science that Helps Us Investigate the Effects of Multiple Factors (Including Interactions\*) by **SIMULTANEOUSLY** Varying These Factors According to a Mathematically/Statistically **FIXED** Set of Recipes. Results Include Predictive Equations and Possibly Optimization. This Contrasts With One-Factor-At-A-Time Experimentation.

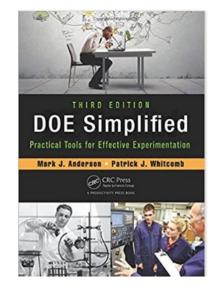


# Many People Who Learn DoE Learn it in a Graduate Level Course or 3-5 Day Seminar









## Why Introduce DoE in Introductory Statistics?

- Why (Educational/Cognitive):
  - Multi Causal Systems (Understanding Needed in Science and Society)
  - Process of Scientific Discovery
    - Iterative
    - Discovery Vs. Demonstrative
    - Discuss Engineering Trade-Offs
  - Omnipresence of Variation
  - Interactions, Predictive Equations, and Optimization
  - Randomization
  - Statistical vs. Practical Significance (if Use Software)
  - Efficiency vs. One-Factor-At-A Time
  - Use of Statistical Graphics
  - Used Business and Industry
    - Manufacturing (Six Sigma Programs)
    - Marketing Experiments
- Pedagogy/Andragogy
  - Cognitive Domain
  - Psychomotor Domain
  - Affective Domain
    - For the Paper Helicopter Example, Model of Autorotation (Flight Time) if Engine Fails



The Flight time of 8 Different Paper\* Helicopter Designs:

- Not Just a Toy
- A Model of <u>Autorotation</u> (you want this to be as long as possible—how long you stay in the air if the engine fails

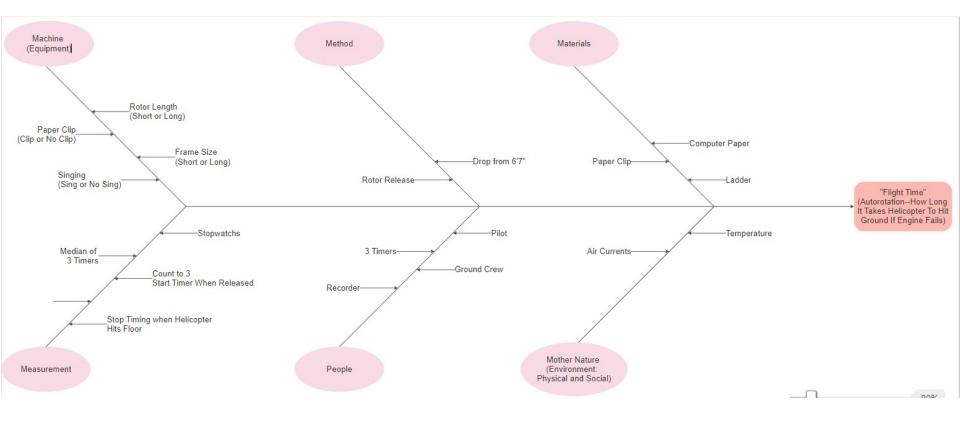
Photo curtesy of Mark Anderson of Stat-Ease

#### Also see

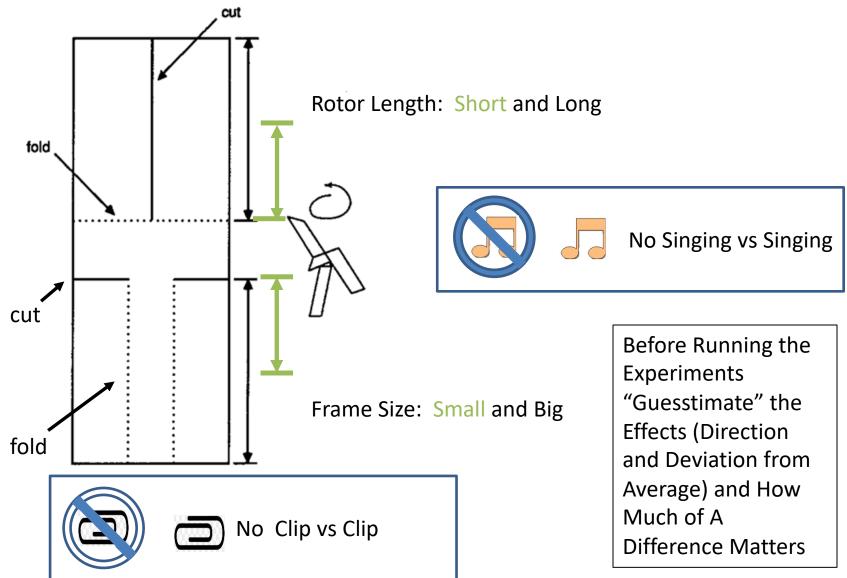
https://www.statease.com/publications/newsl etter/stat-teaser-03-15

\*Paper Helicopter Were Popularized As a DoE Educational Tool by G.E.P.Box (Fisher's Son-In-Law)

# Fishbone Diagram (Brainstorming)



We Investigate 4 Factors That <u>*Might*</u> Impact Flight Time: Rotor Length (Long vs. Short), Frame Size (Big vs. Small), Paper Clip (No Clip vs. Clip), Singing (No Singing vs. Singing)



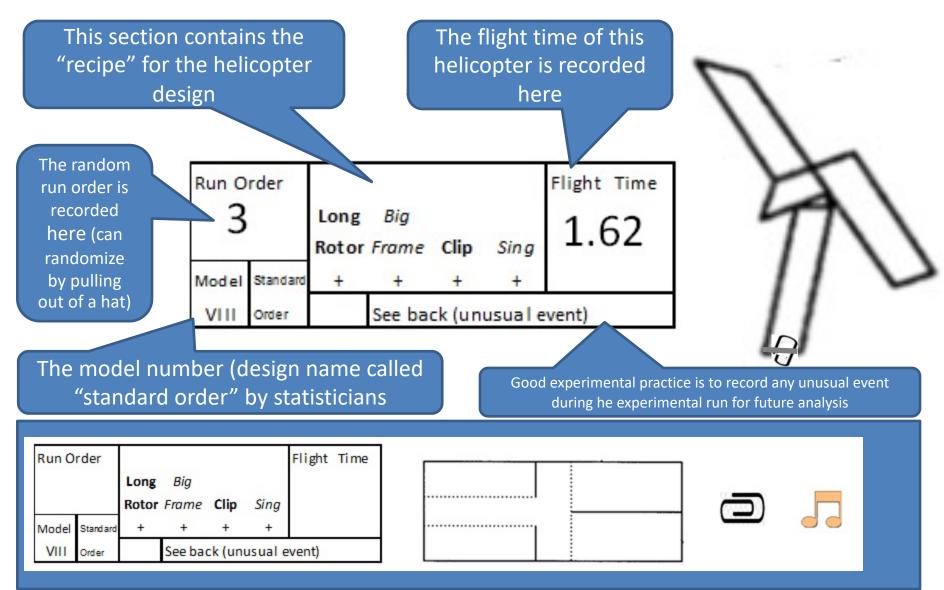
### A Statistically Determined <u>Fixed Set</u> of 4 Factor 8 "Run" (Each a Different Helicopter Design) Used In This DoE Example (There are Thousands of Other Possible Designs)

Model	Rotor I	Frame			"Standard	
<u>Name</u>	<u>Length</u>	<u>Size</u>	<u>Clip</u>	<u>Singing</u>	Order"	Convention Used Here:
I	Short	Small	No Clip	No Sing		"Diggor" or "Drocopt" is a ""
Ш	Long	Small	No Clip	Sing	++	"Bigger" or "Present" is a "+"
111	Short	Big	No Clip	Sing	- + - +	"Smaller" or "Absent" is a "-"
IV	Long	Big	No Clip	No Sing	+ +	
V	Short	Small	Clip	Sing	++	
VI	Long	Small	Clip	No Sing	+-+-	
VII	Short	Big	Clip	No Sing	- + + -	
VIII	Long	Big	Clip	Sing	+ + + +	Beautiful Geometry!

## Why This Works—Matrix Algebra

	Rotor   <u>Length</u>		<u>Clip</u>	<u>Singing</u>	"Standard Order"	
I	Short	Small	No Clip	No Sing	-1 -1 -1 -1	Put a "1" with every "+" and "-"
II	Long	Small	No Clip	Sing	+1 -1 -1 +1	When Multiply the Rows, the Sum (Dot
111	Short	Big	No Clip	Sing	-1 +1 -1 +1	Product) is Zero→ These are Orthogonal
IV	Long	Big	No Clip	No Sing	+1 +1 -1 -1	Vectors
V	Short	Small	Clip	Sing	-1 -1 +1 +1	
VI	Long	Small	Clip	No Sing	+1 -1 +1 -1	
VII	Short	Big	Clip	No Sing	-1 +1 +1 -1	
VIII	Long	Big	Clip	Sing	+1 +1 +1 +1	
				The "Sir	nging" Column is the produce columns. For example, for +1 x +1 x +1 = -	or Model VIII:

## There is One Recipe Card Corresponding to Each of the Helicopter Designs: Example of Design VIII



## Helicopter Designs I through IV

Run Order						Flight	Time
		Short	Small	No	No		
		Rotor	Frame	Clip	Sing		
Model	Standard	-	-	-	-		
Ι	Order		See ba	vent)			

:
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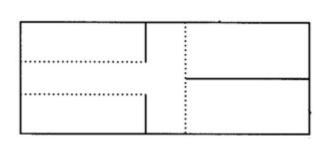
Run Order						Flight	Time
		_	Small				
		Rotor	Frame	Clip	Sing		
Model	Standard	+	-	-	+		
П	Order		See bad	vent)			

<u> </u>	
1	



Run O	rder					Flight	Time
		Short Rotor	Big Frame	No Clip	Sing		
Model	Standard	-	+	-	+		
111	Order		See ba	event)			

ſ	Run Order						Flight	Time
			Long	Big Frame	No	No		
			Rotor	Frame	Clip	Sing		
	Model	Standard	+	+	-	-		
	IV	Order		See ba	vent)			





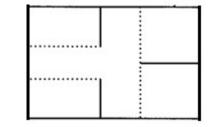
## Helicopter Designs V through VIII

Run Order						Flight	Time
		Short	Small				
		Rotor	Frame	Clip	Sing		
Model	Standard	-	-	+	+		
V	Order		See ba	ck (un	usual e	vent)	

Run Order						Flight	Time
		Long Rotor	Small Frame	Clip	No Sing		
Model	Standard	+	-	+	-		
VI	Order		See ba	vent)			

Run O	rder					Flight	Time
		Short	Big		No		
		Rotor	Frame	Clip	Sing		
Model	Standard	-	+	+	-		
VII	Order		See bad	ck (uni	usual e	vent)	

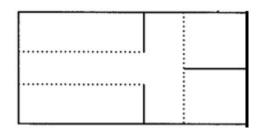
Run O	rder					Flight	Time
		Long	Big				
	-	Rotor	Frame	Clip	Sing		
Model	Standard	+	+	+	+		
VIII	Order		See bao	ck (uni	usual e	vent)	











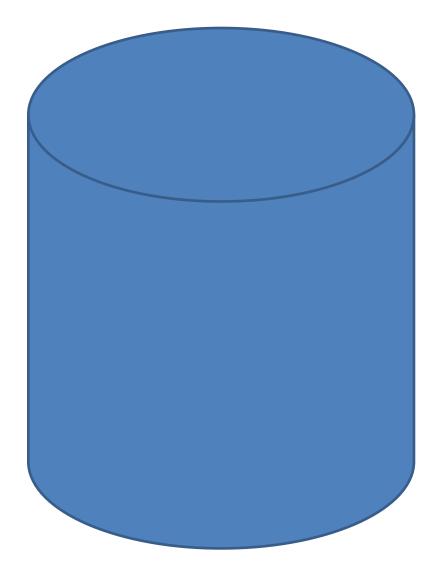
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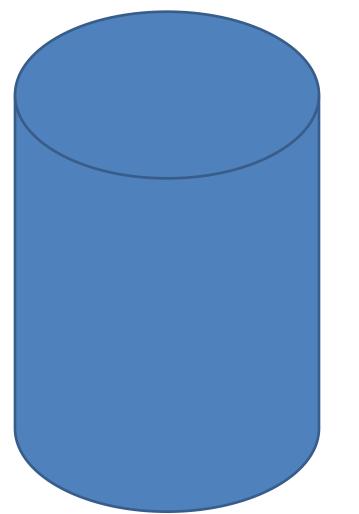
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#### One way to randomize (Accesses the Psychomotor Domain): Put each recipe card in a container

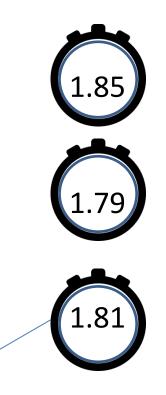
Run C	Inder	1	Flight Time
		Short Small No No	
		Rotor Frame Clip Sing	
/edel	Stards	d	
1	Order	See back (unusual e	event)
un O	rder		Flight Time
		Long Small No	
		Rotor Frame Clip Sing	
e de l	Stardard		
	Order	See back (unusual e	(ant)
-			
	rder		Flight Time
unc	rder	Short B/g No	Hight time
		Rotor Frame Clip Sing	
-	Stardar		
	Order		-
ш	Crow.	See back (unus ual e	event)
un O	rder		Flight Time
		Long Big No No	
_		Rotor Frame Clip Sing	
te de l	Stardar	+ +	
IV	Order	See back (unusual e	(vent)
_			
un O	rder		Flight Time
		Short Small	
		Rotor Frame Clip Sing	
a de l	Sarciaro		
v	Order	See back unusual e	rentj
n Or	der		Flight Time
		Long Small No	
		Long Small No Rotor Frame Clip Sing	
del	Randard	+ - + -	
	Order	See back (unus vali ev	enti
			- 1
_	_		
in Or	der		light Time
		Short Big No	25 AL
_		Rotor Frame Clip Sing	
del	Randard	· + + ·	
11	Order	See back (unus val ev	entj
in Or	der	F	light Time
n Or	der	Long Big	light Time
	der	2.2.1.1.1.1.1.1.1.1.1.1.1.1.1.1.1.1.1.1	light Time

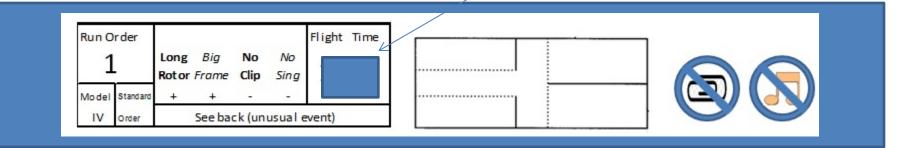


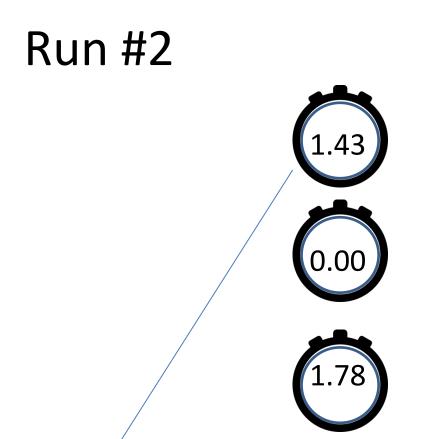
Draw a "Recipe Card" Write the Order Drawn on The Card Stir and Repeat Until All Recipe Cards Are Drawn Run the Experiments In This Order

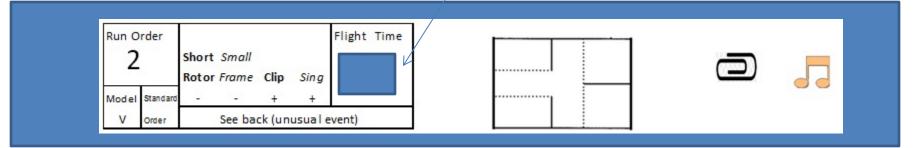


## Run #1

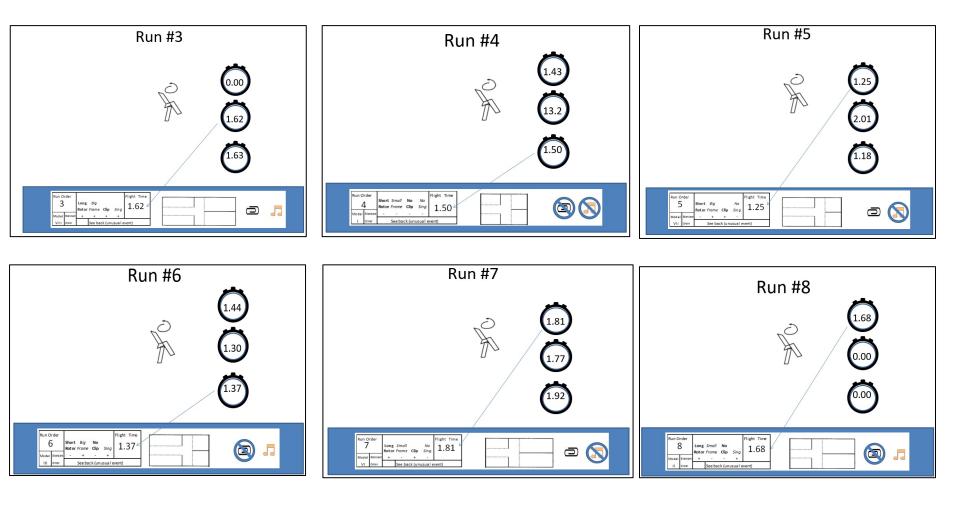








## Repeat for Runs 3-8 Remember: Each Is a Different Helicopter Design



## Put "Recipe Cards" In Standard Order Calculate the Grand Average

Nun Orde	FIGHT TIME
4	Short Small No No Rotor Frame Clip Sing 1.50
Medel Star	LSU I.SU
1 Orde	
Run Order	Flight Time
8	Long Small No
	Rotor Frame Clip Sing 1.68
Model Stard	30 + +
II Order	See back (unus ual event)
Run Order	
6	Short B/g No 1.27
	Rotor Frame Clip Sing 1.37
Medel Stat	
III Orde	See back (unus ual event)
Run Order	
1	Long Big No No Rotor Frame Clip Sing 1.81
Medel Stard	
IV Order	
TV Order	See balok (unus dail event)
Run Order	Flight Time
2	Chart Small
-	Rotor Frome Clip Sing 1.43
Model Sard	ard + +
V Order	See back (unusual even t)
Run Order	Flight Time
7	
	Rotor Frame Clip Sing
Model Sards	ro + - + -
VI Order	See back (unus ual even t)
Run Order	Flight Time
5	
	Rotor Frame Clip Sing 1.25
Mo de l Sanda	rd - + + -
VII Order	See back (unus uai even t)
	••••
Run Order	Flight Time
3	Long Rig
2	Rotor Frame Clip Sing 1.62
Model Sanda	
VIII Order	
AU1 0.96	and the rest of the rest of the rest of

Flight Time

Run Order

Average

(Total/8) 1.155875

## Next, Group By Rotor Length

Run Order		Flight Time
4	Short Small No No Rotor Frame Clip Sing	1 50
Model Stards	Rotor Prome Clip Sing	1.50
Order	see back (unusual)	(*****
1 1		
Run Order	1	Right Time
8	Long Small No	-
0	Rotor Frame Clip Sing	1.68
Nodel Station		
II Order	See back (unus ualle	went)
Run Order		<b>Flight Time</b>
6	Short Big No Rotor Frame Clip Sing	1.27
		1.57
Nodel States		
III Order	See back (unusual)	event)
Run Order		Flight Time
1	Long Big No No Rotor Frame Clip Sing	1.81
Nodel Staday	+ +	1.01
IV order	See back (unusual o	(treese
Run Order	•	Flight Time
	Short Small	
2	Short Show	1 / 2
	Rotor Frame Clip Sing	1.43
Model Sardard	Rotor Frame Clip Sing + +	
	Rotor Frame Clip Sing	
Model Sardard	Rotor Frame Clip Sing + +	
Model Sardard	Rotor Frame Clip Sing + + See back (unusual e	
Model Standard V Order	Rotor Frame Clip Sing + + See back (unusual e	vent) Flight Time
No de l Sandaro V Order Run Order 7	Rotor Frame Clip Sing + + See back (unusual e Long Small No Rotor Frame Clip Sing	ventj
No de l 2andaro V Order Run Order 7	Rotor Frome Olip Sing + + See back (unusual e Long Small No Rotor Frome Olip Sing + + +	ventj Flight Time 1.81
No de l Sandaro V Order Run Order 7	Rotor Frame Clip Sing + + See back (unusual e Long Small No Rotor Frame Clip Sing	ventj Flight Time 1.81
Model 2andaro V Order Run Order 7 Model 2andard Order	Rotor Frame Olip Sing - + + See back (unus usi e Long Small No Rotor Frame Olip Sing + + See back (unus usi e	vent) Flight Time 1.81 vent)
Ma del 2andaro V Order Run Order 7 Ma del 2andard VI 2andard Order	Rotor Frome Clip Sing - + + See back (unusual e Long Small No Rotor Frame Clip Sing + - + - See back (unusual e	ventj Flight Time 1.81
Model 2andaro V Order Run Order 7 Model 2andard Order	Retor Frame Clip Sing + + See back (unusual e Long Small No Retor Frame Clip Sing + + See back (unusual e Short Sig No	vent) Flight Time 1.81 vent)
Run Order 7 Run Order 7 Madei aarded VI order 5	Retor Frame Clip Sing - + + See back (unus ual e Long Small No Rotor Frame Clip Sing + + + See back (unus ual e Short Big No Rotor Frame Clip Sing	vent) Flight Time 1.81 vent) Flight Time
Run Order 7 No dei 2antard 7 No dei 2antard 0der 5 No dei 2antard	Rotor Frame Clip Sing - + + See back (unus usi e Long Small No Rotor Frame Clip Sing + + + See back (unus usi e Short Big No Rotor Frame Clip Sing - + + -	vent) Flight Time 1.81 rent) Flight Time 1.25
Run Order 7 Run Order 7 Madei aarded VI order 5	Retor Frame Clip Sing - + + See back (unus ual e Long Small No Rotor Frame Clip Sing + + + See back (unus ual e Short Big No Rotor Frame Clip Sing	vent) Flight Time 1.81 rent) Flight Time 1.25
No dei andardar V Order Run Order 7 No dei andard VI Order 5 No dei andard VI Order	Rotor Frame Clip Sing - + + See back (unusual e Long Small No Rotor Frame Clip Sing + + + See back (unusual e Short Big No Rotor Frame Clip Sing - + + See back (unusual e	vent) Flight Time 1.81 vent) Flight Time 1.25 ent)
Run Order Studies ander Run Order Run Order Run Order S Model ander VII oder Run Order	Retor Frame Clip Sing - + + See back (unusual e Long Small No Rotor Frame Clip Sing + + + See back (unusual e Short Big No Rotor Frame Clip Sing - + + - See back (unusual e	rentj Flight Time 1.81 rentj Flight Time 1.25 entj Flight Time
No dei andardar V Order Run Order 7 No dei andard VI Order 5 No dei andard VI Order	Retor Frame Clip Sing - + + See back (unus usi e Long Small No Rotor Frame Clip Sing + + See back (unus usi e Short Big No Rotor Frame Clip Sing - + - See back (unus usi e Long Big	vent) Flight Time 1.81 vent) Flight Time 1.25 ent)
Run Order 7 Run Order 7 Masei aandad VI oder 8 Wit oder 8 Wit oder 3	Retor Frame Clip Sing - + + See back (unus usi e Long Small No Rotor Frame Clip Sing + + - See back (unus usi e Short Big No Rotor Frame Clip Sing - + - See back (unus usi e Long Big Rotor Frame Clip Sing	rentj Flight Time 1.81 rentj Flight Time 1.25 entj Flight Time
Run Order Studies ander Run Order Run Order Run Order S Model ander VII oder Run Order	Retor Frame Clip Sing - + + See back (unus usi e Long Small No Rotor Frame Clip Sing + + - See back (unus usi e Short Big No Rotor Frame Clip Sing - + - See back (unus usi e Long Big	rentj Fight Time 1.81 Fight Time 1.25 entj Fight Time 1.62

## CALCULATE MAIN EFFECT OF DIFFERENT ROTOR LENGTHS

#### Short Rotor

Run O	rder					<b>Flight Time</b>	
	4		Small Frame		No	1.50	
Medel	Stardard	-	-	-	-		
1	Order	See back (unusual event)					

Run O	rder					Flight Time	
6		Short Big Rotor Frame	No Clip	Sing	1.37		
Medel	Standard	-	+	-	+		
	Order	See back (unusual event)					

~		Short Small Rotar Frame Clip Sing			Flight Time 1.43	
Ma de l	Sardard	-	-	+	+	
v	Order	See back (unus ual eve				venti

Run O	5	Short Rotor		Clip	No Sing	Flight Time 1.25
Ma de l	Randard	-	+	+	-	
WI.	Order	See back (unus valieven t)				

Total	5.55					
Avg. (Total / 4)	1.3875					
Effect (Long – Short)						
Coefficient (Effect / 2)						

0.3425 0.17125

#### Long Rotor

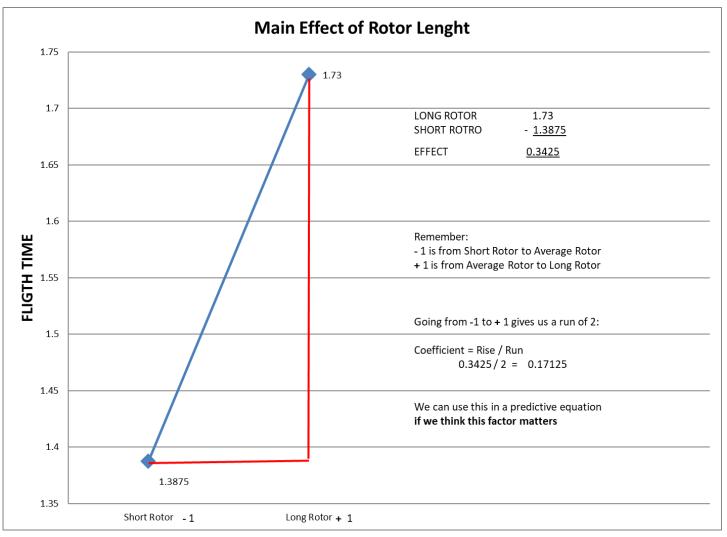
Run O						Flight Time
	8		Small Frame		Sing	1.68
Nedel	Stardard	+	-	-	+	
	Order		See ba	ck (un	us ual e	avent)

Run O	rder	1.1				<b>Flight Time</b>
	1	Long Rotor	Big Frame	No Clip	No Sing	1.81
Nedel	Standard	+	+	-	-	
IV	Order		See ba	went)		

Run O	7	Long Rotor	Small Frame	all ne Clip	No Sing	Flight Time 1.81
Ma de l	Sardard	+	-	+	-	
N	Order		Seeba	ck (un	sventj	

Run O	rder }	Long	Big Frame	Clip	Sing	Flight Time 1.62
Ma de l	Sandard	+	+	+	+	
IIIV	Order		See ba	ck (un	us ual e	sven tj
						6.92
						1.730

# Why We Divide The Effect by 2 (*in this example*) To Obtain Equation Coefficients



## CALCULATE MAIN EFFECT OF DIFFERENT FRAME SIZES

#### Small Frame

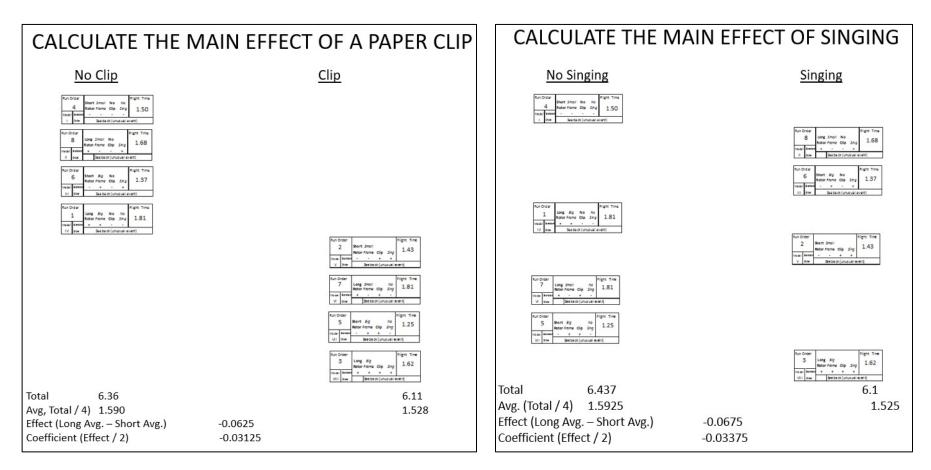
#### **Big Frame**

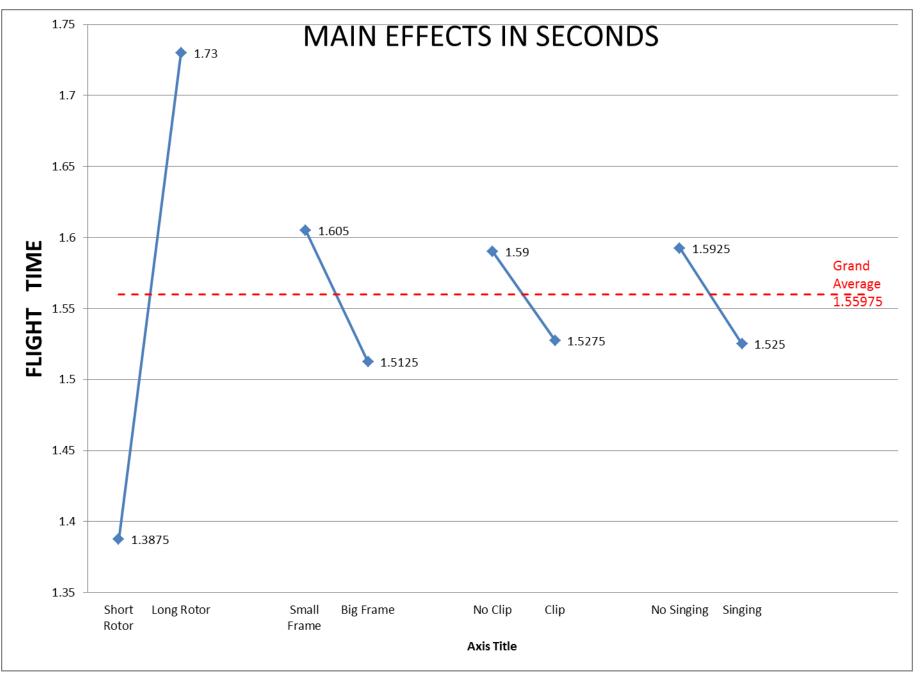
Run Order	Short Small No No	Flight Time
4	Rotor Frame Clip Sing	1.50
Model Stards		1.50
Order	See back (unus ual	event)
_		
Run Order	Long Small No	Flight Time
8	Long Small No Rotor Frame Clip Sing	1.68
Nodel Station		
II Order	See back (unus ual e	went)
Run Order	Short Big No	Flight Time
6	Short Big No Rotor Frame Clip Sing	1.37
Model Starlard		
III Order	See back (unusual ev	vent)
_		
Run Order		Right Time
1	Long Big No No Rotor Frame Clip Sing	1.81
Medic   Standard		
IV Order	See back (unusual ev	(ent)
Run Order		Flight Time
2	Short Small Rotor Frame Clip Sing	1.43
Model Sardard	· · + +	
V Order	See back (unus ual e	ventj
Run Order		Flight Time
7	Long Small No Rotor Frame Clip Sing	1.81
Model Sardard		
VI Order	See back (unus ual ex	(ent)
Run Order		Flight Time
5	Short Big No	1.25
	Rotor Frame Clip Sing	1.20
Model Standard	- + + - See back (unusual e	
VII SO	See balok junids ball e	and a
Run Order		Flight Time
3	Long Big	1.62
	Hotor Frome Clip Sing	1.02
Model Standard	+ + + +	-
VIII Order	See back (unus val ex	वार्य
	~	40
	6.	42

Total6.42Avg. (Total / 4)1.605Effect (Long Avg. – Short Avg.)Coefficient (Effect / 2)

-0.0925 -0.04625 6.05 1.513

## Calculate Other Two Main Effects





# The Helicopter Experiment

- "The Helicopter Experiment" is used extensively in 6-Sigma/Quality/Statistics training in industry
- More Sophisticated Versions:
  - Key Source:
    - George Box, FRS:
      - Teaching Engineers Experimental Design With A Paper Helicopter, *Quality Engineering*, 1992, Vol. 4, No. 3, pp. 453-459
      - Also Report No. 76 of the Center for Quality and Productivity Improvement of the University of Wisconsin
  - Slightly more complex Paper Helicopter Experiment:
    - Matthew Barsalou:
      - Teaching DoE with Paper Helicopters and Minitab <u>http://www.minitab.com/en-us/Published-Articles/Teaching-DoE-with-Paper-Helicopters-and-Minitab/</u>
  - More Advance Paper Helicopter Experiment
    - Erik Barry Erhardt
      - Designing a Better Paper Helicopter Using Response Surface Methodology. *Stats*, Issue 48, pp. 14-19, also see p. 2.
  - Statistical Software:
    - DesignExpert <u>https://www.statease.com/</u>
    - JMP <u>https://www.jmp.com/en\_us/applications/design-of-experiments.html</u>
    - Minitab <u>http://www.minitab.com/en-us/</u>

# More Information

- Box, G. E. P. (1992), "Teaching Engineers Experimental Design with a Paper Helicopter," *Quality Engineering*, 4, 453–459. Found at <u>Teaching Engineers Experimental Design</u> <u>with a Paper Helicopter (williamghunter.net)</u> also see <u>Learning Design of Experiments</u> <u>with Paper Helicopters » Curious Cat Science and Engineering Blog (curiouscatblog.net)</u>
- and for a more advanced optimization approach see Erik Barry Erhardt "Designing a Better Paper Helicopter Using Response Surface Methodology," *Stats* Issue 48, pp. 14-21.
- <u>2004-08Stat-Teaser.qxd (statease.com)</u>
- <u>Creativity defeats sensibility for paper helicopter</u> <u>fly-off « Stats Made Easy</u>
  - Video of paper-helicopter fly-offs at South Dakota
     School of Mines & Technology « Stats Made Easy
- Learning Design of Experiments with Paper Helicopters and Minitab

# Discussion

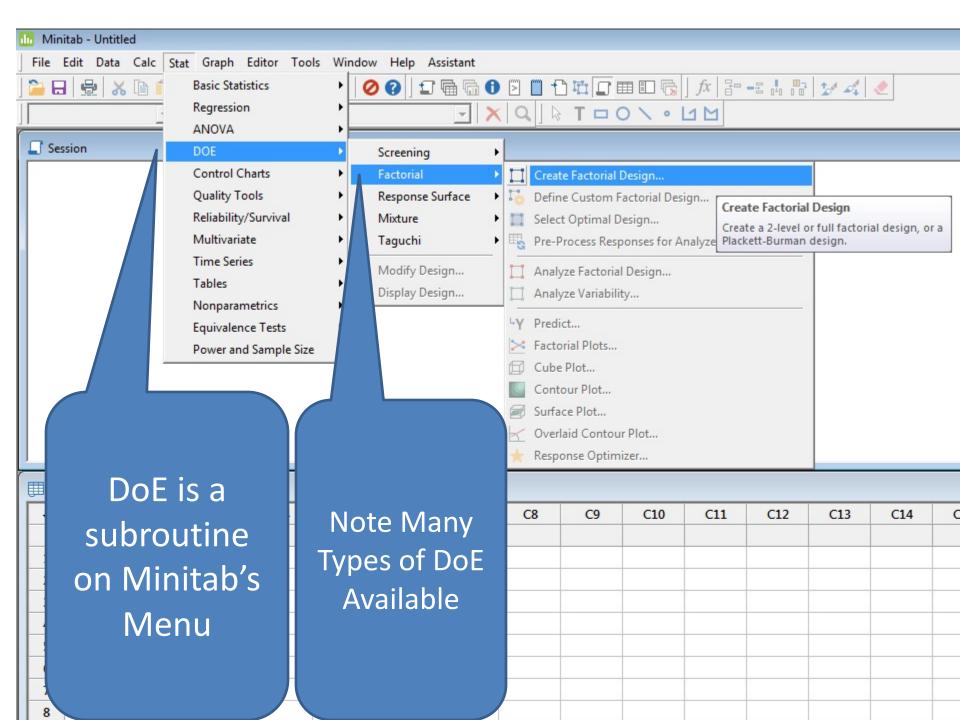
- Should Introductory Statistics Students See a Demonstration—or Preferably Participate in the Planning, Execution, and Analysis—of a Simplified Multifactor Statistically Design of Experiments (DoE)?
- What About Students Who Do Not Take Stat 101?
- Is the Recipe Card Approach A Good Example of How To Introduce DoE?
  - How Can It Be Improved?
- Are You Interested In Continuing the Conversation?
  - fluharty.earlydoe@gmail.com

Appendix I

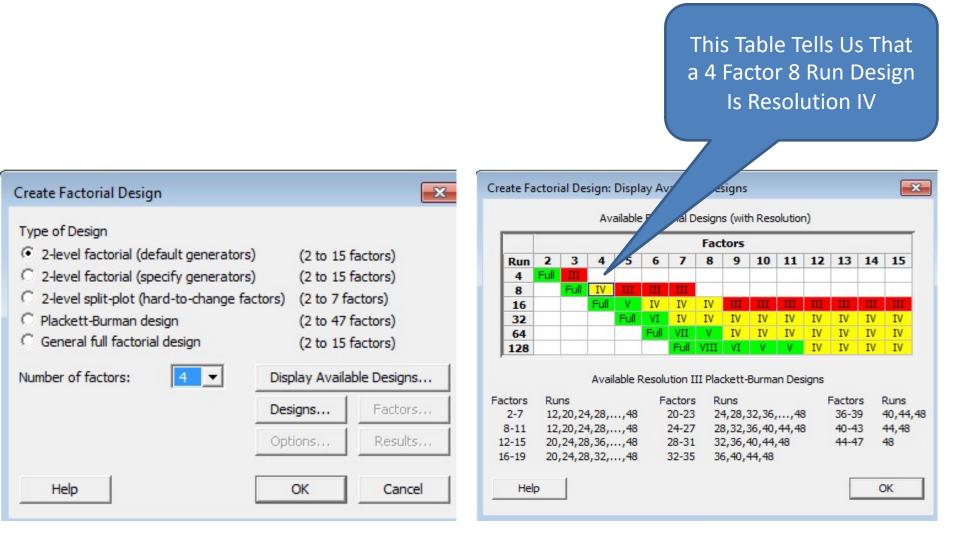
## SOFTWARE IMPLEMENTATION

# Using Software for DoE

- Software: Among the Statistical Software Programs With Extensive DoE Implementations Are the Following:
  - Minitab (Used In This Example, USCOTS 2021 Sponson)
  - JMP(USCOTS 2021 Sponson)
  - SAS (USCOTS 2021 Sponson)
  - StatEase Design Expert (Specialized DoE Software)
- This Example Is an Intermediate Model to Show Interaction
  - Most Experimenters Would Develop A Reduced Model Which Would Probably Not Include Interaction and Several Other Terms



# Menu Guides Experimenter Through Design Generation



## What We Give Up When We Use Fractional Factorials

Search Minitab 18 Support

۹

## What is the design resolution in a factorial design?

Learn more about Minitab 18

Design resolutions describe how much the effects in a fractional factorial design are aliased with other effects. When you do a fractional factorial design, one or more of the effects are confounded, meaning they cannot be estimated separately from each other. Usually, you want to use a fractional factorial design with the highest possible resolution for the amount of fractionation required. For example, it is usually better to choose a design where main effects are confounded with 3-way interactions (Resolution IV) instead of a design where main effects are confounded with 2-way interactions (Resolution III).

Resolution III, IV, and V designs are most common:

#### Resolution III

No main effects are aliased with any other main effect, but main effects are aliased with 2-factor

### Resolution IV

No main effects are aliased with any other main effect or 2-factor interactions, but some 2-factor interactions are aliased with other 2-factor interactions and main effects are aliased with 3-factor interactions.

#### Resolution V

No main effects or 2-factor interactions are aliased with any other main effect or 2-factor interactions, but 2-factor interactions are aliased with 3-factor interactions and main effects are aliased with 4-factor interactions.

**Resolution IV** No main effects are aliased with any other main effect or 2-factor interactions, but some 2-factor interactions are aliased with other 2-factor interactions and main effects are aliased with 3factor interactions.

# Specifying the Design and Naming the Factor Levels

Designs	Runs	Resolution	2^(k-p)
1/2 fraction	8	IV	2^(4-1)
Full factorial	16	Full	2^4
Number of center poir Number of replicates f Number of blocks: Help	for corner (		-

Name	Туре		Low	High
Rotor Length	Text	•	Short	Long
B	Text	•	-1	1
C	Text	-	-1	1
D	Text	-	-1	1
	B C	B Text C Text	B Text  C Text	B Text -1 C Text -1

actor	Name	Туре		Low	High
Α	Rotor Length	Text	•	Short	Long
В	Frame	Text	-	Small	Big
С	Clip	Text	-	No Clip	Clip
D	Singing	Text	-	No Sing	Sing

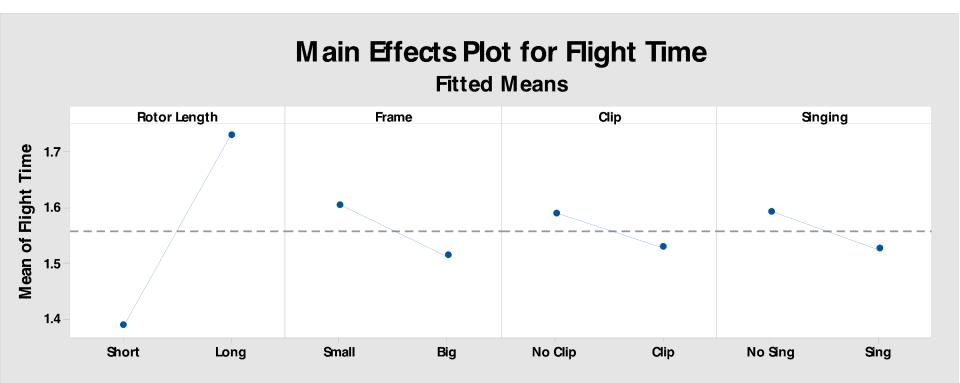
Coded Coeffic	ients		
Term	Effect	Coef	SE Coef
Constant		1.5588	0.0249
Rotor Length	0.3425	0.1713	0.0249
Frame	-0.0925	-0.0462	0.0249
Clip	-0.0625	-0.0313	0.0249
Singing	-0.0675	-0.0338	0.0249
Frame*Clip	-0.0925	-0.0463	0.0249

The Coef(ficients) can be used to develop predictive equations, including interactions. Experimenter would decide which terms to include.

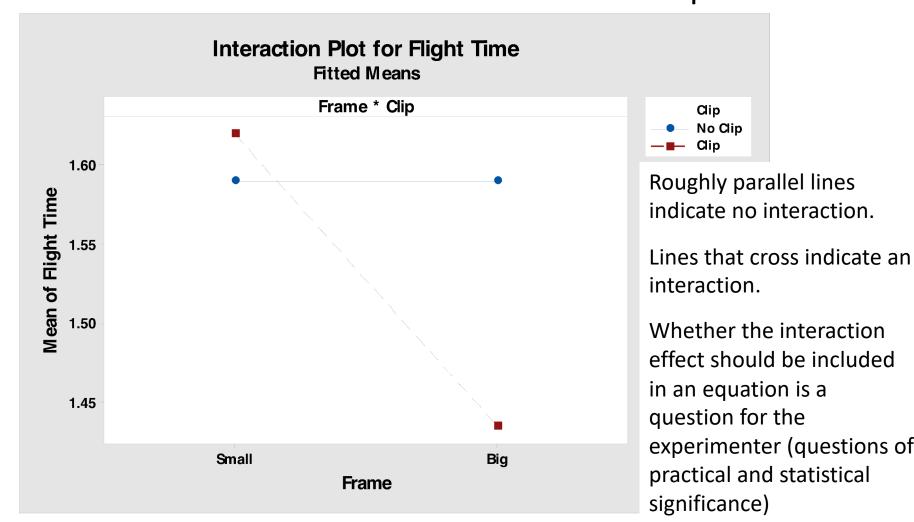
NOTE: A reduced model would probably not include any Terms except the Constant and Rotor Length

A likely "reduced form" equation Flight Time = Average + or – Times Coefficient for Rotor Length Flight Time = 1.5588 + [(+ if Long, - if Short) x 0.1713 For Long Rotor: Flight Tim = 1.5588 + 0.1713 For Short Rotor: Flight Time = 1.5588 - 0.1713

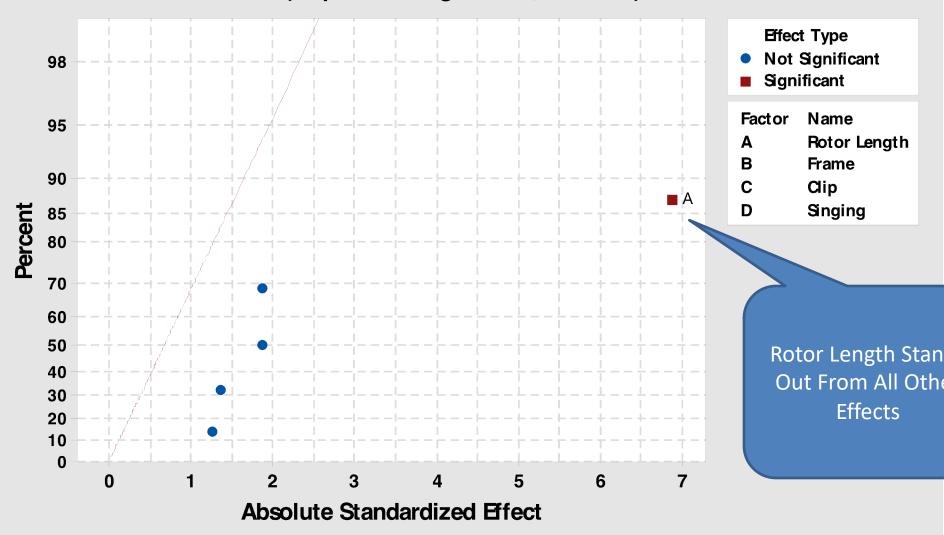
# Plot of Results



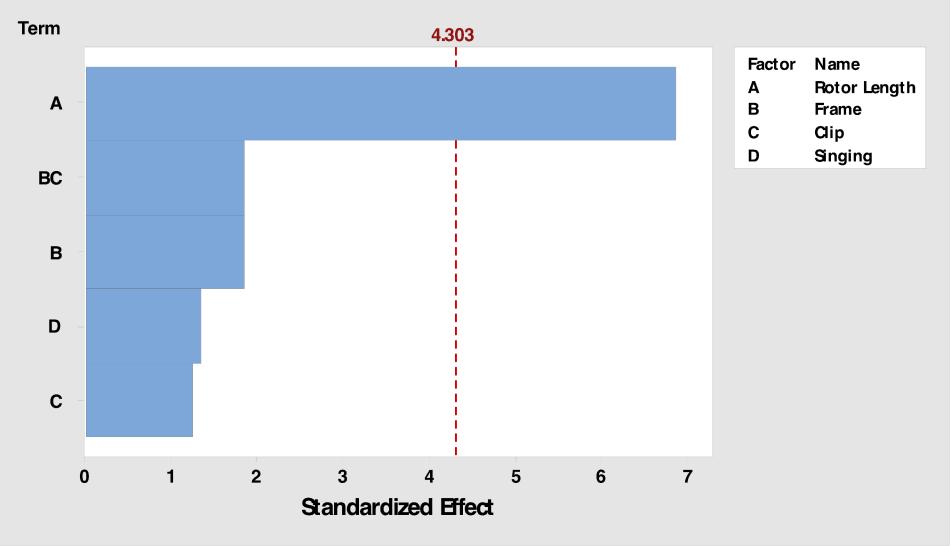
This Interaction Plot Splits the Main Effect Plot for Frame Size Into Two Lines: One Where There Is a Clip, The Other Where There Is Not a Clip



#### Half Normal Plot of the Standardized Effects (response is Flight Time, a = 0.05)



#### Pareto Chart of the Standardized Effects (response is Flight Time, $\alpha = 0.05$ )



# SHORT OUTLINE OF SELECTED STEPS IN A DOE

Appendix II

## Short Outline of Selected Steps in a DoE (1 of 2)

- 1. Define the problem or opportunity
- 2. Identify the response (what are you interested in)
- 3. Specify the objective(s) for the response (minimize, hit a value, maximize, etc.)
  - Are there tradeoffs between objectives, e.g., flight time and land in a specific location?
- 4. Identify potential causes
  - Brainstorm
  - Research
  - Literature Search
  - Textbooks
- 5. Classify potential causes as control (can be changed relatively easily in practice) and noise (can not be changed in practice)
  - This distinction is very important in 'Robust Design"
- 6. Develop experimental strategy
  - Screening/Optimization/Confirmation
  - Includes budget (time, materials, money)
  - Perhaps 25% devoted to initial screening experiment
- 7. Choose the experimental factors and select factor levels (may be iterative with the "Generate the DoE" step
- 8. Identify restrictions and constraints on factors and randomization

## Short Outline of Selected Steps in a DoE (2 of 2)

- 9. Ensure all experimental runs are safe to perform
- 10. Obtain IRB (Institutional Review Board) approval if necessary
- 11. Choose/Generate the DoE Plan with the response and chosen factor levels
  - The 4 factor 8 run example used in the USCOTS Beyond Session is one of many thousands of possible DoEs
  - Some of these DoEs have been used for years and can be found in standard texts—others can be generated by DoE software for specific purposes
- 12. Prepare to conduct the DoE
  - Time and place to run the experiments
  - Participant roles clear
- 13. Ensure the measurement system is capable
- 14. Randomize the runs
- 15. Run the DoE
  - Record information on unforeseen events that might have impacted the experiment
- 16. Collect the data
- 17. Analyze the data
- 18. Draw conclusions and decide on next steps

Subset of Slides 1-45

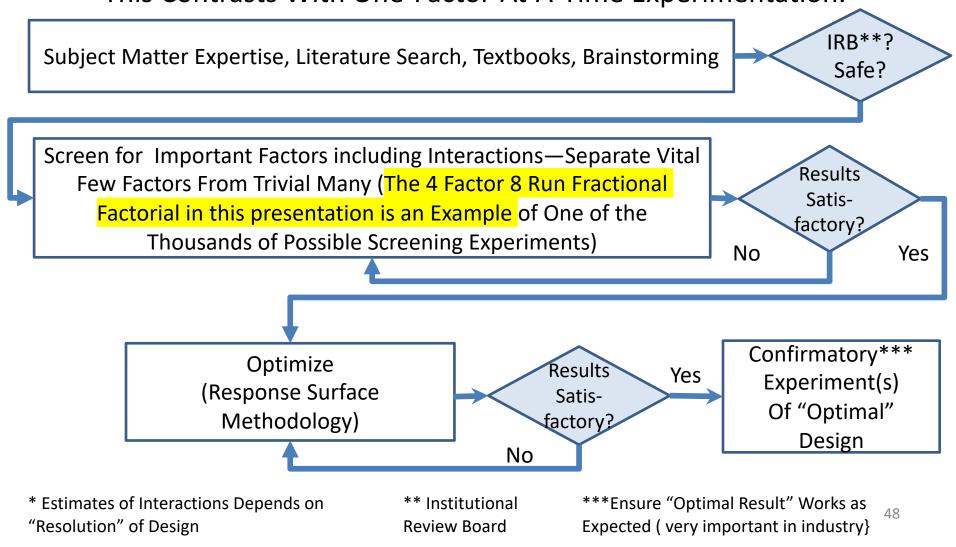
# THE FOLLOWING SLIDES ARE PRESENTED AT THE USCOTS 2021 TUESDAY "BEYOND" SESSION TO START THE DISCUSSION

## Should Introductory Statistics Classes Include Multifactor Statistical Design of Experiments (DoE)?

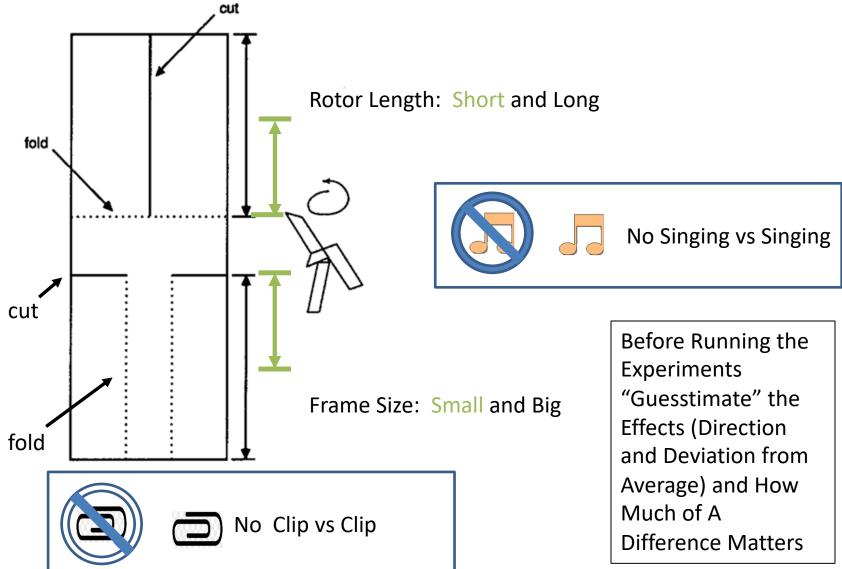
## USCOTS 2021 Tuesday, June 29th 3:00-3:45pm ET

## David Fluharty

Adjunct Professor of Statistics and Economics Ivy Tech Community College—Columbus IN fluharty.earlydoe@gmail.com DoE Is an Art and Science that Helps Us Investigate the Effects of Multiple Factors (Including Interactions\*) by **SIMULTANEOUSLY** Varying These Factors According to a Mathematically/Statistically **FIXED** Set of Recipes. Results Include Predictive Equations and Possibly Optimization. This Contrasts With One-Factor-At-A-Time Experimentation.



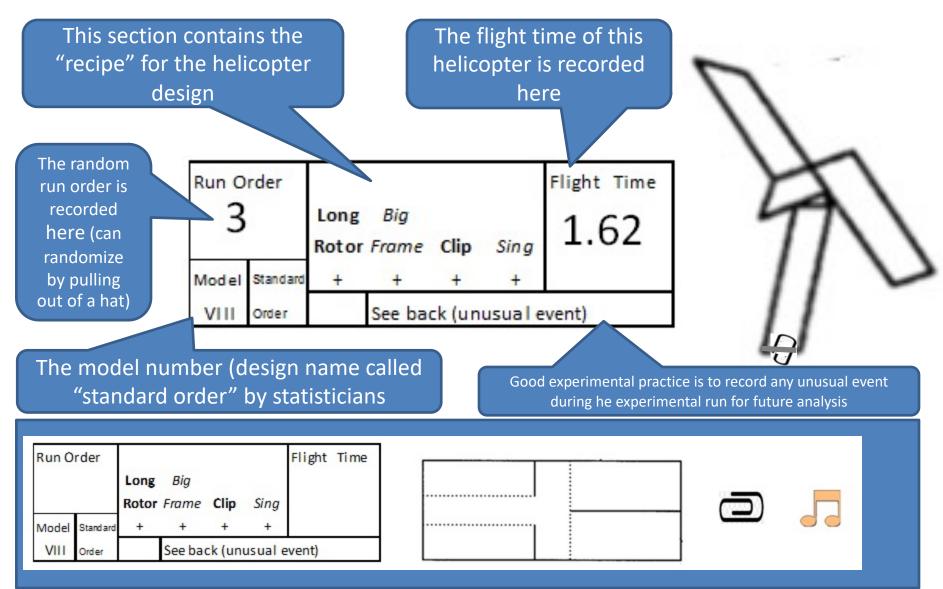
This Example Is Dropping a Paper Helicopter from A Ladder We Investigate 4 Factors That <u>Might</u> Impact Flight Time: Rotor Length (Long vs. Short), Frame Size (Big vs. Small), Paper Clip (No Clip vs. Clip), Singing (No Singing vs. Singing)



## 4 Factors 8 Runs (Each Different) (Why This Works—Matrix Algebra)

	Rotor <u>Length</u>		<u>Clip</u>	<u>Singing</u>	"Standard Order"	
I	Short	Small	No Clip	No Sing	-1 -1 -1 -1	When Multiply the Rows, the Sum (Dot
II	Long	Small	No Clip	Sing	+1 -1 -1 +1	Product) is Zero→ These are Orthogonal
	Short	Big	No Clip	Sing	-1 +1 -1 +1	Vectors
IV	Long	Big	No Clip	No Sing	+1 +1 -1 -1	
V	Short	Small	Clip	Sing	-1 -1 +1 +1	
VI	Long	Small	Clip	No Sing	+1 -1 +1 -1	
VII	Short	Big	Clip	No Sing	-1 +1 +1 -1	
VIII	Long	Big	Clip	Sing	+1 +1 +1 +1	
				The "Sir	nging" Column is the prod columns. For example, for +1 x +1 x +1 =	or Model VIII:

## There is One Recipe Card Corresponding to Each of the Helicopter Designs: Example of Design VIII



One way to randomize (Accesses the Psychomotor Domain):

Put Each Recipe Card in a Container

Mix

Draw a Card Establishing "Run Order"

Repeat Mix and Draw

Run O	rder		-			Flight Time
			Small Frame		No	1.1.1.1.1.1.1
Medel	Standard	-	-	-	-	
1	Order		See ba	ck (un	usual e	(vent)

		_	Small Frame		Sha	
Nedel	Stardard	+	-		-	
н	Order		Seeba	ck (un	us ual e	vent)

Run O	rder					Flight	Time
			Big Frame		Sing		
Nedel	Stardard	-	+	-	+		
	Order		See ba	ck (un	usual e	went)	

Rotor Frame Clip Sing	Tim	Fi light	No		Big			Run O
			Sing	Clip	Frome +	Rotor +		Nedel
IV order See back (unusual event)		(ent)	is uall e	ck (unu	See ba	3	Order	IV

v	Order		See ba	ck (un	us ual e	wentj	
Madel	Sardard		-	+	+		
		Short Rotor		Clin	Sina		
Run O	rder					Flight	Tim

Run O	rder					Flight	Time
			Small Frame	Clip	No Sing		
Ma de l	Randard	+	-	+	-		
N	Order		Seeba	ck (un	us ual e	s/ent)	

Run O	rder					Flight Time
		Short Rotor		Clip	No Sing	
Madel	Randard	-	+	+	-	
NI.	Order	-	See ba	ck (un	us ual e	sventj

Run O	rder					Flight Time
		Long Rotor		Clip	Sing	
Ma de l	Randard	+	+	+	+	
VIII	Order		See ba	ck (uni	us ual e	sventj

Run O	1	Long	Big		No	Flight	Time
Medel	Stardard	+	+				
IV	Order		See ba	ck (un	us ual e	event)	
Run C						Flight	Time
Run C		Short		2			Time
Run C	order	Short Rotor	Small	2			Time

Run O	rder	Long	Big			Flight Time
		Rotor	Frame	Clip	Sing	
Ma de l	Randard	+	+	+	+	
MII	Order		See ba	ck (uni	us ual e	sentj

Run O	rder					Flight Time
		Short	5mall	No	No	
1.1	4	Rotor	Frame	Clip	Sing	
Medel	Grandand	-	-	-	-	
1	Order		See ba	ck (un	usual e	event)

Run O	5	Short	-		No	Fight	Time
		Rotor	Frame	Clip	Sing		
Ma de l	Sardard	-	+	+	-		_
NI IN	Order		See ba	ck (un	us ual e	ventj	

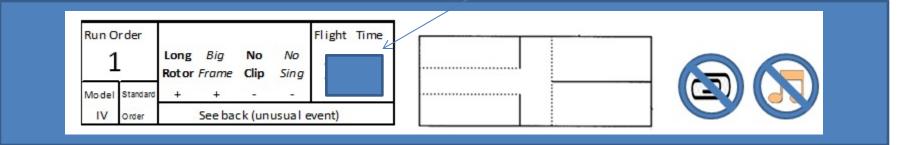
Run O	rder					Flight Time
	6	Short Rotor	Big Frome	Clip	Sing	1
Nedel	Stardard	-	+	-	+	
	Order		See ba	ck (un	usual e	went)

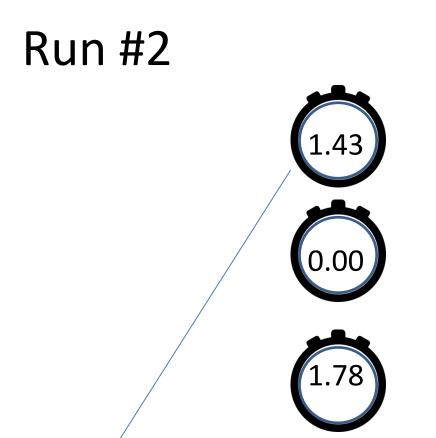
Run O	7	Long	Small Frame	Clip	No Sing	Flight Time
Ma de l	Randard	+	-	+	-	
v	Order		See ba	ck (un	us ual e	vent)

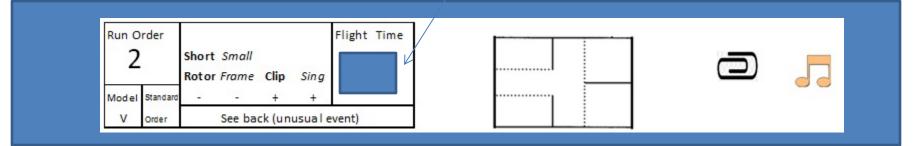
Run O	rder					<b>Flight Time</b>
	8		Small Frame		Sing	
Nedel	Stardard	+	-	-	+	
	Order		Seeba	ck (un	us ual e	(travent)

# Run #1

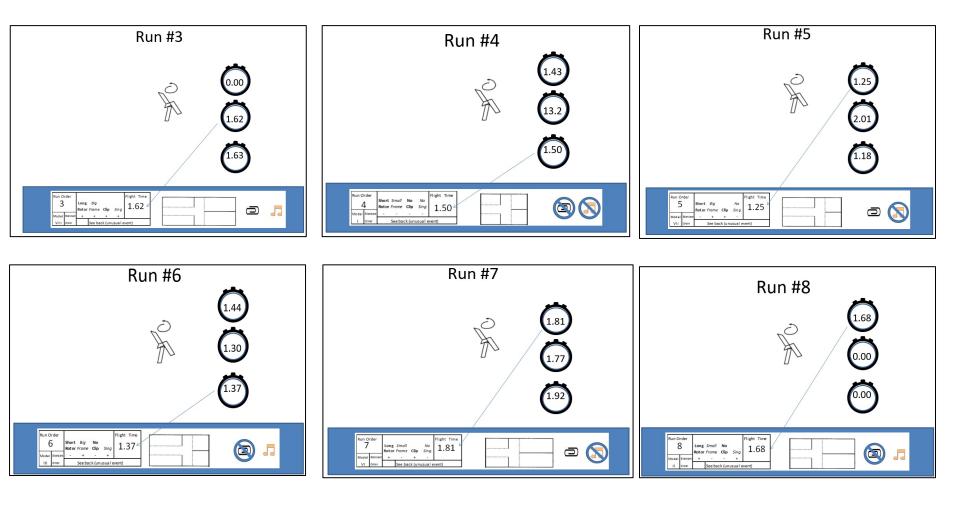








## Repeat for Runs 3-8 Remember: Each Is a Different Helicopter Design



#### Put "Recipe Cards" In Standard Order Calculate the Grand Average

		6-7 - 1 - C - C - C - C - C - C - C - C - C
Run Order		Flight Time
4 Rotor	Small No No Frame Clip Sing	4.50
Model Stardard -	Frome Clip Sing	1.50
Order	See back (unusual	event)
Run Order		
	Small No	Flight Time
8 Long	Frame Clip Sing	1.68
Model Stardard +	Frome Cap Serg	
	See back (unus ual o	(*****
iii Odar	See be ck ( drids der v	even.)
Run Order		Flight Time
e Chart	B/g No	
Rotor	Frame Clip Sing	1.37
Model Stardard -	+ - +	
	See back (unusual	event)
Run Order		Flight Time
1.1.1.1	Big No No	
Rotor	Blg No No Frame Clip Sing	1.81
Nodel Standard +		
IV Order	See back (unusual)	event)
Run Order		Flight Time
2 Short	Small	1.43
Rotor	Frame Clip Sing	
Model Sandard -		
V Order	See back (unus ual e	sventj
Run Order		Flight Time
/ Long	Small No Frame Clip Sing	1.81
Model Sardard +	torne chip sing	
	See back (unus ual e	on the
· Joar 3	accession formes delle	and a
		-1
Run Order		Flight Time
5 Short		1.25
	rome Clip Sing	
	+ + - eeback (unusual e	-
VII USA S	ee oa ok junus ual e	(ent)
Run Order		Flight Time
3 Long		1.62
	name Clip Sing	1.02
Model Standard +	+ + +	
VIII Order 3	See back (unus ual e	ventj

Total 12.47

Average

(Total/8) 1.155875

### Next, Group By Rotor Length

Run Order		Flight Time
4	Short Small No No Rotor Frame Clip Sing	1 50
Model Stards	Rotor Prome Clip Sing	1.50
Order	see back (unusual)	(*****
1 1		a a a a a a a a a a a a a a a a a a a
Run Order	1	Right Time
8	Long Small No	-
0	Rotor Frame Clip Sing	1.68
Nodel Station		
II Order	See back (unus ualle	went)
Run Order		<b>Flight Time</b>
6	Short Big No Rotor Frame Clip Sing	1.27
		1.57
Nodel States		
III Order	See back (unusual)	event)
Run Order		Flight Time
1	Long Big No No Rotor Frame Clip Sing	1.81
Nodel Staday	+ +	1.01
IV order	See back (unusual o	(treese
Run Order	•	Flight Time
	Short Small	
2	Short Show	1 / 2
	Rotor Frame Clip Sing	1.43
Model Sardard	Rotor Frame Clip Sing + +	
	Rotor Frame Clip Sing	
Model Sardard	Rotor Frame Clip Sing + +	
Model Sardard	Rotor Frame Clip Sing + + See back (unusual e	
Model Standard V Order	Rotor Frame Clip Sing + + See back (unusual e	vent) Flight Time
No de l Sandaro V Order Run Order 7	Rotor Frame Clip Sing + + See back (unusual e Long Small No Rotor Frame Clip Sing	ventj
No de l 2andaro V Order Run Order 7	Rotor Frome Olip Sing + + See back (unusual e Long Small No Rotor Frome Olip Sing + + +	ventj Flight Time 1.81
No de l Sandaro V Order Run Order 7	Rotor Frame Clip Sing + + See back (unusual e Long Small No Rotor Frame Clip Sing	ventj Flight Time 1.81
Model 2andaro V Order Run Order 7 Model 2andard Order	Rotor Frame Olip Sing - + + See back (unus usi e Long Small No Rotor Frame Olip Sing + + See back (unus usi e	vent) Flight Time 1.81 vent)
Ma del 2andaro V Order Run Order 7 Ma del 2andard VI 2andard Order	Rotor Frome Clip Sing - + + See back (unusual e Long Small No Rotor Frame Clip Sing + - + - See back (unusual e	ventj Flight Time 1.81
Model 2andaro V Order Run Order 7 Model 2andard Order	Retor Frame Clip Sing + + See back (unusual e Long Small No Retor Frame Clip Sing + + See back (unusual e Short Sig No	vent) Flight Time 1.81 vent)
Run Order 7 Run Order 7 Madei aarded VI order 5	Retor Frame Clip Sing - + + See back (unus ual e Long Small No Rotor Frame Clip Sing + + + See back (unus ual e Short Big No Rotor Frame Clip Sing	vent) Flight Time 1.81 vent) Flight Time
Run Order 7 No dei 2antard 7 No dei 2antard 0der 5 No dei 2antard	Rotor Frame Clip Sing - + + See back (unus usi e Long Small No Rotor Frame Clip Sing + + + See back (unus usi e Short Big No Rotor Frame Clip Sing - + + -	vent) Flight Time 1.81 rent) Flight Time 1.25
Run Order 7 Run Order 7 Madei aarded VI order 5	Retor Frame Clip Sing - + + See back (unus ual e Long Small No Rotor Frame Clip Sing + + + See back (unus ual e Short Big No Rotor Frame Clip Sing	vent) Flight Time 1.81 rent) Flight Time 1.25
No dei andardar V Order Run Order 7 No dei andard VI Order 5 No dei andard VI Order	Rotor Frame Clip Sing - + + See back (unusual e Long Small No Rotor Frame Clip Sing + + + See back (unusual e Short Big No Rotor Frame Clip Sing - + + See back (unusual e	vent) Flight Time 1.81 vent) Flight Time 1.25 ent)
Run Order Studies ander Run Order Run Order Run Order S Model ander VII oder Run Order	Retor Frame Clip Sing - + + See back (unusual e Long Small No Rotor Frame Clip Sing + + + See back (unusual e Short Big No Rotor Frame Clip Sing - + + - See back (unusual e	rentj Flight Time 1.81 rentj Flight Time 1.25 entj Flight Time
No dei andardar V Order Run Order 7 No dei andard VI Order 5 No dei andard VI Order	Retor Frame Clip Sing - + + See back (unus usi e Long Small No Rotor Frame Clip Sing + + See back (unus usi e Short Big No Rotor Frame Clip Sing - + - See back (unus usi e Long Big	vent) Flight Time 1.81 vent) Flight Time 1.25 ent)
Run Order 7 Run Order 7 Masei aandad VI oder 8 Wit oder 8 Wit oder 3	Retor Frame Clip Sing - + + See back (unus usi e Long Small No Rotor Frame Clip Sing + + - See back (unus usi e Short Big No Rotor Frame Clip Sing - + - See back (unus usi e Long Big Rotor Frame Clip Sing	rentj Flight Time 1.81 rentj Flight Time 1.25 entj Flight Time
Run Order Studies ander Run Order Run Order Run Order S Model ander VII oder Run Order	Retor Frame Clip Sing - + + See back (unus usi e Long Small No Rotor Frame Clip Sing + + See back (unus usi e Short Big No Rotor Frame Clip Sing - + - See back (unus usi e Long Big	rentj Fight Time 1.81 Fight Time 1.25 entj Fight Time 1.62

### CALCULATE MAIN EFFECT OF DIFFERENT ROTOR LENGTHS

#### Short Rotor

Run O	rder					<b>Flight Time</b>
	4		Small Frame		No	1.50
Medel	Stardard	-	-	-	-	
1	Order		See ba	ck (un	usual e	went)

Run O	rder					Flight Time
	6	Short Rotor		No Clip	Sing	1.37
Medel	Standard	-	+	-	+	
	Order		See ba	ck (un	usual e	went)

Run O	2	Short Rotor		Clip	Sina	Flight Time 1.43
Ma de l	Sardard	-	-	+	+	
v	Order		venti			

Run O	5	Short Rotor	Big Frame	Clip	No Sing	Flight Time 1.25
Ma de l	Sardard	-	+	+	-	
IN	Order	-	Seeba	sventj		

Total	5.55					
Avg. (Total / 4)	1.3875					
Effect (Long – Short)						
Coefficient (Effe	ct / 2)					

0.3425 0.17125

#### Long Rotor

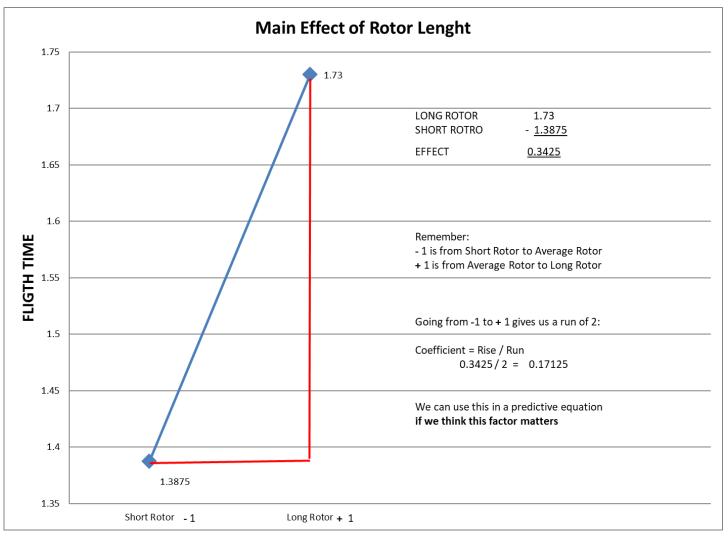
Run O						Flight Time	
	8		Small Frame		Sing	1.68	
Nedel	Stardard	+	-	-	+		
	Order	See back (unus ual event)					

Run O	rder	1.1				<b>Flight Time</b>
	1	Long Rotor	Big Frame	No Clip	No Sing	1.81
Nedel	Standard	+	+	-	-	
IV	Order		See ba	went)		

Run Order 7		Long Rotor	Small Frame	Clip	No Sing	Flight Time 1.81
Ma de l	Sardard	+	-	+	-	
N	Order		Seeba	us ual e	sventj	

Run O	rder }	Long	Big Frame	Clip	Sing	Flight Time 1.62
Ma de l	Sandard	+	+	+	+	
IIIV	VIII Order		See ba	ck (un	us ual e	sven tj
						6.92
						1.730

# Why We Divide The Effect by 2 (*in this example*) To Obtain Equation Coefficients



## CALCULATE MAIN EFFECT OF DIFFERENT FRAME SIZES

#### Small Frame

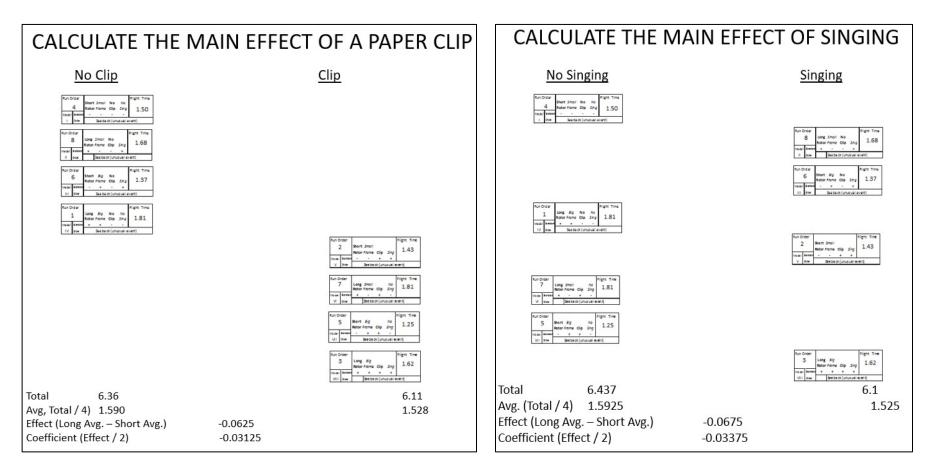
#### **Big Frame**

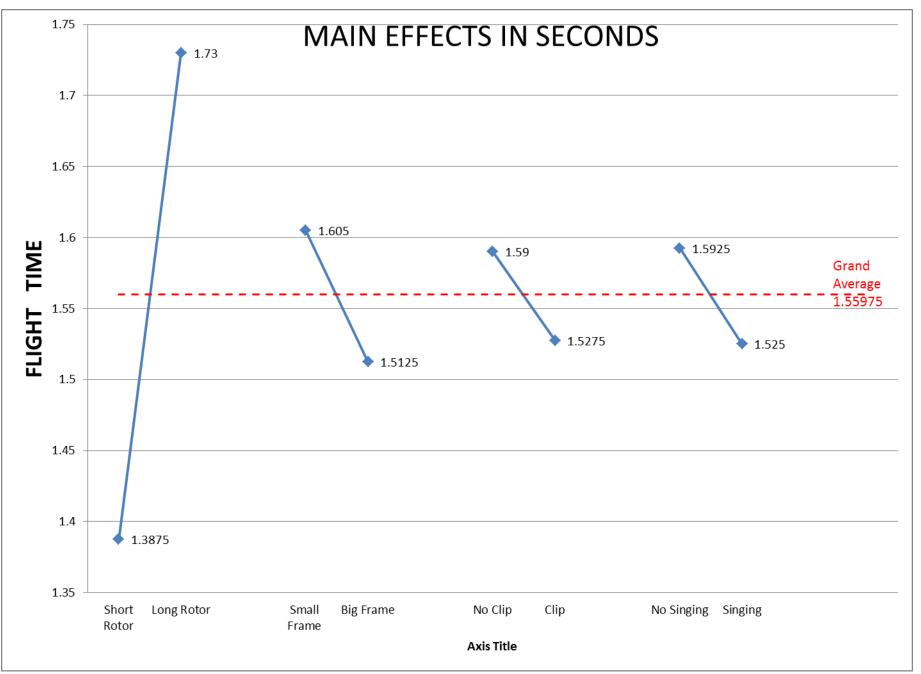
Run Order	These French Man Ma	Flight Time
4	Short Small No No Rotor Frame Clip Sing	1.50
Model Stards		1.50
Order	See back (unusual)	event)
	×	
Run Order		Right Time
8	Long Small No Rotor Frame Clip Sing	1.68
Model Standard	+ · · · ·	100000
II Order	See back (unusual e	(vent)
Run Order		Flight Time
6	Short Big No Rotor Frame Clip Sing	1.37
Nodel Standard	- + - +	
III Order	See back (unusual ev	(ent)
Run Order		Flight Time
1	Long Blg No No	
_	Rotor Frame Clip Sing	1.81
Medicil Standard	* *	
IV Order	See back (unusual ev	ent)
Run Order		Flight Time
2	Short Small	1.42
	Short Small Rotor Frame Clip Sing	1.45
Model Standard	+ +	
V Order	See back (unusual e	vent
Run Order 7	Long Small No	Flight Time
	Long Small No Rotor Frame Clip Sing	1.81
Model Sardard	+ - + -	
VI Order	See back (unus ual e	(ent)
(Carlot and Carlot and	5M 902	
Run Order		Flight Time
5	Short Big No	1.25
	Rotor Frame Clip Sing	
Model Standard	- + + - See back (unusual e	(m) fl
VII GO	ace baller, junids ball e	and a
Run Order		Flight Time
3	Long Big	-
	Rotor Frame Clip Sing	1.62
Model Standard	+ + + +	
VIII Order	See back (unus ual ex	entj
	_	
	6	42
	0.	. –

Total6.42Avg. (Total / 4)1.605Effect (Long Avg. – Short Avg.)Coefficient (Effect / 2)

-0.0925 -0.04625 6.05 1.513

# Calculate Other Two Main Effects





# The Helicopter Experiment

- "The Helicopter Experiment" is used extensively in 6-Sigma/Quality/Statistics training in industry
- More Sophisticated Versions:
  - Key Source:
    - George Box, FRS:
      - Teaching Engineers Experimental Design With A Paper Helicopter, *Quality Engineering*, 1992, Vol. 4, No. 3, pp. 453-459
      - Also Report No. 76 of the Center for Quality and Productivity Improvement of the University of Wisconsin
  - Slightly more complex Paper Helicopter Experiment:
    - Matthew Barsalou:
      - Teaching DoE with Paper Helicopters and Minitab <u>http://www.minitab.com/en-us/Published-Articles/Teaching-DoE-with-Paper-Helicopters-and-Minitab/</u>
  - More Advance Paper Helicopter Experiment
    - Erik Barry Erhardt
      - Designing a Better Paper Helicopter Using Response Surface Methodology. *Stats*, Issue 48, pp. 14-19, also see p. 2.
  - Statistical Software:
    - DesignExpert <u>https://www.statease.com/</u>
    - JMP <u>https://www.jmp.com/en\_us/applications/design-of-experiments.html</u>
    - Minitab <u>http://www.minitab.com/en-us/</u>

# More Information

- Box, G. E. P. (1992), "Teaching Engineers Experimental Design with a Paper Helicopter," *Quality Engineering*, 4, 453–459. Found at <u>Teaching Engineers Experimental Design</u> <u>with a Paper Helicopter (williamghunter.net)</u> also see <u>Learning Design of Experiments</u> <u>with Paper Helicopters » Curious Cat Science and Engineering Blog (curiouscatblog.net)</u>
- and for a more advanced optimization approach see Erik Barry Erhardt "Designing a Better Paper Helicopter Using Response Surface Methodology," *Stats* Issue 48, pp. 14-21.
- <u>2004-08Stat-Teaser.qxd (statease.com)</u>
- <u>Creativity defeats sensibility for paper helicopter</u> <u>fly-off « Stats Made Easy</u>
  - Video of paper-helicopter fly-offs at South Dakota
     School of Mines & Technology « Stats Made Easy
- Learning Design of Experiments with Paper Helicopters and Minitab

# Discussion

• Are You Interested In Continuing the Conversation?

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- Should Introductory Statistics Students See a Demonstration—or Preferably Participate in the Planning, Execution, and Analysis—of a Simplified Multifactor Statistically Design of Experiments (DoE)?
- What About Students Who Do Not Take Stat 101?
- Is the Recipe Card Approach A Good Example of How To Introduce DoE?
  - How Can It Be Improved?

## Why Introduce DoE in Introductory Statistics?

- Why (Educational/Cognitive):
  - Multi Causal Systems (Understanding Needed in Science and Society)
  - Process of Scientific Discovery
    - Iterative
    - Discovery Vs. Demonstrative
    - Discuss Engineering Trade-Offs
  - Omnipresence of Variation
  - Interactions, Predictive Equations, and Optimization
  - Randomization
  - Statistical vs. Practical Significance (if Use Software)
  - Efficiency vs. One-Factor-At-A Time
  - Use of Statistical Graphics
  - Used Business and Industry
    - Manufacturing (Six Sigma Programs)
    - Marketing Experiments
- Pedagogy/Andragogy
  - Cognitive Domain
  - Psychomotor Domain
  - Affective Domain
    - For the Paper Helicopter Example, Model of Autorotation (Flight Time) if Engine Fails