An interactive presentation for the

Canada
Ottawa Valley Section
ASQ The Global Voice of Quality™

DOE Made Easy

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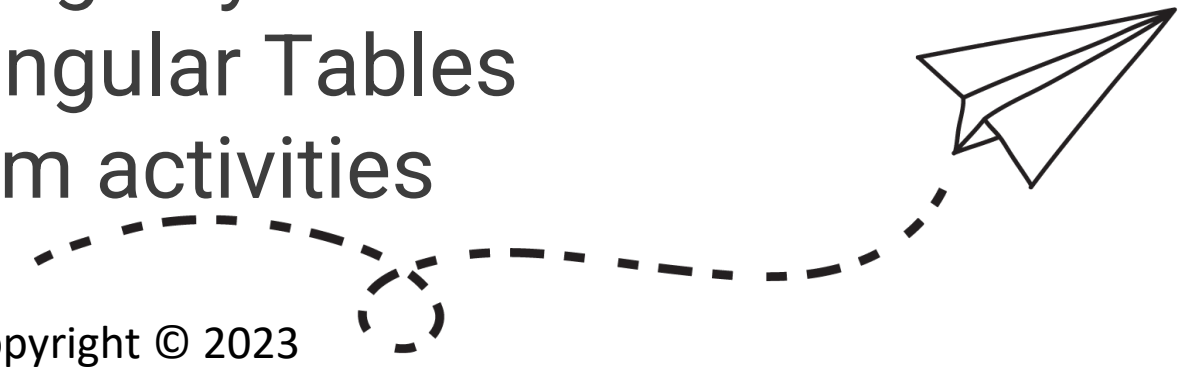
What We'll Learn About in this Presentation

- Introduction to DOE
- History of DOE
- Factors and Levels
- Full vs Fractional Factorials
- Orthogonal Arrays
- Linear Graphs
- Change Symbols
- Triangular Tables
- Team activities



ISO 9001:2015

Helps you to meet

10 Improvement

The organization shall determine and select opportunities for improvement and implement any necessary actions to meet customer requirements and enhance customer satisfaction.

What is Design of Experiments (DOE)

Design of experiments (DOE) is one of the most powerful quality improvement techniques for reducing process variation, enhancing process effectiveness and process capability.

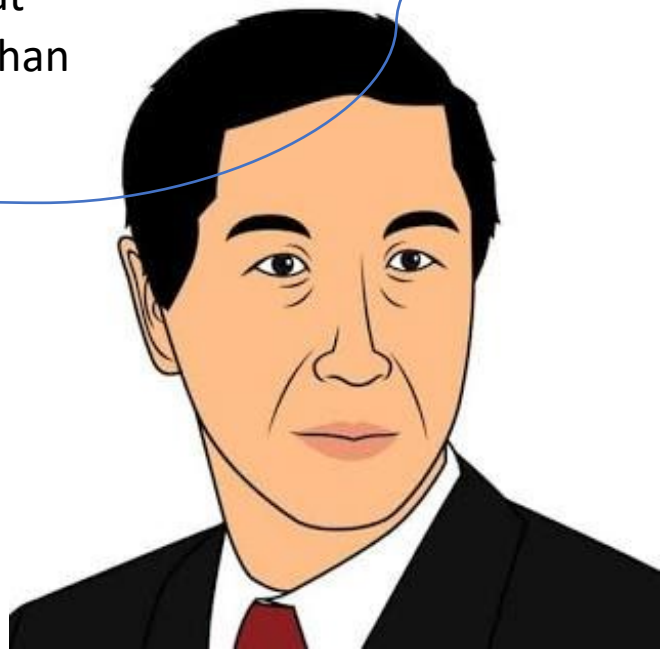
It is also widely recognized in many quality engineering and management training programs today such as Lean Six Sigma.

While it is normally used for product, system and process design in manufacturing, we'll discuss how it might be used in services at the end of the workshop.

History of Design of Experiments (DOE)

Before DOE - Vary one variable at a time.

Classical DOE - first introduced by Sir Ronald Fisher in his book "The Design of Experiments" in **1935**. He argued that factorial designs were more efficient than studying one factor at a time.

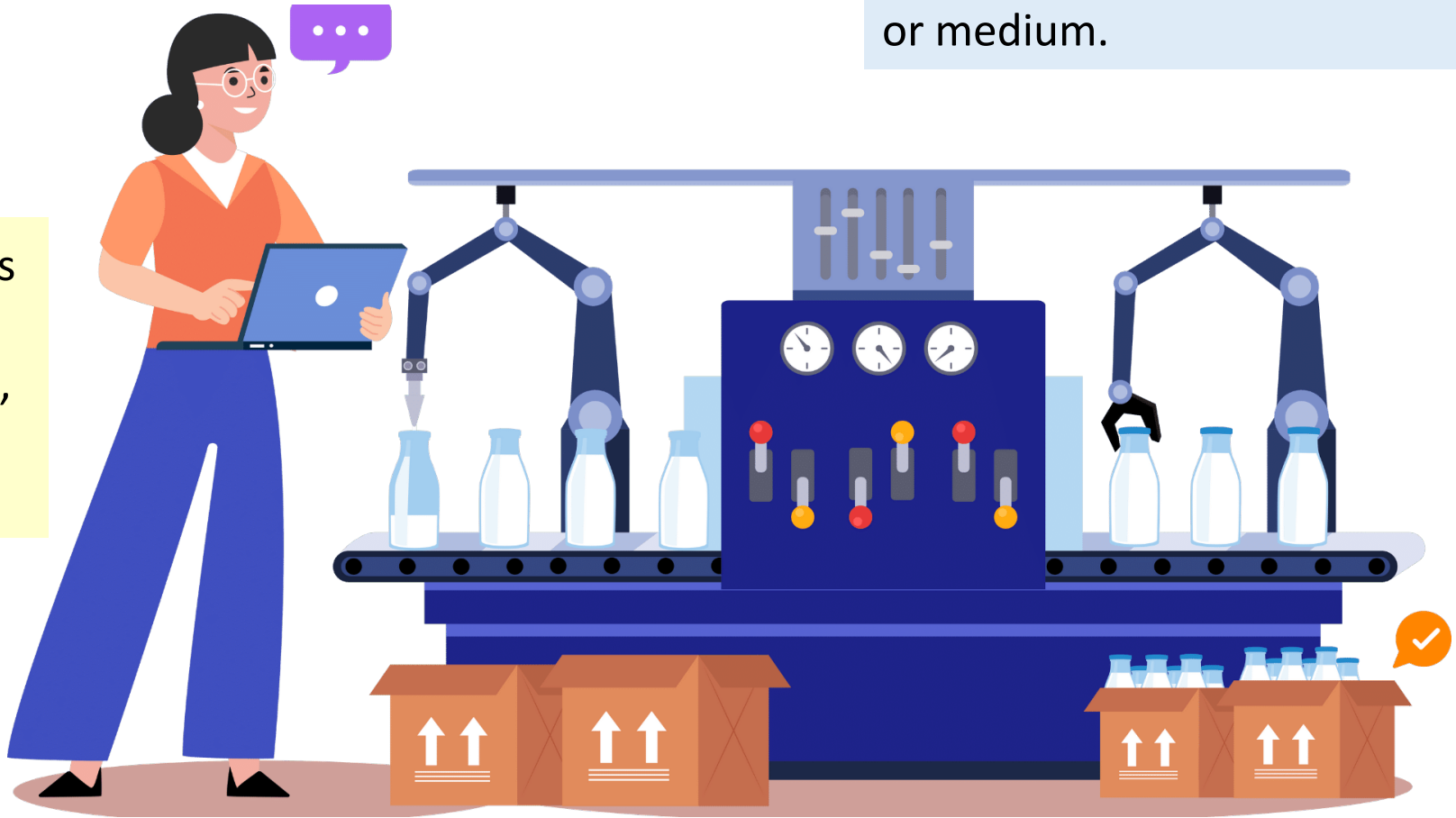


Taguchi's DOE - developed in the **1950s** by Dr G. Taguchi, a Japanese quality engineering Guru and more widely recognized as the father of quality engineering. Introduced into North America in the early **1980s**. He argued that it was more efficient to determine significant factors and any interactions ahead of time and developed mathematical models to design these experiments.

Factors and Levels in a DOE

Levels are the specific values or settings of each factor that you want to compare, such as high, low, or medium.

Factors are the input variables that you want to test and manipulate in your experiment, such as temperature, pressure, speed, or material.



Full Factorial vs Fractional Factorial DOEs

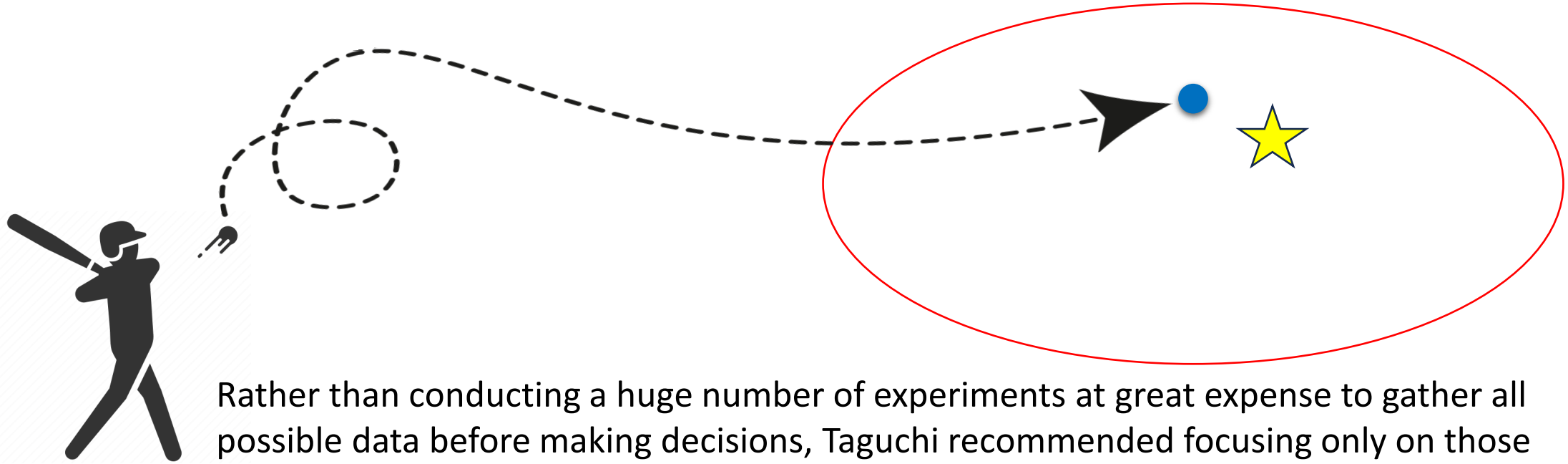
Full factorial designs are a **Classical** type of DOE. They look at all possible combinations of factor levels and interactions between the factors.

Fractional factorial designs are a **Taguchi** type of DOE. They look only at those factor levels and interactions that are thought to be significant.

Factors	Levels	Full Factorial	Fractional Factorial
3	2	8	4
7	2	128	8
4	3	102	9
13	3	1,594,323	27

Taguchi's DOE Strategy

first we get going - then we get better.

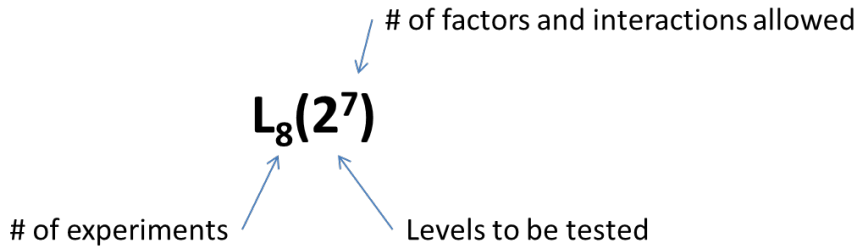


Rather than conducting a huge number of experiments at great expense to gather all possible data before making decisions, Taguchi recommended focusing only on those factors and interactions that were thought to be significant, just to get it into the ballpark.

Once there, further actions could get it closer to optimum but only if needed.

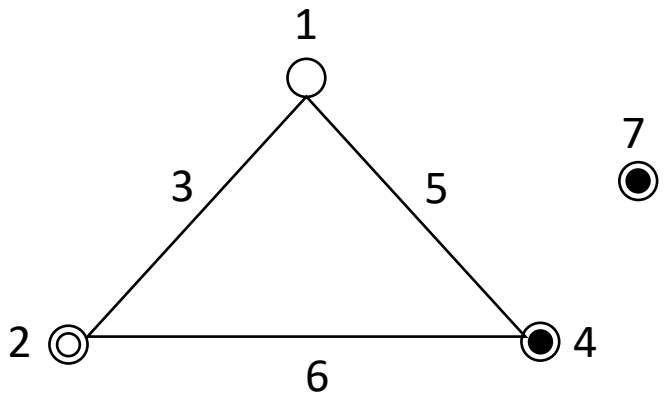
Taguchi Tools – Orthogonal Arrays and Linear Graphs

Orthogonal Arrays are mathematical models that allow you to test multiple factors and interactions with a minimal number of experiments. There are many prepared models available.



	1	2	3	4	5	6	7	Effect
1	1	1	1	1	1	1	1	
2	1	2	2	2	2	2	2	
3	1	1	2	1	1	2	2	
4	1	2	1	2	2	1	1	
5	2	1	2	1	2	1	2	
6	2	1	2	2	1	2	1	
7	2	2	1	1	2	2	1	
8	2	2	1	2	1	1	2	

Linear graphs are the graphical representation showing interactions among the columns of an orthogonal array.



Change Symbols	
SYMBOL	NUMBER OF CHANGES
○	Least changes
◎	Less changes
◉	More changes
●	Most changes

Linear graphs also show those columns that would require the **least** to **most** number of level changes during the experiments. This helps you decide what factors to place in what columns.

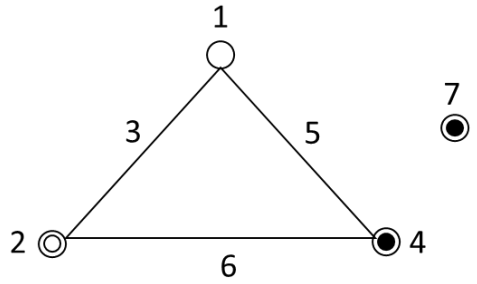
Taguchi Tools – Triangular Table

What if we needed to change our Linear Graph to better suit our needs?

The **Triangular Table** is a simple calculating matrix. It can help to legally change the Linear Graph to better suit your needs.
To find an interaction between two column numbers (representing factors), use the bracketed number to represent your lowest number, then move to the right until you come to the column representing your higher number. The number between them represents the column with the interaction.

COL	1	2	3	4	5	6	7 ⇩
⇨	(1)	3	2	5	4	7	6 ★
		(2)	1	6	7	4	5
			(3)	7	6	5	4
				(4)	1	2	3
					(5)	3	2
						(6)	1
							(7)

TRIANGULAR TABLE

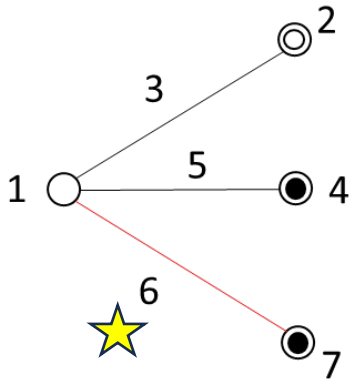


BEFORE

Our original Linear Graph for the $L_8(2^7)$ Orthogonal Array.

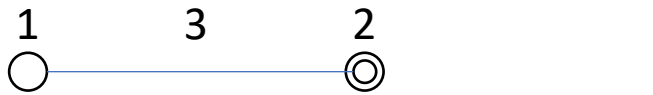
AFTER

Our new Linear Graph for the $L_8(2^7)$ Orthogonal Array.



Additional examples

Here are a couple of additional examples of Orthogonal Arrays and their Linear Graphs.



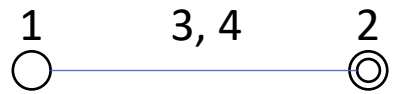
# of factors and interactions allowed

$L_4(2^3)$

# of experiments

Levels to be tested

	1	2	3	Effect
1	1	1	1	
2	1	2	2	
3	2	1	2	
4	2	2	1	



# of factors and interactions allowed

$L_9(3^4)$

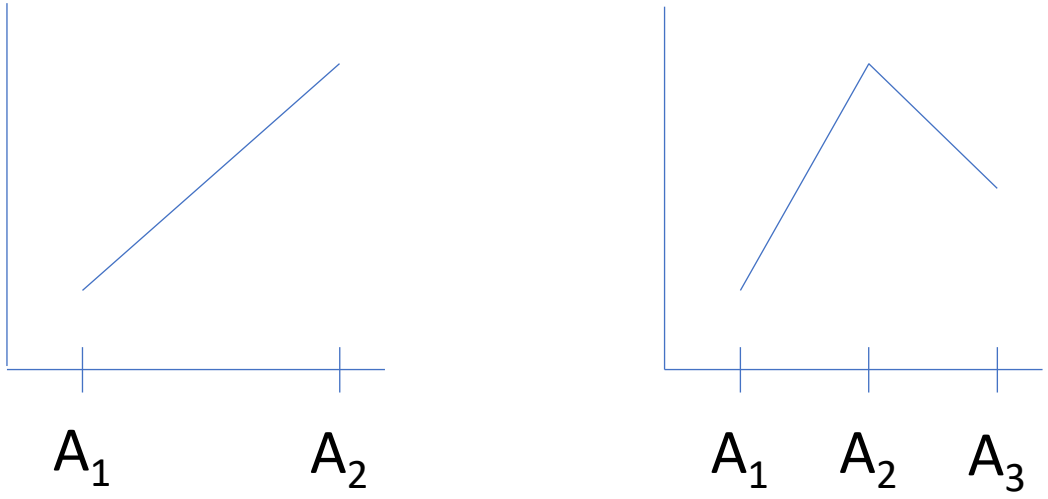
# of experiments

Levels to be tested

	1	2	3	4	Effect
1	1	1	1	1	
2	1	2	2	2	
3	1	3	3	3	
4	2	1	2	3	
5	2	2	3	1	
6	2	3	1	2	
7	3	1	3	2	
8	3	2	1	3	
9	3	3	2	1	

Advantages and disadvantages of a 3-level experiment

Advantage – 2 Level experiments may not give the whole picture

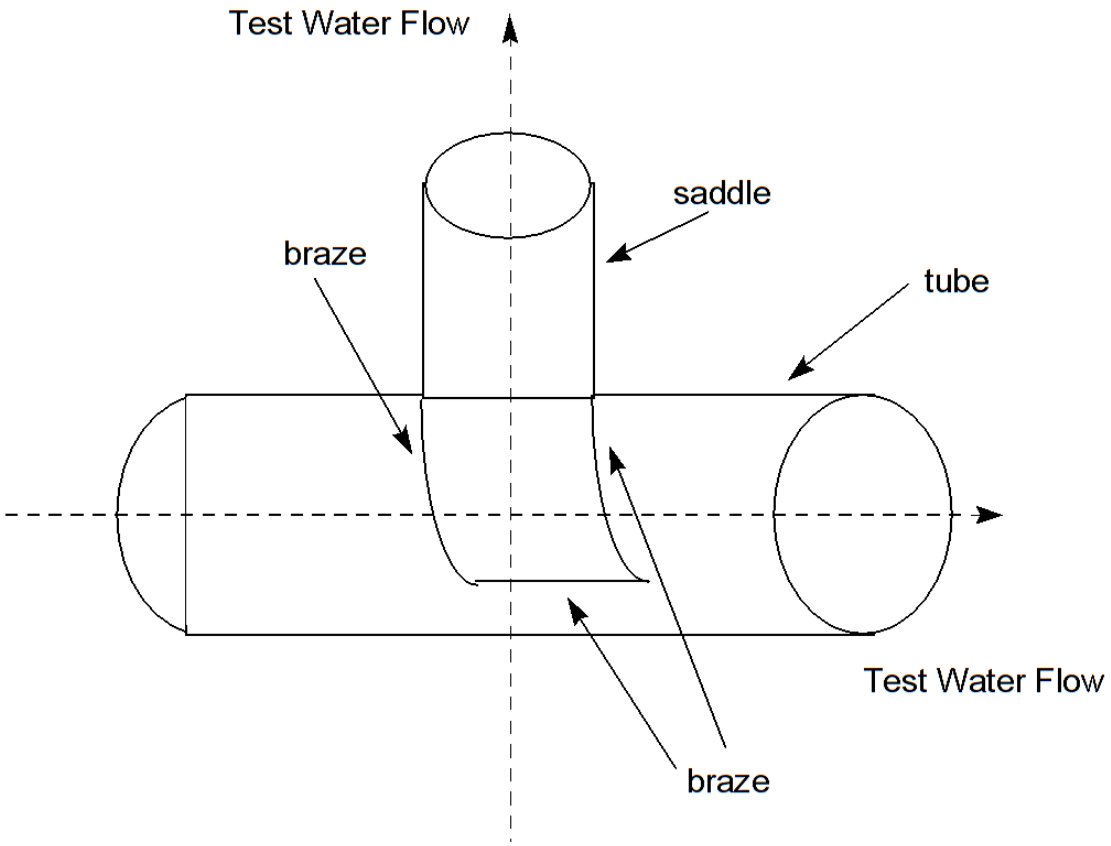


Disadvantage – more levels mean more experiments

A **2 Level** experiment $\mathbf{L_{16}\,(2^{15})}$ allows **15 factors** and requires **16 experiments**

A **3 Level** experiment $\mathbf{L_{27}\,(2^{13})}$ allows **13 factors** and requires **27 experiments**

Let’s try an example DOE – a Brazed Tube Assembly



BRAZED TUBE ASSEMBLY

The completed assembly of a metal saddle tube brazed to a large diameter metal tube is subjected to 100% water leakage test.

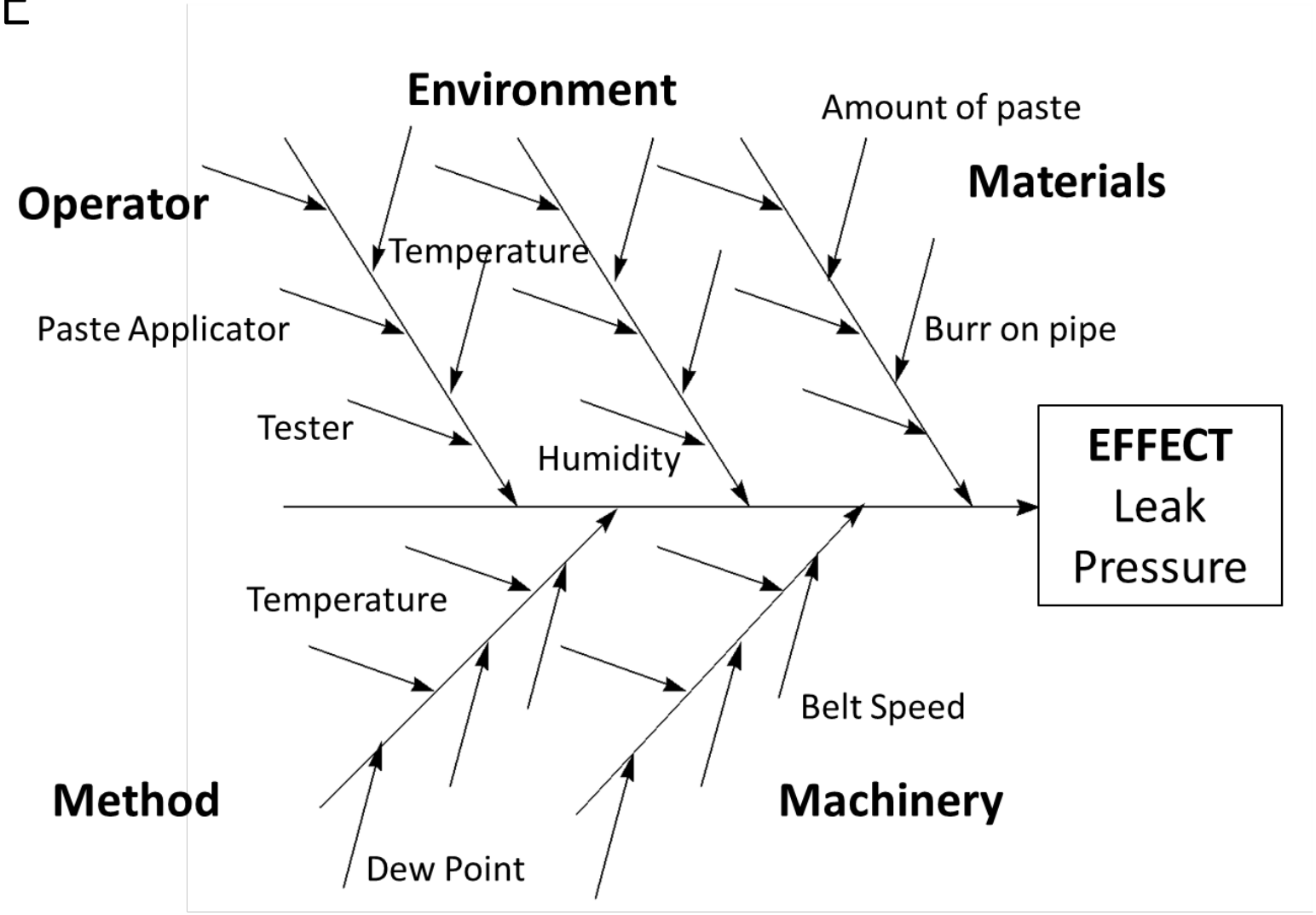
A stopper is inserted into the saddle tube while both ends of the large diameter metal tube is connected to hoses through which water pressure is applied.

Test ends when the braze between the two tubes leak.

The **Effect** that we’ll be measuring is **Leak Pressure**.

Steps to complete a DOE

Step 1 – brainstorm using a Cause & Effect Diagram to determine the “Factors” that are significant to the “Effect”.



Note: The dew point is the temperature below which the water vapour in a volume of humid air at a given constant barometric pressure will condense into liquid water at the same rate at which it evaporates. Condensed water is called dew when it forms on a solid surface.

Steps to complete a DOE

Step 2 – create a Factor Table based on the results of the brainstorming.

1. Determine your Factors
2. Determine your significant Interactions (if any)
3. Assign a Letter
4. Set your levels

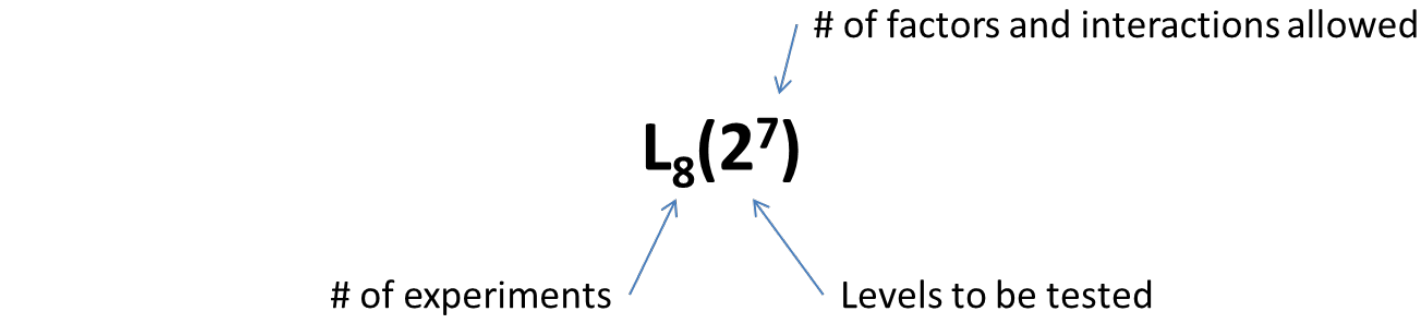
Note: The "Factors" you select must be controllable. If there are any uncontrollable factors that you feel may be present during the experiments (i.e., environment), take what steps you feel are needed to minimize influence.

LETTER	FACTOR	LEVEL 1	LEVEL 2
A	Temperature	1850^0 F	1900^0 F
B	Speed	20 in/min	30 in/min
C	Dew Point	30^0 F	40^0 F
D	Amount of Paste	1x current	2x current
E	Burr on Pipe	No Burr	Burr
AxB	Interaction	NA	NA
AxC	Interaction	NA	NA

Steps to complete a DOE

Step 3 – select an "Orthogonal Array" to match the needs for the DOE.

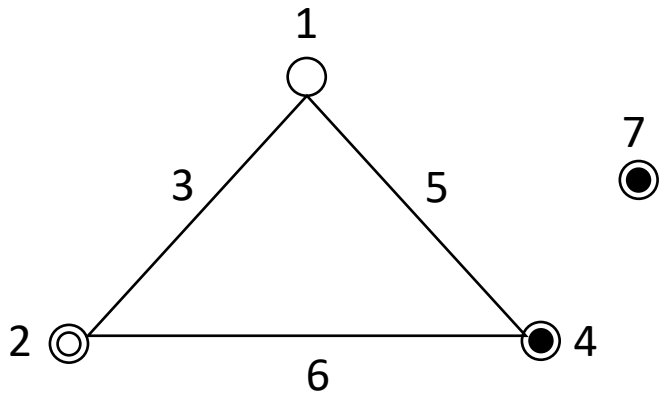
There were 5 "Factors" and 2 "Interactions" identified which would need a total of **7 columns**. In addition, **2 levels** were determined for each factor.



	1	2	3	4	5	6	7	Effect
1	1	1	1	1	1	1	1	
2	1	2	2	2	2	2	2	
3	1	1	2	1	1	2	2	
4	1	2	1	2	2	1	1	
5	2	1	2	1	2	1	2	
6	2	1	2	2	1	2	1	
7	2	2	1	1	2	2	1	
8	2	2	1	2	1	1	2	

Steps to complete a DOE

Step 4 – select a "Linear Graph" to match the needs of the DOE.



This will help us determine which controlling (and controllable) factors we will place over which columns of the Orthogonal Array we have selected (i.e., hardest to change over least number of changes, potential interactions, etc.

Change Symbols	
SYMBOL	NUMBER OF CHANGES
○	Least changes
◎	Less changes
◉	More changes
●	Most changes

Steps to complete a DOE

Step 5 – setup our Orthogonal Array and run our experiments.

It was decided ahead of time what factors and interactions were likely to be most significant. These were placed on the Orthogonal Array, and it became the recipe for each experiment.

LETTER	FACTOR	LEVEL 1	LEVEL 2
A	Temperature	1850^0 F	1900^0 F
B	Speed	20 in/min	30 in/min
C	Dew Point	30^0 F	40^0 F
D	Amount of Paste	1x current	2x current
E	Burr on Pipe	No Burr	Burr
AxB	Interaction	NA	NA
AxC	Interaction	NA	NA

$L_8(2^7)$

	1 **C**	2 **A**	3 **AxC**	4 **B**	5 **D**	6 **AxB**	7 **E**	Leak Pressure
1	1	1	1	1	1	1	1	193
2	1	2	2	2	2	2	2	239
3	1	1	2	1	1	2	2	192
4	1	2	1	2	2	1	1	196
5	2	1	2	1	2	1	2	210
6	2	1	2	2	1	2	1	220
7	2	2	1	1	2	2	1	173
8	2	2	1	2	1	1	2	217

Steps to complete a DOE

Step 6 – analyze the results and add them to the Factor Table.

To analyze the results, we calculate the average for the different factor levels and supposed interactions. The interaction columns are calculated the same way as each of the factor columns.

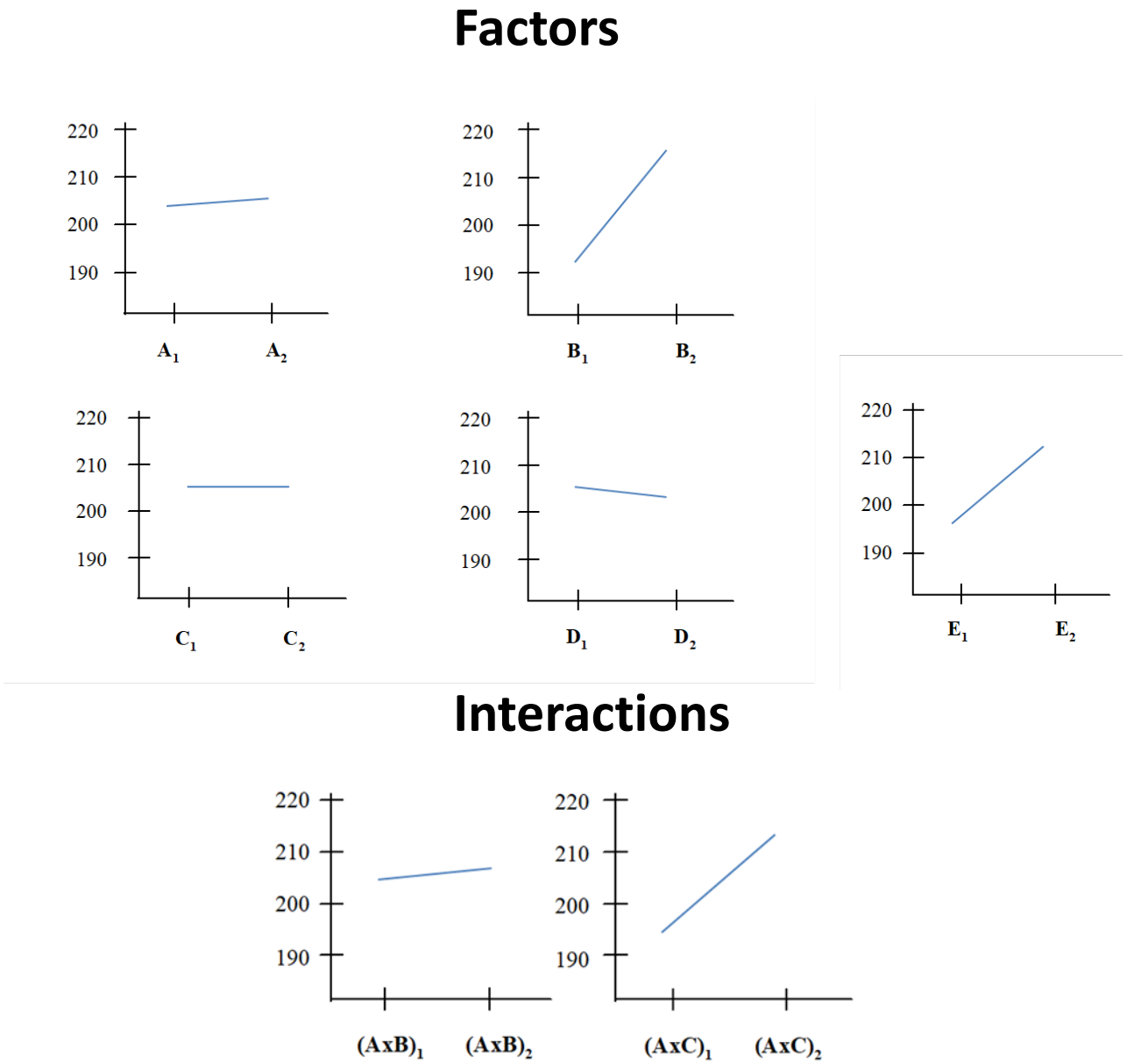
Example $A_1 = \frac{(193 + 192 + 210 + 220)}{4} = \frac{815}{4} = \mathbf{203.8}$

COLUMN	LETTER	FACTOR	LEVEL 1 RESULTS	LEVEL 2 RESULTS
2	A	Temperature	**203.8**	206.3
4	B	Speed	192.0	218.0
1	C	Dew Point	205.0	205.0
5	D	Amount of Paste	205.0	204.5
7	E	Burr on Pipe	195.5	214.5
6	AxB	Interaction	204.0	206.0
3	AxC	Interaction	194.8	215.3

Steps to complete a DOE

Step 7 – chart the results for each of the factor and interaction columns.

Charting the averages within each column gives us a visual way of determining whether the difference between the levels are significant. Each graph must have identical scales in order to compare one against the other.

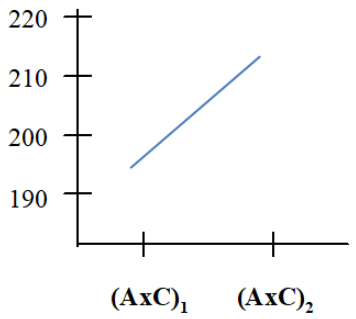


Steps to complete a DOE

Step 8 – test the interactions to see if they even exist.

Interactions must be calculated and viewed in two ways. In **Step 7**, we tested to see if they exerted any significant influence over the effect if they existed, but now we'll test to see if they even exist in the first place.

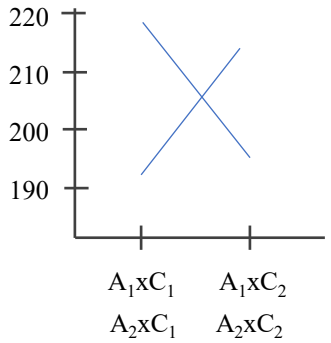
The interaction AxC looks significant.



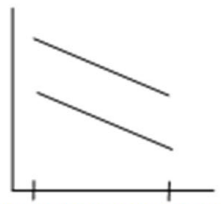
By calculating the averages of A_1xC_1, A_1xC_2, A_2xC_1 and A_2xC_2 and graphing the points, we find that the interaction not only looks significant, but that it exists as well.

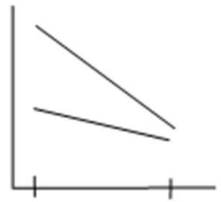
Example

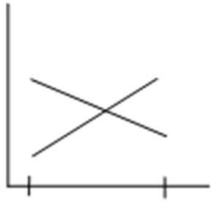
$$A_1xC_1 = \frac{(193 + 192)}{2} = \frac{385}{2} = \mathbf{192.5}$$



This would cause some additional focused experiments between **Factor A** (Temperature) and **Factor C** (Dew Point) to explore how it may affect the optimum result.


NO INTERACTION SINCE LINES ARE PARALLEL


LIGHT INTERACTION SINCE LINES ARE ALMOST PARALLEL


HEAVY INTERACTION SINCE LINES ARE OPPOSED

Steps to complete a DOE

Step 9 – interpret the results.

The Optimum Level for the process is now easy to spot. The process formula shown in the table is not represented on the Orthogonal Array. Create a sample using the optimum recipe and there's a chance the results will be even better.

LETTER	FACTOR	LEVEL 1	LEVEL 2
A	Temperature	1850^0 F	**1900^0 F**
B	Speed	20 in/min	**30 in/min**
C	Dew Point	30^0 F	40^0 F
D	Amount of Paste	**1x current**	2x current
E	Burr on Pipe	No Burr	**Burr**
AxB	Interaction	NA	NA
AxC	Interaction	NA	NA

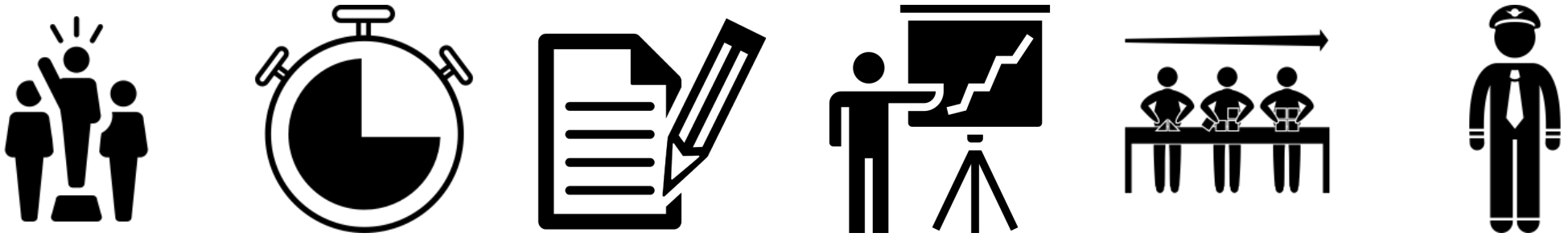
And don't forget the **significant interaction** between **Factor A** (Temperature) and **Factor C** (Dew Point). Even though changes to the Dew Point in the experiment runs did not show up on the radar, an interaction between that factor and temperature did.

It would be worthwhile to look further into that interaction to see if the optimum level can be raised even further.

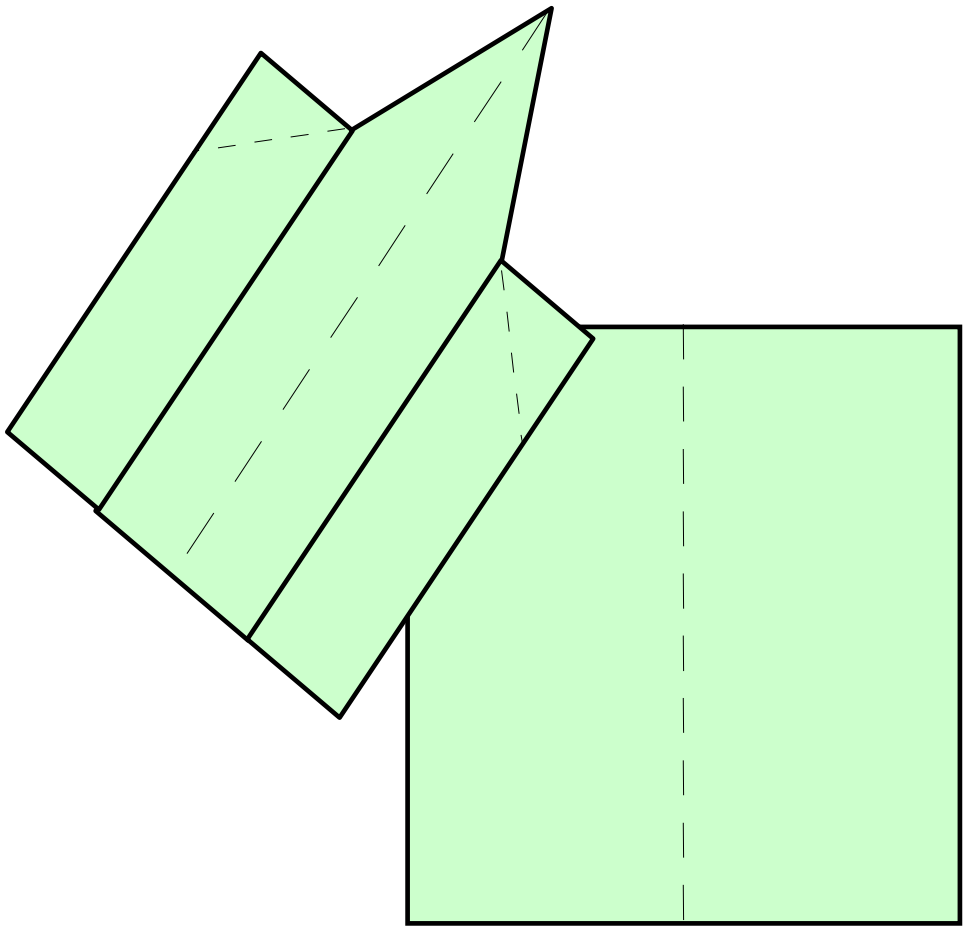
Let’s design a DOE of our own

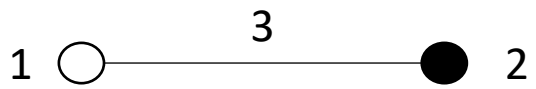
First let’s take **5 minutes** to set up some team responsibilities:

- **Facilitator** – lead the team and make sure everyone gets involved.
- **Timekeeper** – makes sure that the team completes their tasks on time.
- **Recorder** – records results and places key information on flipcharts.
- **Presenter** – presents the results of their team DOE.
- **Designer** – builds the airplanes according to team instructions.
- **Pilot** – pilots the airplane designs (unless this is elected as a factor).



We'll make paper airplanes





Linear Graph

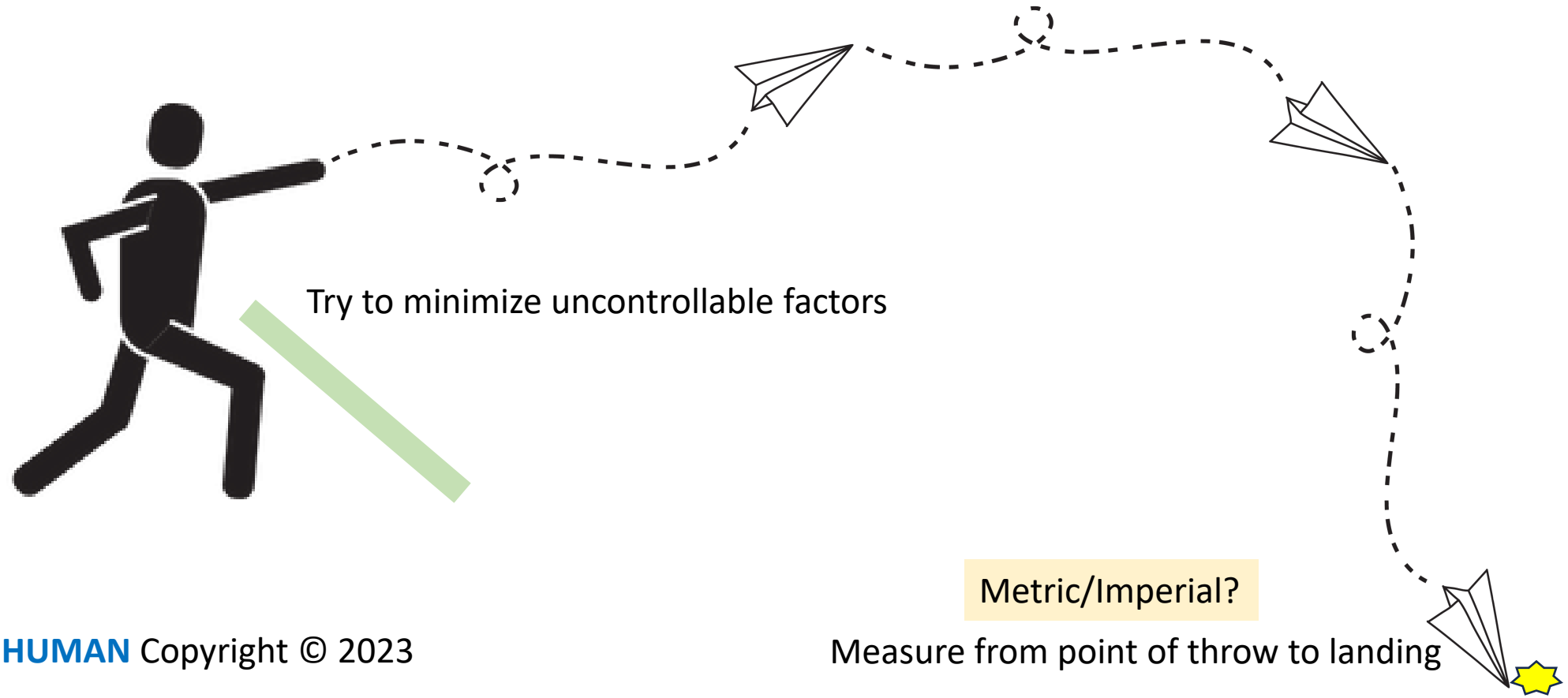
$L_4(2^3)$

	1	2	3
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

Orthogonal Array

Objective of the airplane DOE

The objective is to produce a design and process that will **fly the farthest**.



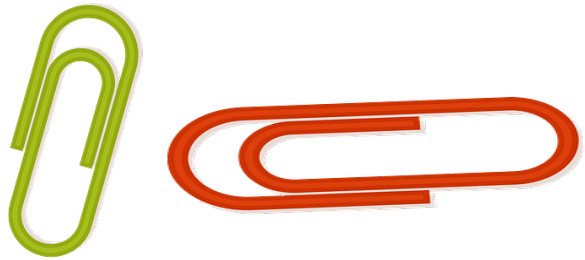
Try to minimize uncontrollable factors

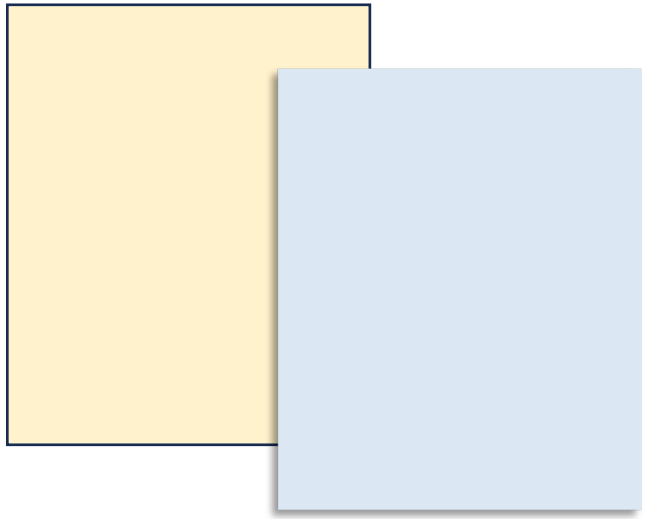
Metric/Imperial?

Measure from point of throw to landing

Materials and tools available

Materials and Tools are available on the back table.

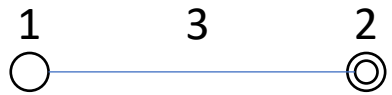




Use a tape measure to measure distance.

Use a Smart Phone to keep time and calculate results.

We'll use an $L_4(2^3)$ Orthogonal Array



# of factors and interactions allowed

$L_4(2^3)$

# of experiments

Levels to be tested

	1	2	3	Effect
1	1	1	1	
2	1	2	2	
3	2	1	2	
4	2	2	1	

Interaction Results – average when both factors are at that level under their columns.

Factor Results – average when factor is at that level under its column.

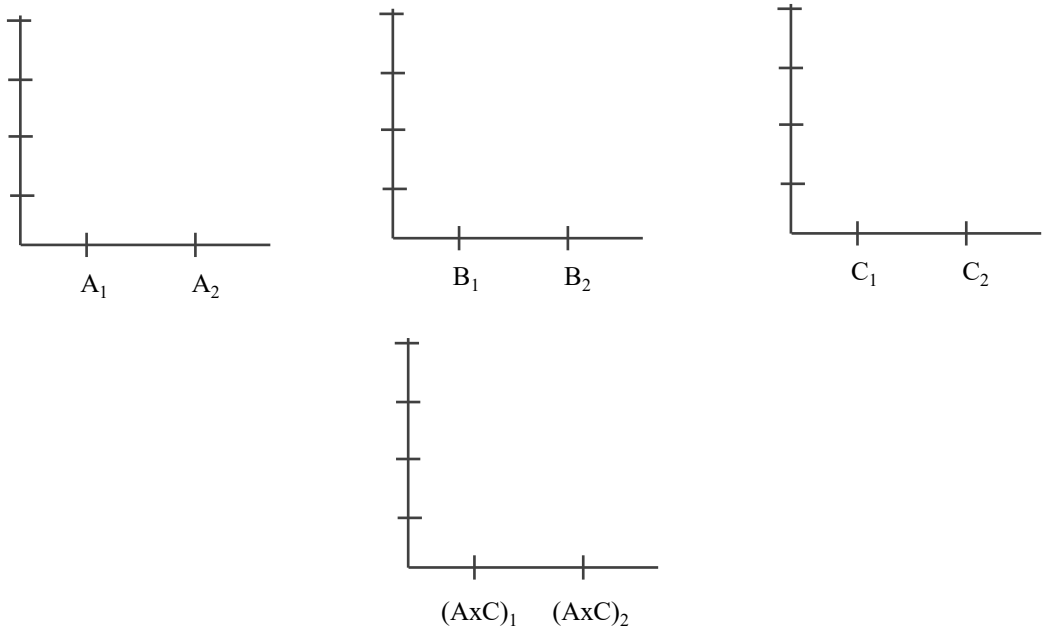
Column	Letter	Factor	Level 1	Level 2	Level 1 Results	Level 2 Results
1						
2						
3						
1 x 3						

Instructions and graphs

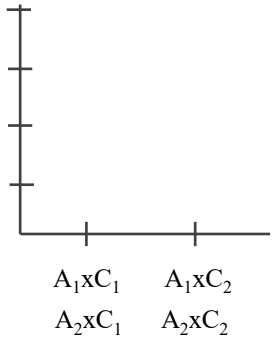
Steps – you have 60 minutes

1. Brainstorm using a Cause & Effect Diagram. The effect is "**Distance**".
2. Select 3 factors and/or interactions and complete the columns "Letter", "Factor", "Level 1" and "Level 2" of your Factor/Results Table.
3. Setup Orthogonal Array, run your experiments and add results to the "Effects" column".
4. Average the results and add them to your Factor/Results Table.
5. Determine the scale and chart the results of your factors and interactions for significance.
6. **If time allows** – average and chart the results of your interaction to see if it even exists.

Factors and Interactions - Significant

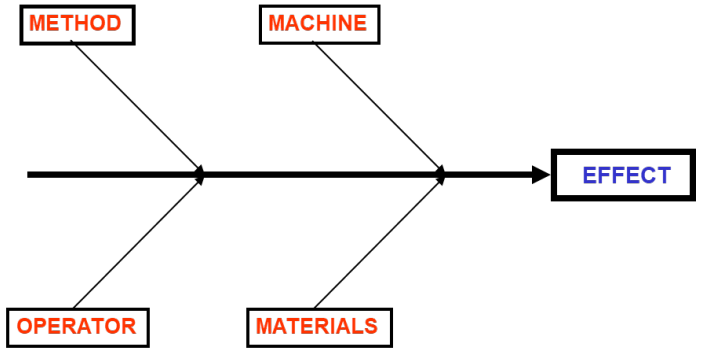


Interactions - Exist

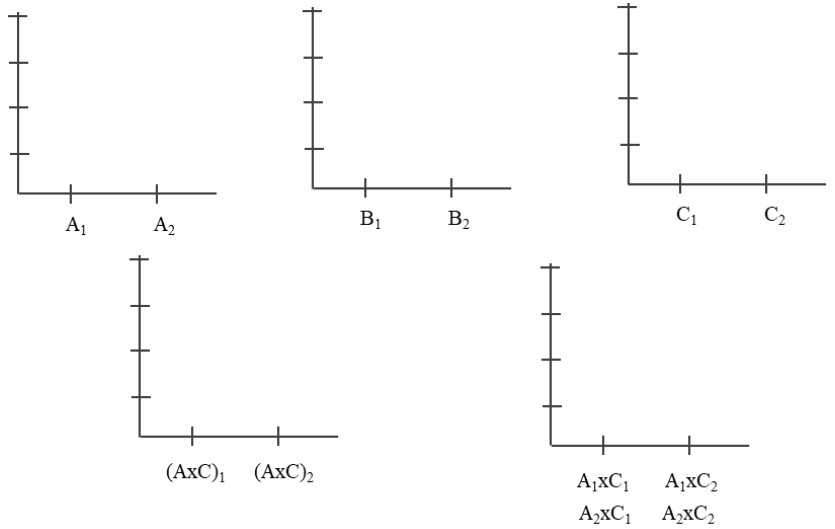


3 Report Outs to tell the story

1. Cause and Effect Diagram



3. Charts for Factors and Interactions



2. Factor/Results Table

Column	Letter	Factor	Level 1	Level 2	Level 1 Results	Level 2 Results
1						
2						
3						
1 x 3						

Teams have 1 hour to be ready for the Report Outs

Suggestions to keep on track

15 minutes to complete the Cause & Effect Diagram and select Factors and Interactions

15 minutes to create the airplane designs and fill out the Factor/Results Table.

15 minutes to calculate the Factors and Interactions and complete the graphs.

15 minutes to ready the Report Out presentations on the Flip Charts.

Can Taguchi DOEs be used to improve services?

No! No! No!

Some Potential Barriers

1. Lack of Awareness, knowledge and misconceptions.
2. Performance is difficult to measure accurately.
3. Performance depends a great deal on behaviour of humans delivering the service.
4. More “noise” factors associated with service processes.
5. Services are often simultaneously created and consumed.
6. A clear description and distinction of service processes is needed.
7. Can’t conduct too many trials of controlled experiments in a service environment.
8. DOE is a “techy” tool and service managers are unlikely to have the proper mathematical background.
9. Lack of standardized work processes.
10. Lack of improvement mindset.

Examples above provided by the paper “Design of Experiments for Non-Manufacturing Processes: Benefits, Challenges and Some Examples” *by Jiju Anthony, Shirley Coleman, Douglas Montgomery, Mark Anderson and Rachel Johnson*

Can Taguchi DOEs be used to improve services?

Yes! Yes! Yes!

Some Potential Motivators

1. Lack of awareness – can this change?
2. Surveys using A/B Concept Testing are already in use in many areas.
3. Automation in services will help to cut down variation.
4. Services are often simultaneously created and consumed – how to gain data from this?
5. A clear description and distinction of service processes is needed – can this change?
6. Can't conduct too many trials of controlled experiments in a service environment – why not?
7. DOE is a "techy" tool and service managers are unlikely to have the proper mathematical background – is this needed? FMEAs used to be used only in manufacturing. Now they are prevalent everywhere!
8. Lack of standardized work processes – is this true?
9. Lack of improvement mindset – is this true?

Can Taguchi DOEs be used to improve services?

Yes! Yes! Yes!

Who's been using it?

1. Hollands and Cravens (1978) – illustrated the effect of advertising and other critical factors on the sales of candy bars.
2. Ledolter and Swersey (2006) described the power of a fractional factorial experiment to increase the subscriptions response rate of Mother Jones magazine. Automation in services will help to cut down variation.
3. Kumar et al. (1996) showed its use to improve the response-time performance of an information group operation responsible for addressing customer complaints in a small software export company.
4. Holcomb (1994) illustrated the use to determine the optimal settings of customer service delivery attributes that reduce cost without affecting quality.
5. Blosch and Antony (1999) demonstrated the use of computer simulation and DoE to identify the key risk variables within the manpower planning system at the UK‟s Royal Navy.
6. Raajpoot et al. (2008) presented the application of Taguchi approach of DoE to retail service.

References

1. Taguchi Techniques for Quality Engineering *by Philip J. Ross*
2. Understanding Industrial Designed Experimentation *by Stephen Schmidt & Robert Launsby*
3. The Experimenter's Handbook *by Richard B. Clements*
4. Design and Analysis of Experiments, 3rd Edition *by Douglas C. Montgomery*
5. Designing for Quality: An Introduction to the Best of Taguchi and Western Methods of Statistical Experimental Design *by Robert H. Lochner and Joseph E. Matar*
6. Introduction to Quality Engineering: Designing Quality into Products and Processes *by Genichi Taguchi*
7. System of Experimental Design (2 volumes) *by Genichi Taguchi (see Chapter 9 for more information about Orthogonal Array column groupings and change symbols)*

for listening

We hope that you enjoyed this interactive workshop

DOE Made Easy

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