



# Teaching and Learning from Effective Experimentation

What the Practice of DOE Teaches Us About Deriving Meaning from any Data



1

# Topics

-  • DOE - WHAT & WHY?
-  • CASE STUDY
-  • 5 CARDINAL RULES
-  • 5-STEP PROTOCOL
-  • 12 LESSONS






2

# BENEFITS

-  • DOE - WHAT & WHY?
-  • CASE STUDY
-  • 5 CARDINAL RULES
-  • 5-STEP PROTOCOL
-  • 12 LESSONS

3

# TEACHING

-  • DOE - WHAT & WHY?
-  • CASE STUDY
-  • 5 CARDINAL RULES
-  • 5-STEP PROTOCOL
-  • 12 LESSONS

4

# UNIVERSALITY

-  • DOE - WHAT & WHY?
-  • CASE STUDY
-  • 5 CARDINAL RULES
-  • 5-STEP PROTOCOL
-  • 12 LESSONS

5

# DOE – WHAT & WHY

---

6

WHAT?

DOE =  
DESIGN OF  
EXPERIMENTS

7

WHAT?

“Design of experiments (DOE) is a **systematic**, rigorous approach to engineering problem-solving that **applies principles and techniques at the data collection stage** so as to ensure the **generation of valid, defensible, and supportable engineering conclusions**. In addition, all of this is carried out under the constraint of a **minimal expenditure** of engineering runs, time, and money.”

NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY U.S. DEPARTMENT OF COMMERCE

8


WHAT?

“Design of experiments (DOE) is **systematic**, rigorous approach to engineering problem-solving that **applies principles and techniques** at the data collection stage so as to ensure the generation of valid, defensible, and **supportable engineering conclusions**. In addition, all of this is carried out under the constraint of **minimal expenditure** of engineering runs, time, and money.”

NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY U.S. DEPARTMENT OF COMMERCE

9


WHY?



LEARN

10


WHY?



GUIDE

11

WHY?



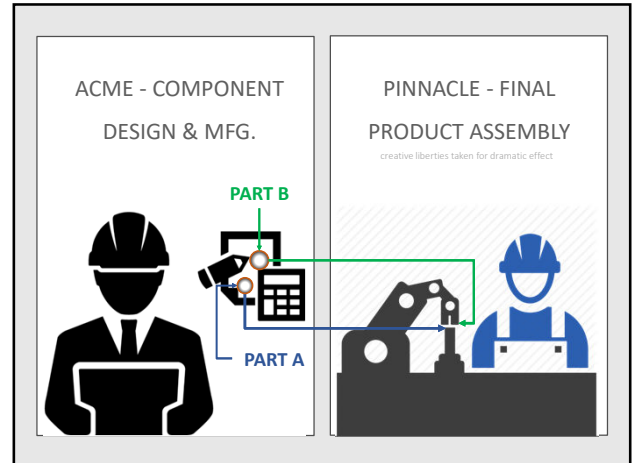
OPTIMIZE

12

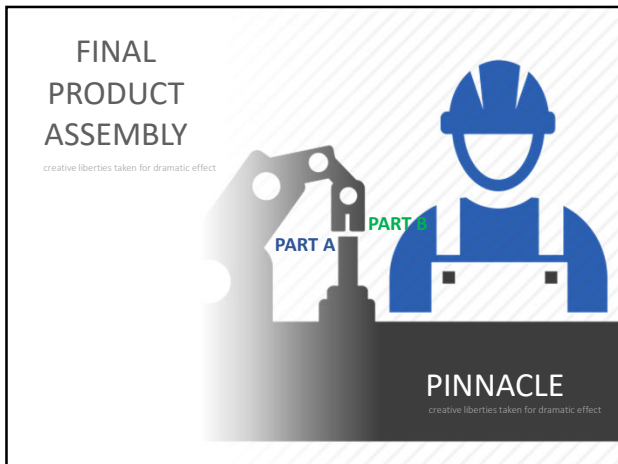
# CASE STUDY

(based on a true story, creative liberties taken for dramatic effect!)

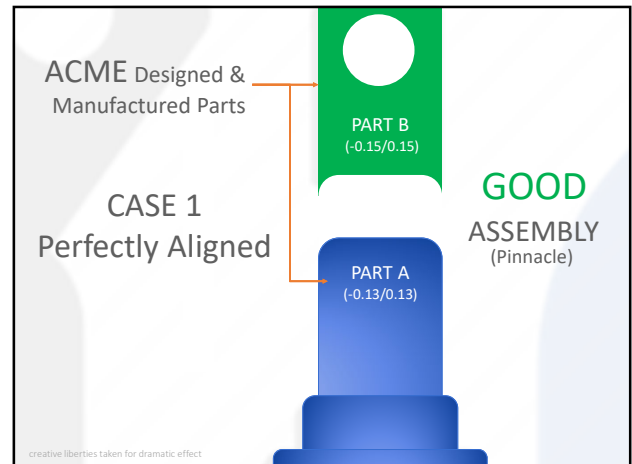
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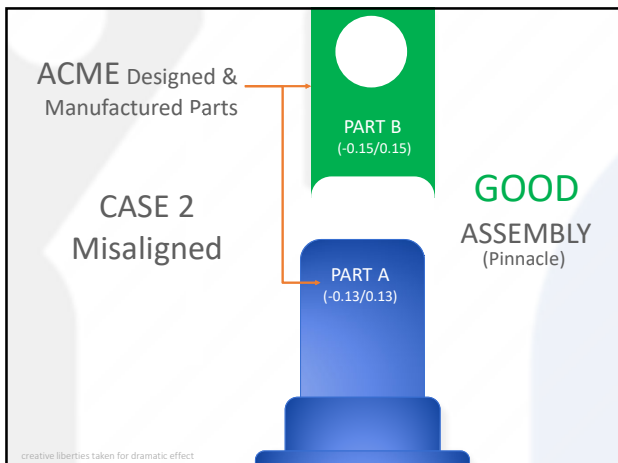
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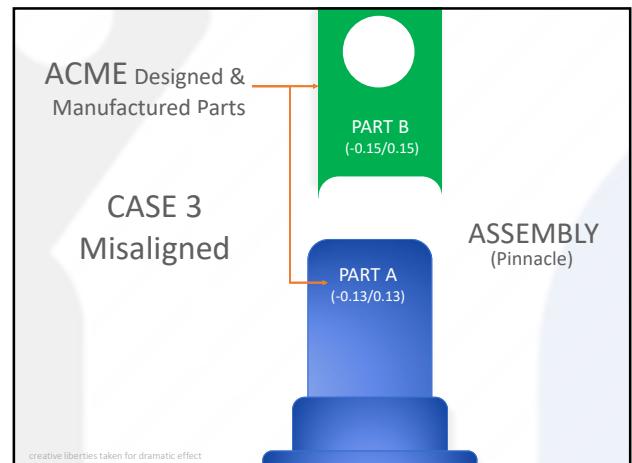
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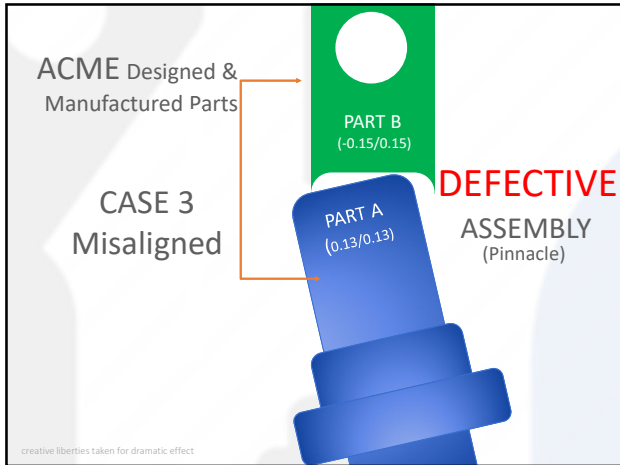
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17



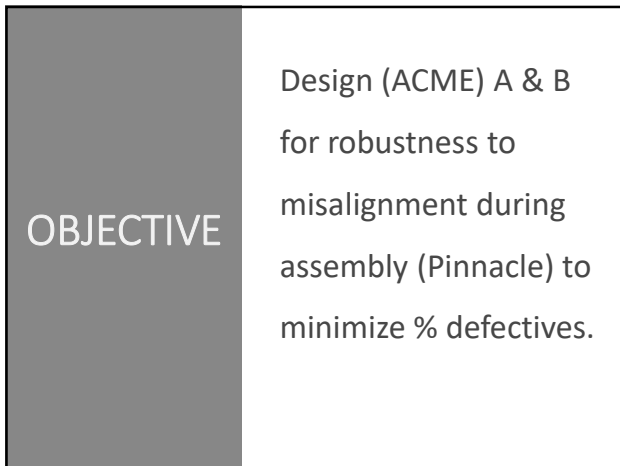
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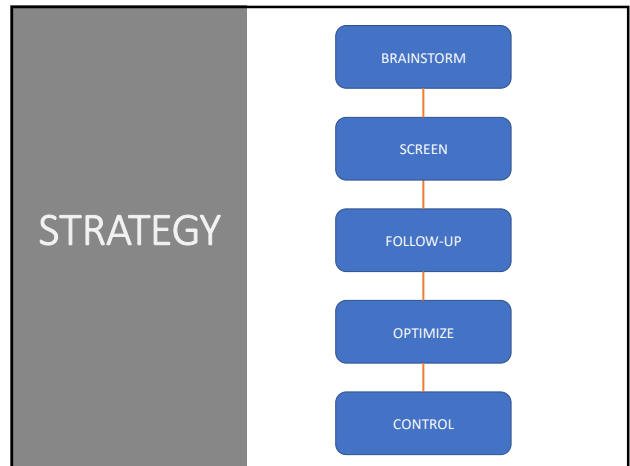
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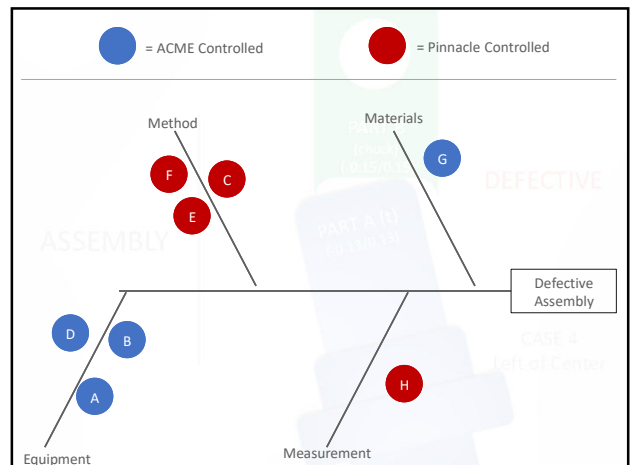
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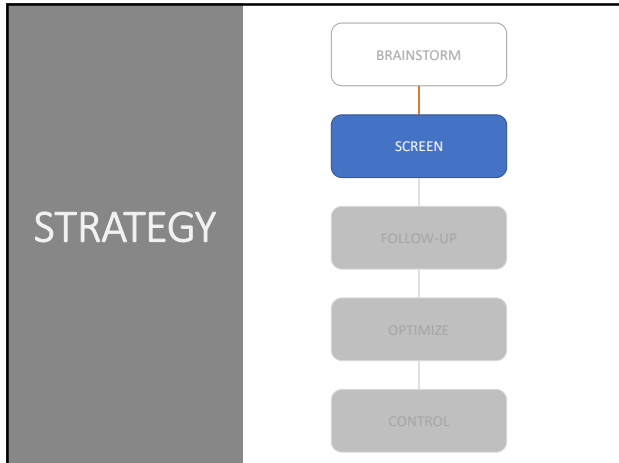
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23



24



25

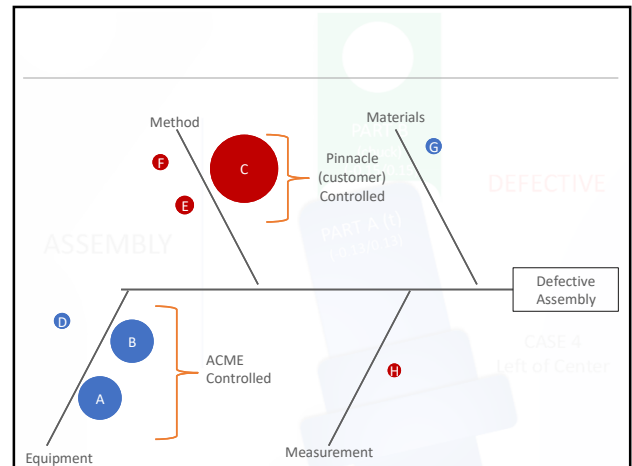
### SCREENING

Name	Units	Type	Low	High
A (Numeric)	A	Numeric	-1	1
B (Numeric)	B	Numeric	-1	1
C (Numeric)	C	Numeric	-1	1
D (Numeric)	D	Numeric	-1	1
E (Numeric)	E	Numeric	-1	1
F (Numeric)	F	Numeric	-1	1
G (Numeric)	G	Numeric	-1	1
H (Numeric)	H	Numeric	-1	1
I (Numeric)	I	Numeric	-1	1
J (Numeric)	J	Numeric	-1	1
K (Numeric)	K	Numeric	-1	1
L (Numeric)	L	Numeric	-1	1

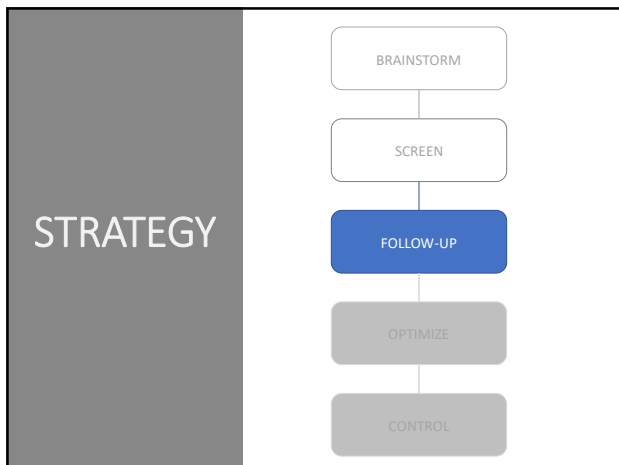
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### SCREENING

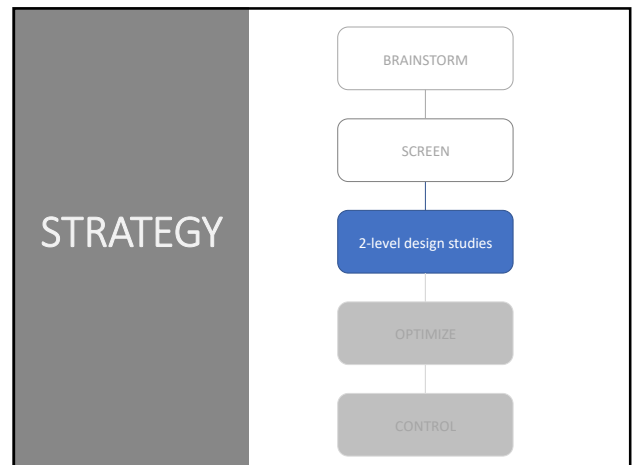
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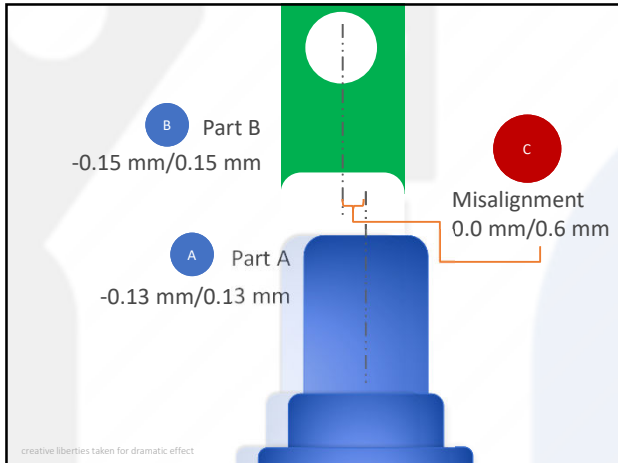
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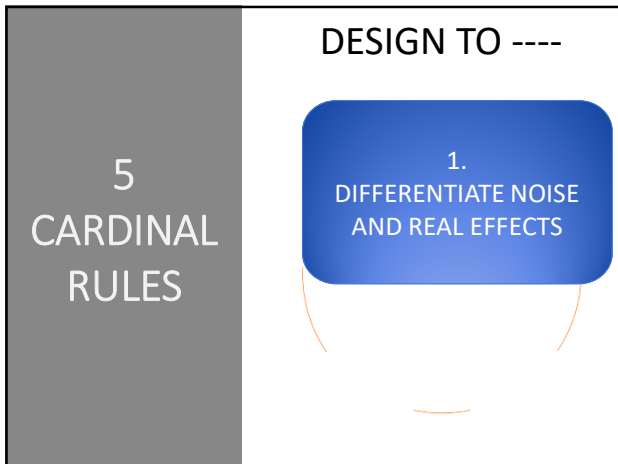
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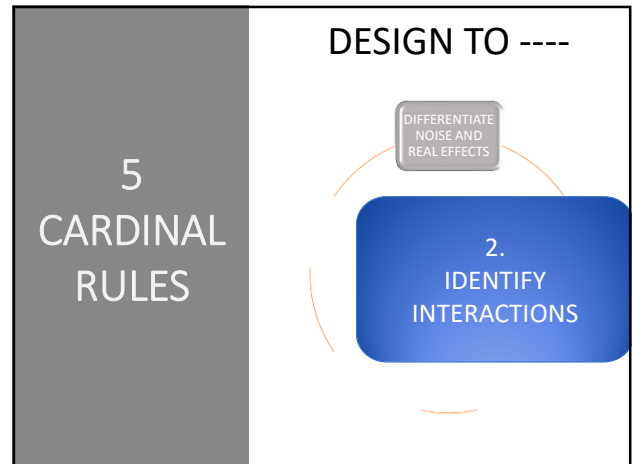
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# FIVE CARDINAL RULES

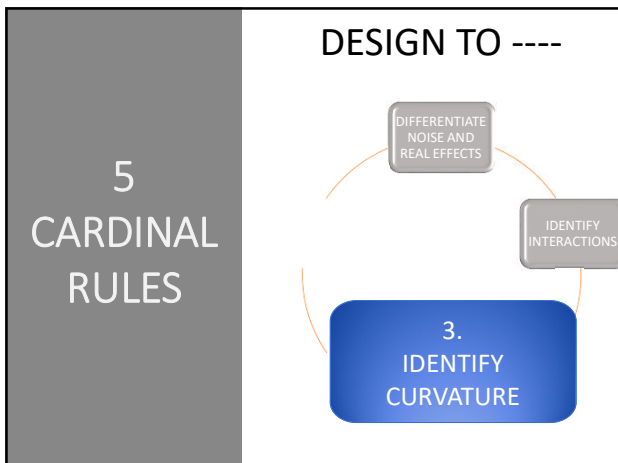
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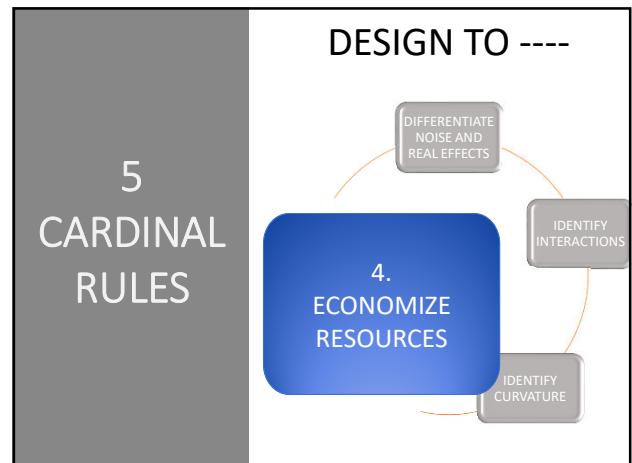
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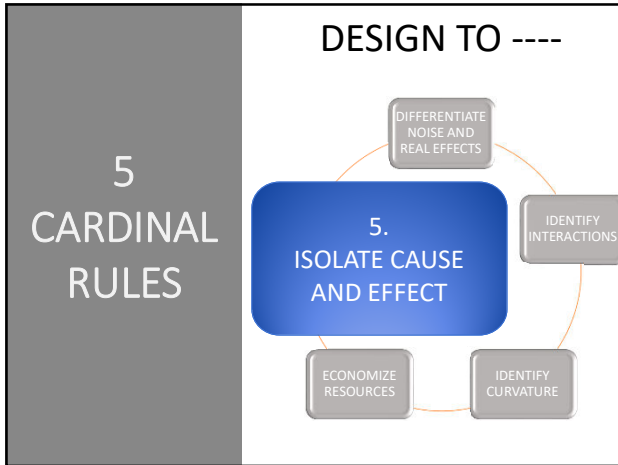
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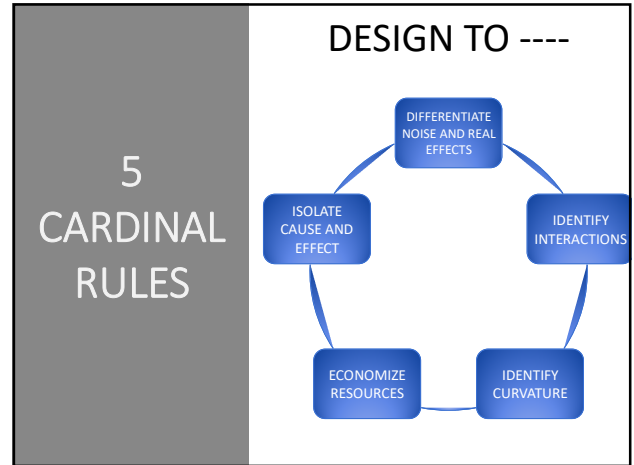
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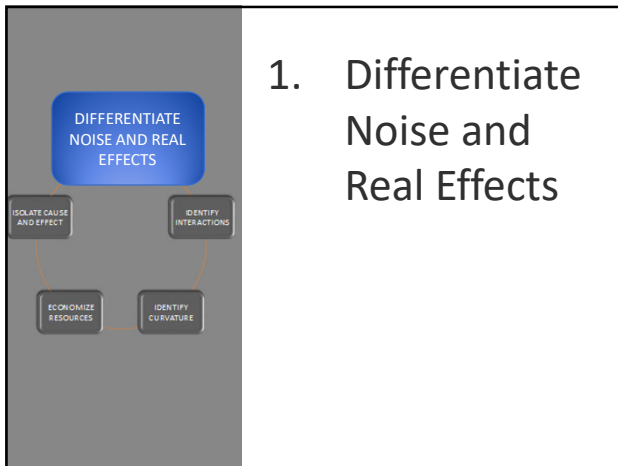
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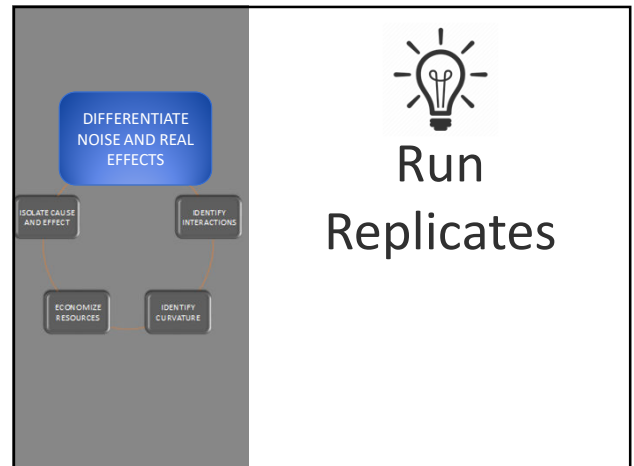
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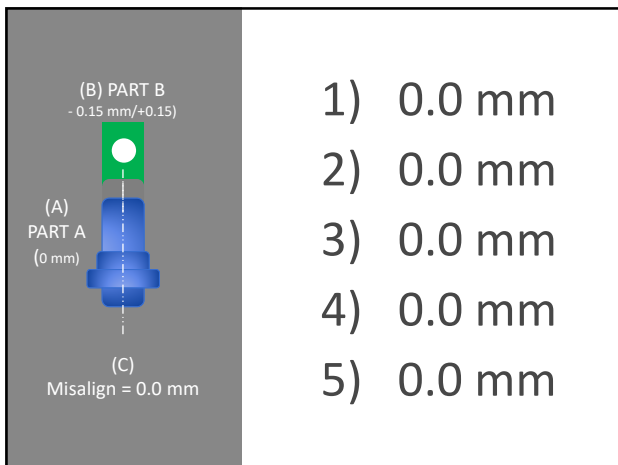
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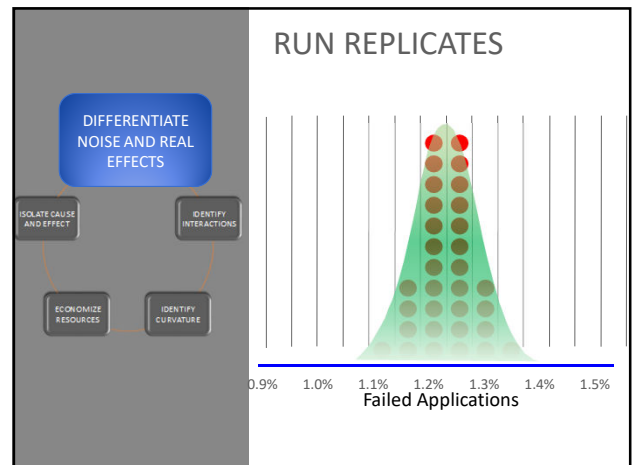
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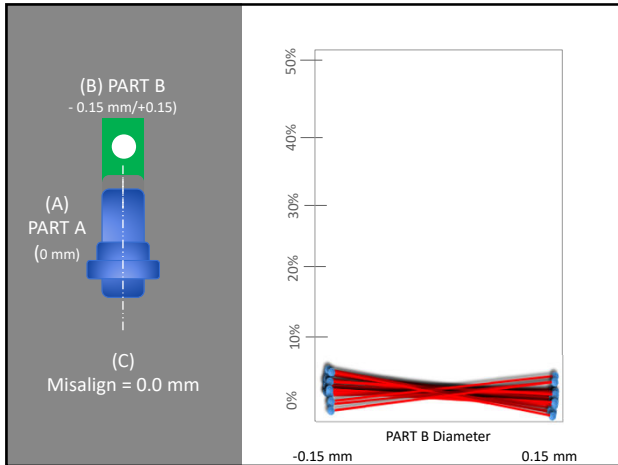
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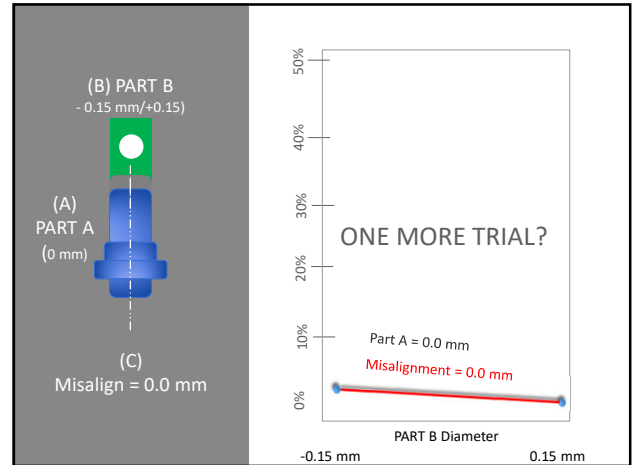
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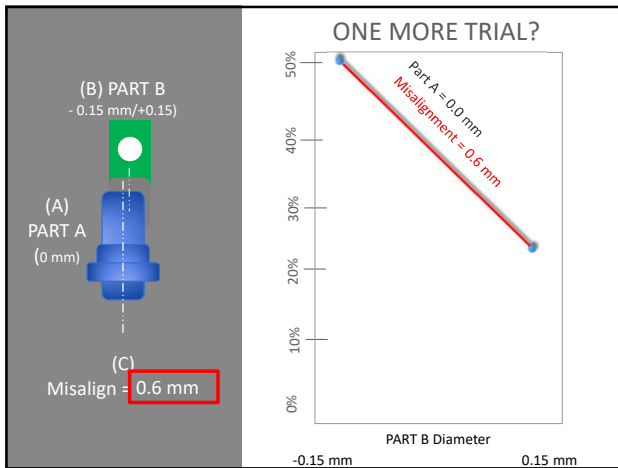
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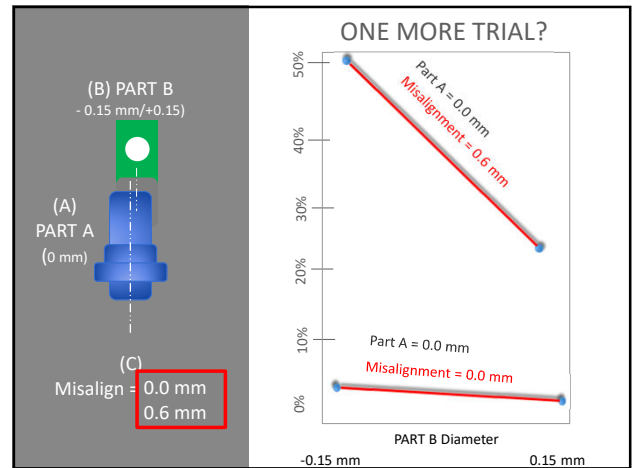
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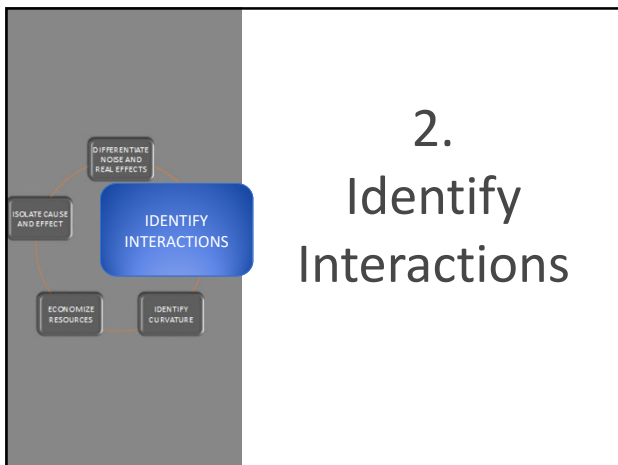
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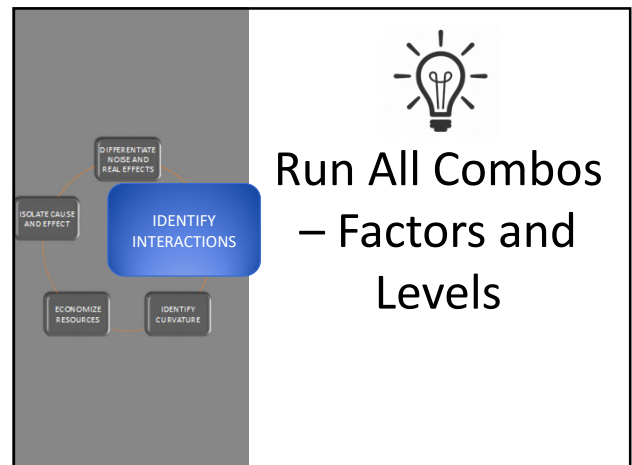
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46

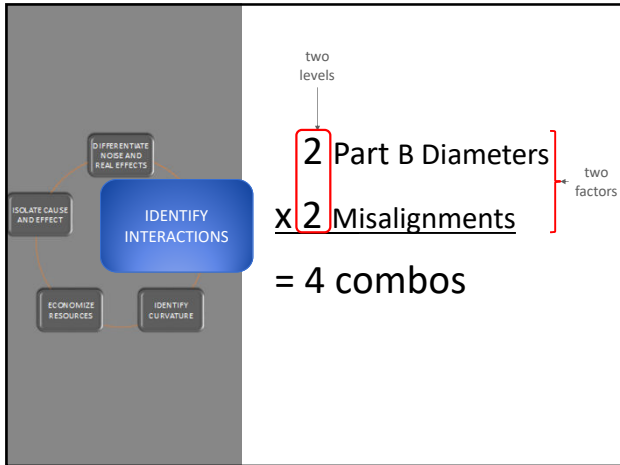


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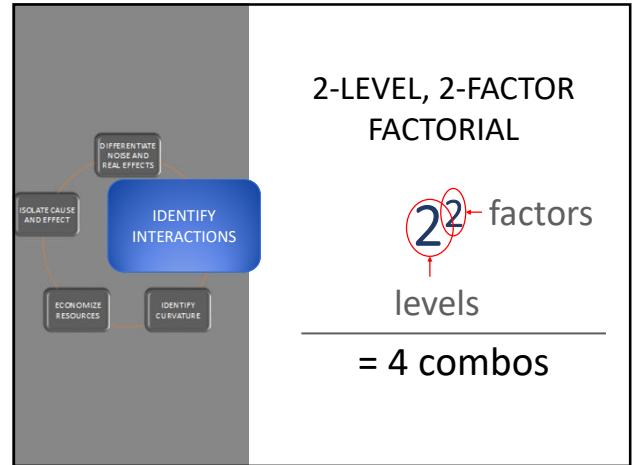


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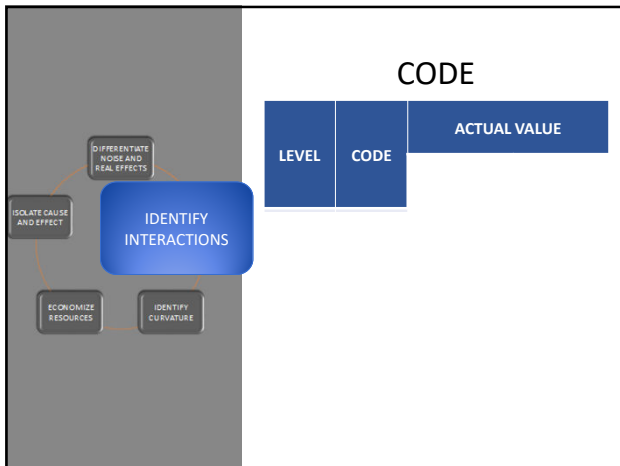




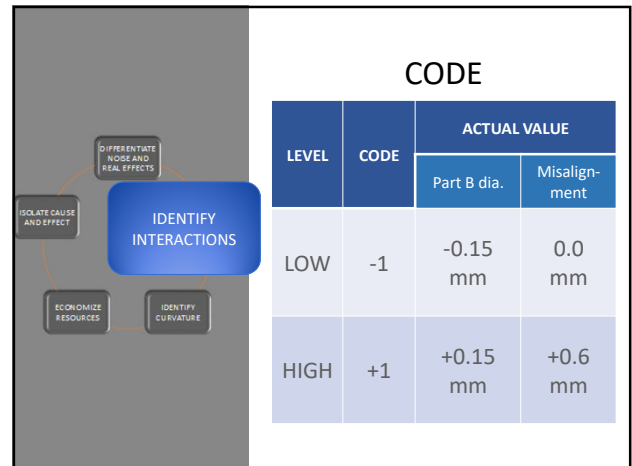
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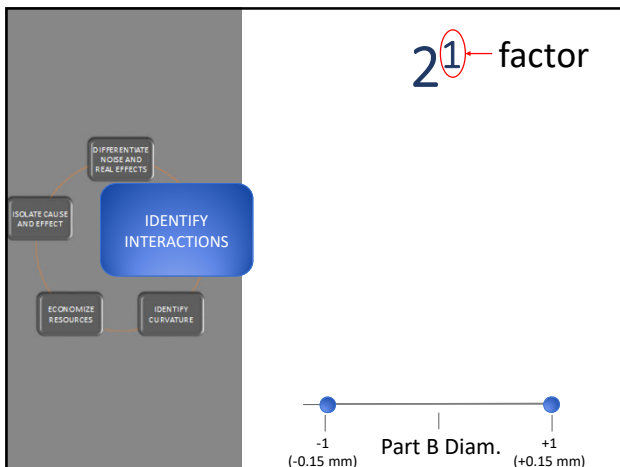
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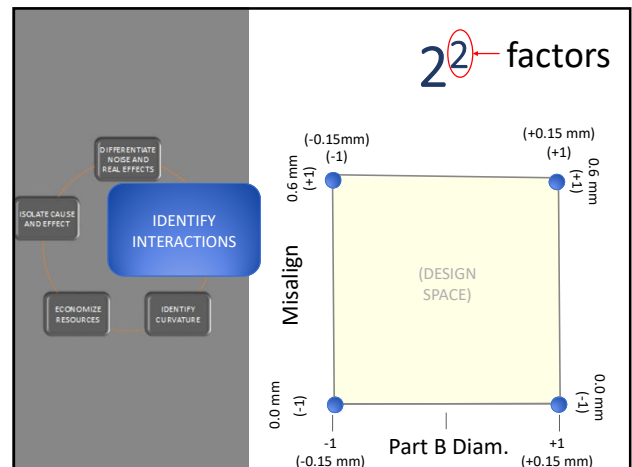
51



52



53



54

DESIGN FOR ALL COMBOS of LEVELS & FACTORS

• Design Order

DESIGN ORDER	B Diam.	code	Misalign.	code
1				
2				
3				
4				

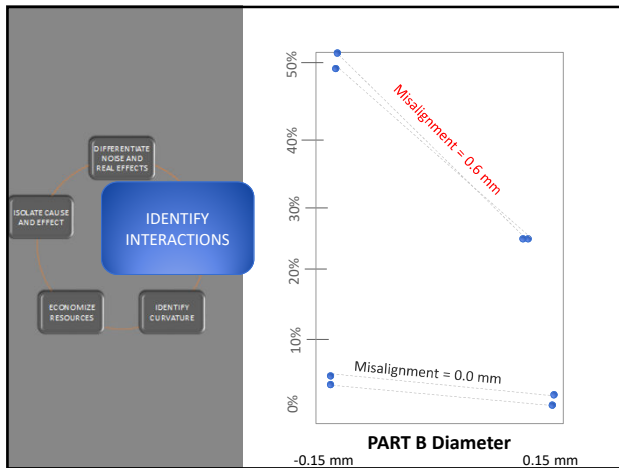
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DESIGN FOR ALL COMBOS of LEVELS & FACTORS

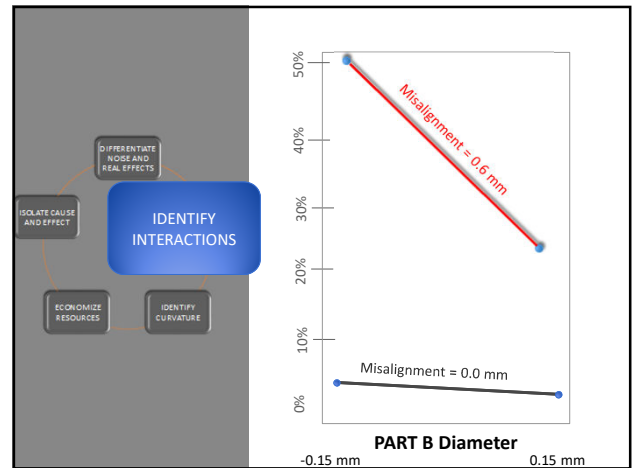
• Replicate

DESIGN ORDER	B Diam.	code	Misalign.	code
1	-0.15	-1	0.0	-1
2	+0.15	+1	0.0	-1
3	-0.15	-1	0.6	+1
4	+0.15	+1	0.6	+1
5	-0.15	-1	0.0	-1
6	+0.15	+1	0.0	-1
7	-0.15	-1	0.6	+1
8	+0.15	+1	0.6	+1

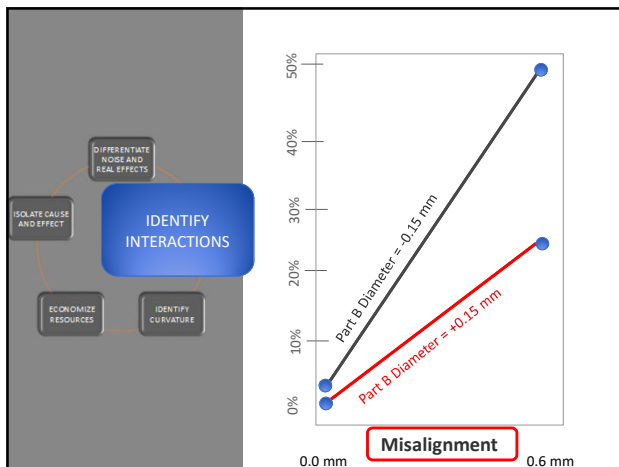
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57



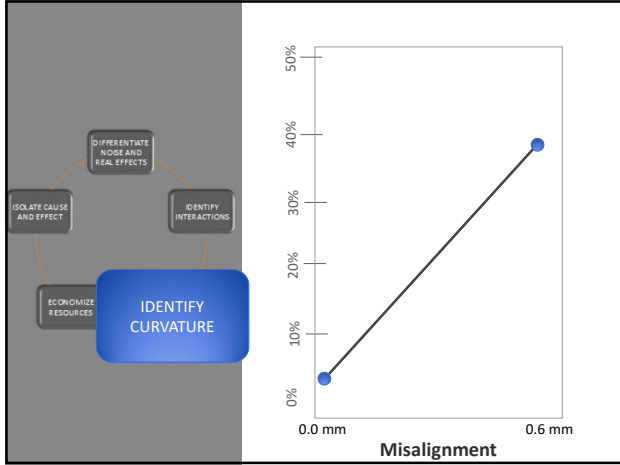
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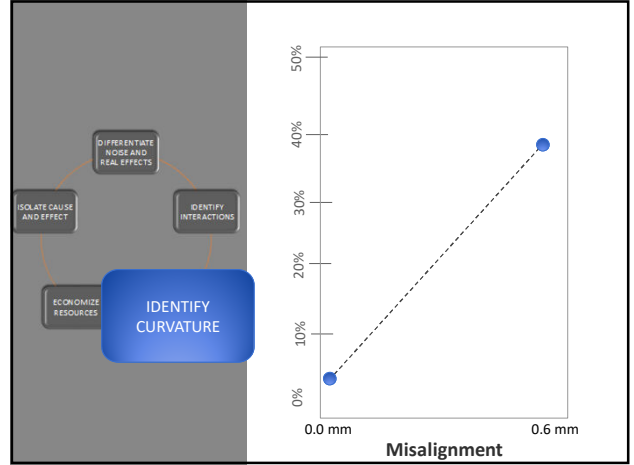
59

3. Identify Curvature

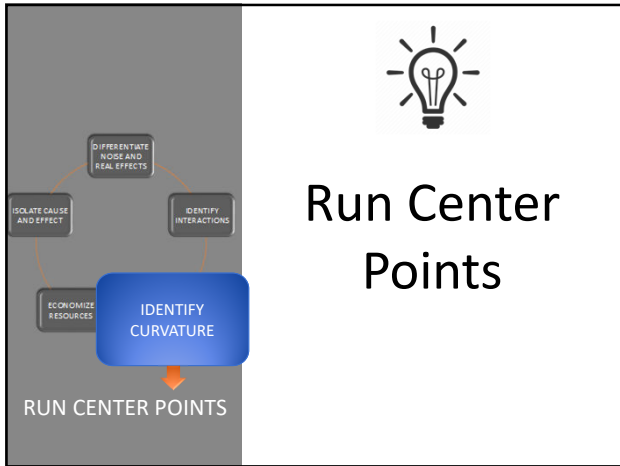
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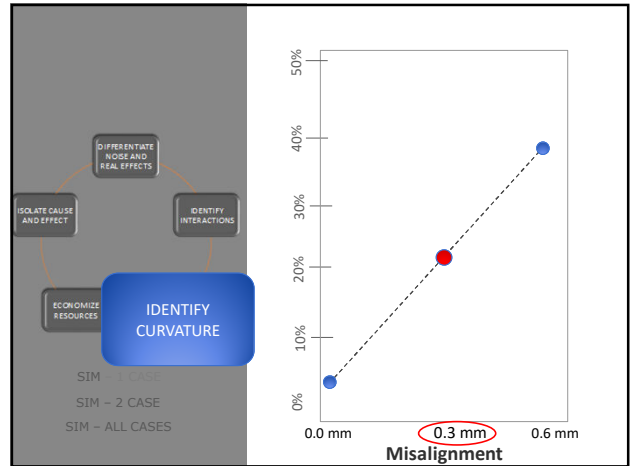
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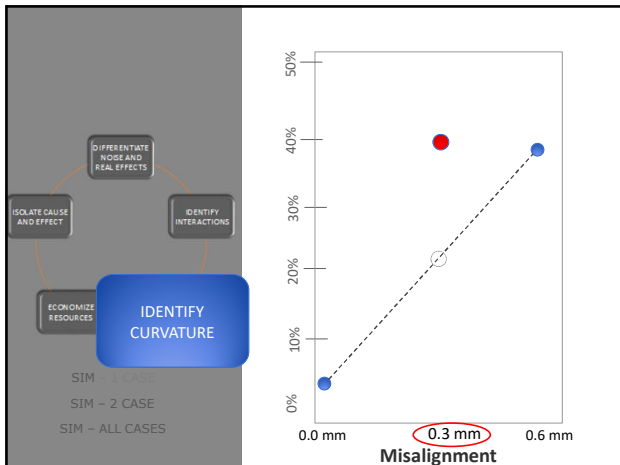
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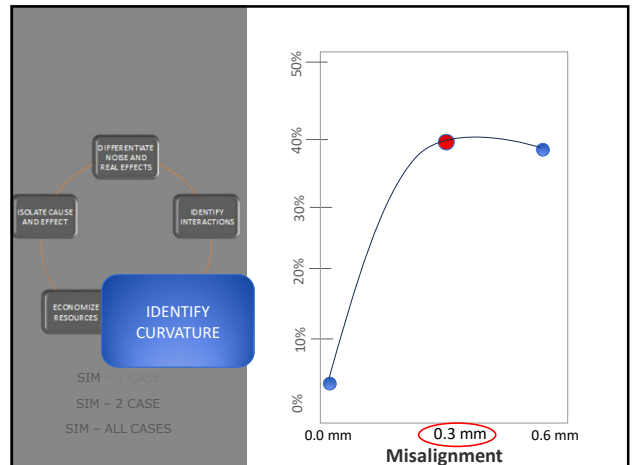
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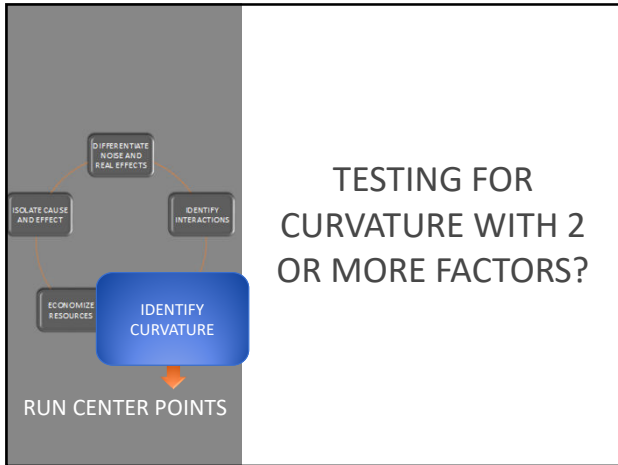
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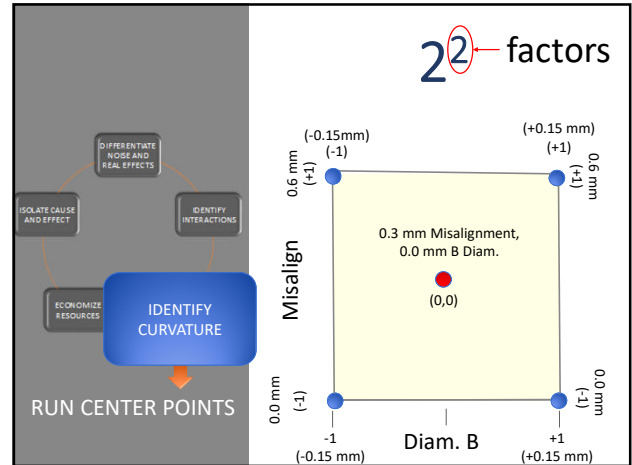
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66



67



68

DESIGN ORDER	B Diam.	code	Misalign.	code
1	-0.15	-1	0.0	-1
2	+0.15	+1	0.0	-1
3	-0.15	-1	0.6	+1
4	+0.15	+1	0.6	+1
5	-0.15	-1	0.0	-1
6	+0.15	+1	0.0	-1
7	-0.15	-1	0.6	+1
8	+0.15	+1	0.6	+1

• Center point = all factors simultaneously at their mid-level

69

DESIGN ORDER	B Diam.	code	Misalign.	code
1	-0.15	-1	0.0	-1
2	+0.15	+1	0.0	-1
3	-0.15	-1	0.6	+1
4	+0.15	+1	0.6	+1
5	-0.15	-1	0.0	-1
6	+0.15	+1	0.0	-1
7	-0.15	-1	0.6	+1
8	+0.15	+1	0.6	+1
9	0	0	0	0
10	0	0	0	0

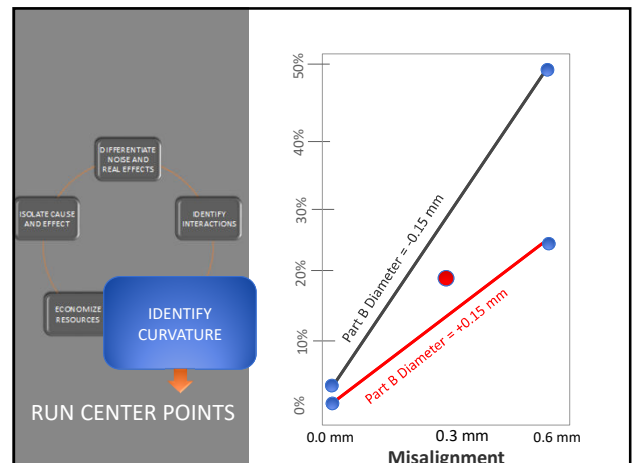
• Center point = all factors simultaneously at their mid-level

70

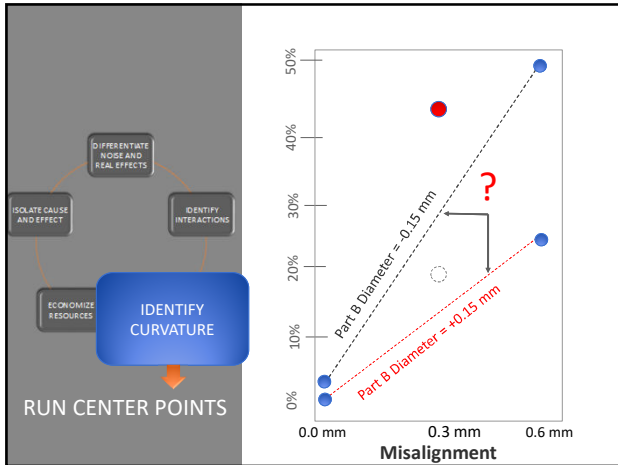
DESIGN ORDER	B Diam.	code	Misalign.	code
1	-0.15	-1	0.0	-1
2	+0.15	+1	0.0	-1
3	-0.15	-1	0.6	+1
4	+0.15	+1	0.6	+1
5	-0.15	-1	0.0	-1
6	+0.15	+1	0.0	-1
7	-0.15	-1	0.6	+1
8	+0.15	+1	0.6	+1
9	0	0	0.3	0
10	0	0	0.3	0

• Center point = all factors simultaneously at their mid-level

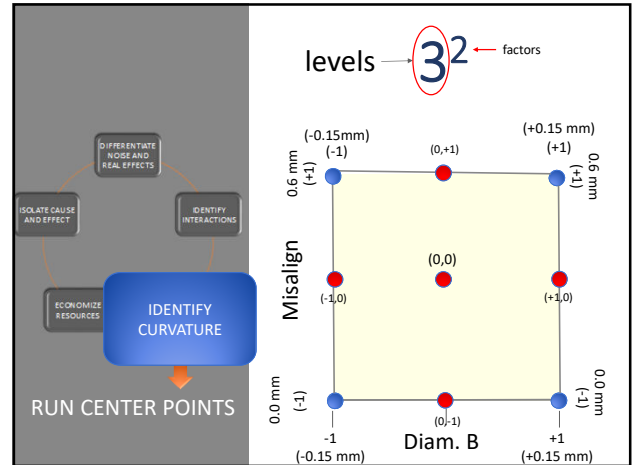
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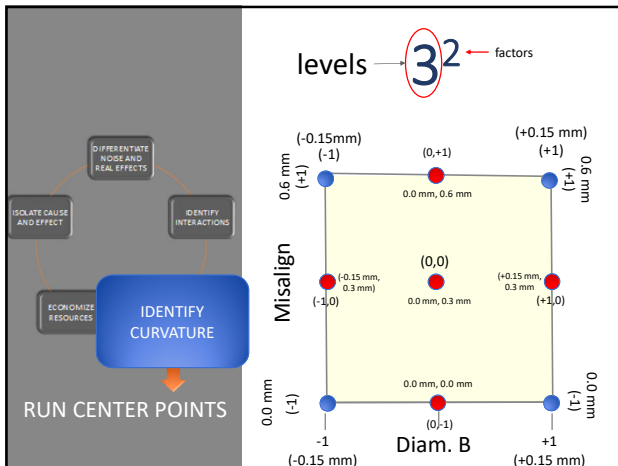
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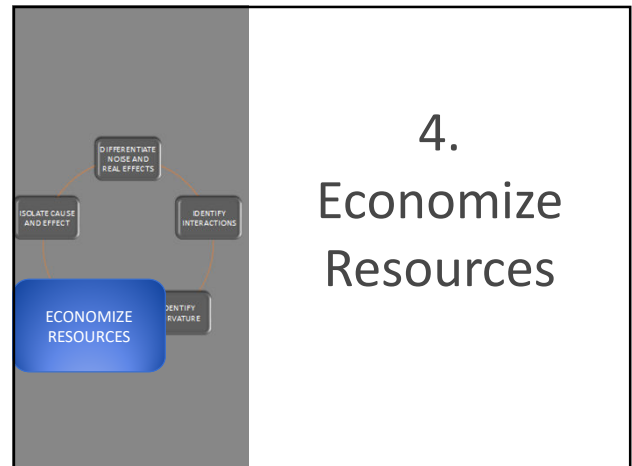
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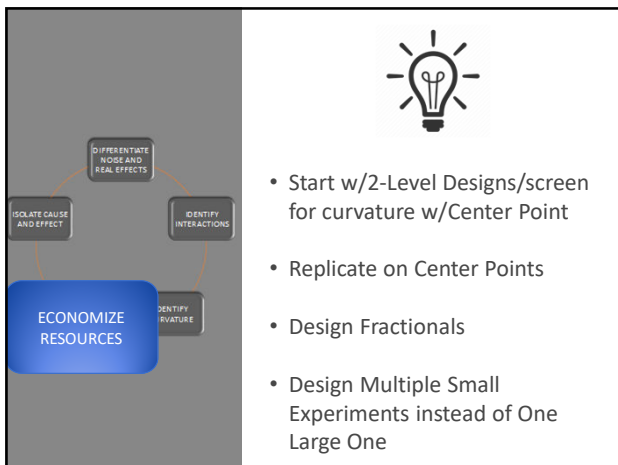
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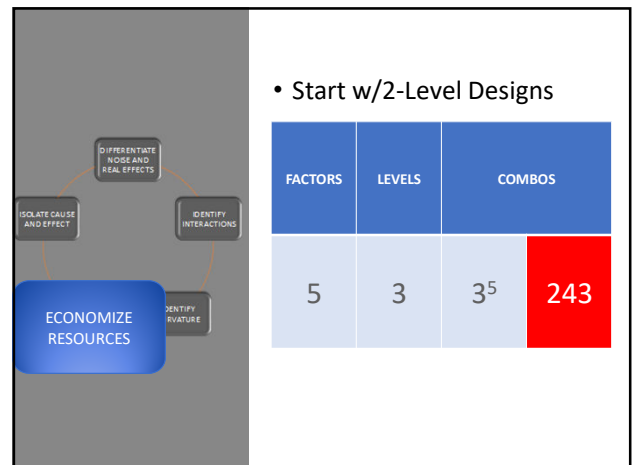
75



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77



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• Start w/2-Level Designs

FACTORS	LEVELS	COMBOS	
5	3	$3^5$	243
5	2	$2^5$	32

79

• Start w/2-Level Designs

FACTORS	LEVELS	COMBOS	
5	3	$3^5$	243
5	2	$2^5$	32
Center Point to Screen for Curvature		1	33

80

• Replicate on Center Points

FACTORS	COMBOS	REPLICATES	CENTER PTS.	RUNS
5	$2^5$	32	2	66
5	$2^5$	32	1	36

81

• Replicate on Center Points

FACTORS	COMBOS	REPLICATES	CENTER PTS.	RUNS
5	$2^5$	32	2	66
5	$2^5$	32	1	36

82

• Use Fractionals

FACTORS	COMBOS	CENTER PTS.	RUNS
5	$2^5$	32	4
5	$2^{5-1}$	16	4

83

• Use Fractionals

FACTORS	COMBOS	CENTER PTS.	RUNS
5	$2^5$	32	4
5	$2^{5-1}$	16	4

84

• Design Multiple Small Experiments instead of One Large One

FACTORS	COMBOS	CENTER PTS.	STUDIES	RUNS
10	$2^{10-1}$	512	4	1
				<b>516</b>

85

• Design Multiple Small Experiments instead of One Large One

FACTORS	COMBOS	CENTER PTS.	STUDIES	RUNS
10	$2^{10-1}$	512	4	1
				<b>516</b>
5	$2^{5-1}$	16	4	2
				<b>2</b>

86

5. Isolate Cause and Effect

87

- Randomize Run Order
- Block
- Document

88

Randomize Run Order

DESIGN ORDER	RUN ORDER	B Diam.	code	Misalign	code
1		-0.15	-1	0.0	-1
2		+0.15	+1	0.0	-1
3		-0.15	-1	0.6	+1
4		+0.15	+1	0.6	+1
5		-0.15	-1	0.0	-1
6		+0.15	+1	0.0	-1
7		-0.15	-1	0.6	+1
8		+0.15	+1	0.6	+1

89

Randomize Run Order

DESIGN ORDER	RUN ORDER	B Diam.	code	Misalign	code
1		-0.15	-1	0.0	-1
2		+0.15	+1	0.0	-1
3	AM	-0.15	-1	0.6	+1
4		+0.15	+1	0.6	+1
5		-0.15	-1	0.0	-1
6		+0.15	+1	0.0	-1
7	PM	-0.15	-1	0.6	+1
8		+0.15	+1	0.6	+1

90

**Randomize Run Order**

DESIGN ORDER	RUN ORDER	B Diam.	code	Misalign	code
1		-0.15	-1	0.0	-1
2		+0.15	+1	0.0	-1
3		-0.15	-1	0.6	+1
4		+0.15	+1	0.6	+1
5		-0.15	-1	0.0	-1
6		+0.15	+1	0.0	-1
7		-0.15	-1	0.6	+1
8		+0.15	+1	0.6	+1

91

**Randomize Run Order**

DESIGN ORDER	RUN ORDER	B Diam.	code	Misalign	code
5	1	-0.15	-1	0	-1
3	2	-0.15	-1	0.6	+1
7	3	-0.15	-1	0.6	+1
2	4	+0.15	+1	0.0	-1
6	5	+0.15	+1	0.0	-1
1	6	-0.15	-1	0.0	-1
8	7	+0.15	+1	0.6	+1
4	8	+0.15	+1	0.6	+1

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**BLOCK**

DESIGN ORDER	Block	RUN ORDER	B Diam.	code	Misalign	code
1	Block 1	8	-0.15	-1	0.0	-1
3	Block 1	5	+0.15	+1	0.0	-1
5	Block 1	4	-0.15	-1	0.6	+1
7	Block 1	6	+0.15	+1	0.6	+1
9	Block 1	7	-0.15	-1	0.0	-1
11	Block 1	3	+0.15	+1	0.0	-1
13	Block 1	1	-0.15	-1	0.6	+1
15	Block 1	2	+0.15	+1	0.6	+1
2	Block 2	14	-0.15	-1	0.0	-1
4	Block 2	10	+0.15	+1	0.0	-1
6	Block 2	11	-0.15	-1	0.6	+1
8	Block 2	15	+0.15	+1	0.6	+1
10	Block 2	16	-0.15	-1	0.0	-1
12	Block 2	12	+0.15	+1	0.0	-1
14	Block 2	13	-0.15	-1	0.6	+1
16	Block 2	9	+0.15	+1	0.6	+1

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**BLOCK - RANDOMIZE**

DESIGN ORDER	Block	RUN ORDER	B Diam.	code	Misalign	code
13	Block 1	1	-0.15	-1	0.6	1
15	Block 1	2	0.15	+1	0.6	1
11	Block 1	3	0.15	+1	0	-1
5	Block 1	4	-0.15	-1	0.6	1
3	Block 1	5	0.15	+1	0	-1
7	Block 1	6	0.15	+1	0.6	1
9	Block 1	7	-0.15	-1	0	-1
1	Block 1	8	-0.15	-1	0	-1
16	Block 2	9	+0.15	+1	0.6	1
4	Block 2	10	+0.15	+1	0	-1
6	Block 2	11	-0.15	-1	0.6	1
12	Block 2	12	+0.15	+1	0	-1
14	Block 2	13	-0.15	-1	0.6	1
2	Block 2	14	-0.15	-1	0	-1
8	Block 2	15	+0.15	+1	0.6	1
10	Block 2	16	-0.15	-1	0	-1

94

- Document
  - Held-constant variables
  - Conditions that could affect results
  - Unusual events

95

**5 CARDINAL RULES**

DESIGN TO --

DIFFERENTIATE NOISE & REAL EFFECTS	IDENTIFY INTERACTIONS	IDENTIFY CURVATURE	ECONOMIZE RESOURCES	ISOLATE CAUSE AND EFFECT
• Run Replicates	• Run All Combos of Factors and Levels	• Run Center Points	• Start with 2-Level Designs	• Randomize Run Order
			• Replicate on Center Points	• Block
			• Design Fractionals	• Document
			• Design Multiple Small Experiments Instead of One Large One	

96



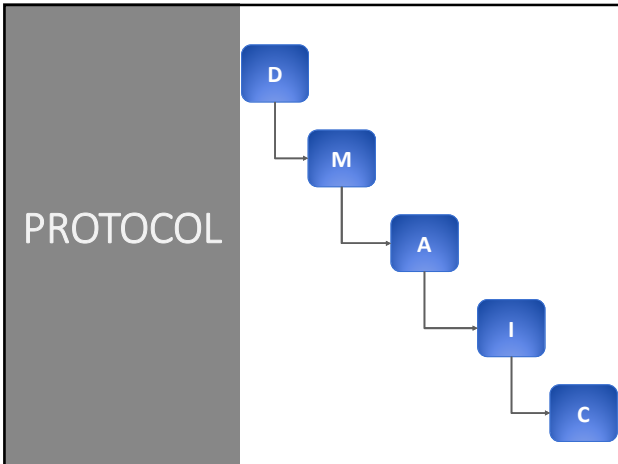
# FIVE-STEP PROTOCOL w/Example

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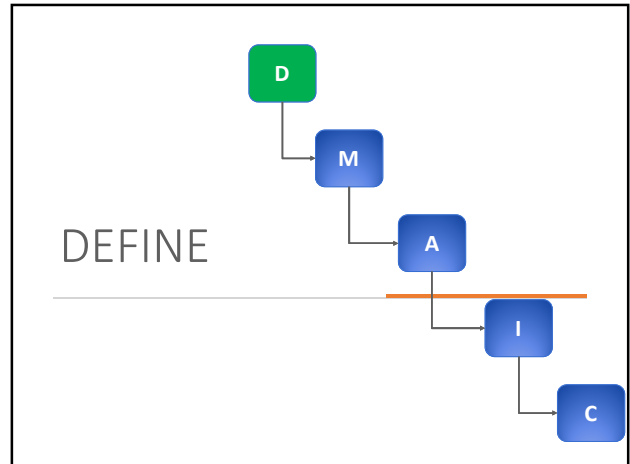
97

# EXAMPLE PROTOCOL

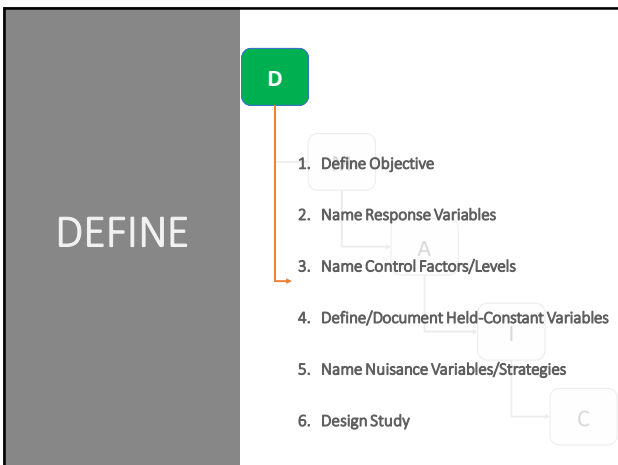
98



99



100



101

DEFINE

1. Define Objective
2. Name Response Variables
3. Name Control Factors/Levels
4. Define/Document Held-Constant Variables
5. Name Nuisance Variables/Strategies
6. Design Study

Design parts A & B to:

- Minimize vulnerability to defective assemblies for misaligned components A & B during finish product manufacturing.

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## DEFINE

**D**

1. Define Objective
2. Name Response Variables
3. Name Control Factors/Levels
4. Define/Document Held-Constant Variables
5. Name Nuisance Variables/Strategies
6. Design Study

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GOOD Assembly      DEFECTIVE Assembly

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## DEFINE

**D**

1. Define Objective
2. Name Response Variables
3. Name Control Factors/Levels
4. Define/Document Held-Constant Variables
5. Name Nuisance Variables/Strategies
6. Design Study

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## DEFINE

**D**

1. Define Objective
2. Name Response Variables
3. Name Control Factors/Levels
4. Define/Document Held-Constant Variables
5. Name Nuisance Variables/Strategies
6. Design Study

creative liberties taken for dramatic effect

- Assembly Speed
- Assembly Stroke
- Feedstock Material

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## DEFINE

**D**

1. Define Objective
2. Name Response Variables
3. Name Control Factors/Levels
4. Define/Document Held-Constant Variables
5. Name Nuisance Variables/Strategies
6. Design Study

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- Line Stops
- End of Feedstock
- Ambient Temperature/RH

106

## DEFINE

**D**

1. Define Objective
2. Name Response Variables
3. Name Control Factors/Levels
4. Define/Document Held-Constant Variables
5. Name Nuisance Variables/Strategies
6. Design Study

creative liberties taken for dramatic effect

1. Run in random order
2. Wait 15 minutes after feedstock change
3. Wait 5 minutes after line stop
4. Document ambient temp. and RH, Raw Materials Lot numbers
5. Validate measurement process

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## DEFINE

**D**

1. Define Objective
2. Name Response Variables
3. Name Control Factors/Levels
4. Define/Document Held-Constant Variables
5. Name Nuisance Variables/Strategies
6. Design Study

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THREE FACTOR  
TWO LEVEL  
FACTORIAL,  
4 CENTER POINTS

2<sup>3</sup>

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### DEFINE

**D**

1. Define Objective
2. Name Response Variables
3. Name Control Factors/Levels
4. Define/Document Held-Constant Variables
5. Name Nuisance Variables/Strategies
6. Design Study

DESIGN ORDER	RUN ORDER	A - A Diameter	B - B Diameter	C - Misalignment
1		-	-	-
2		+	-	-
3		-	+	-
4		+	+	-
5		-	-	+
6		+	-	+
7		-	+	+
8		+	+	+
9		0	0	0
10		0	0	0
11		0	0	0
12		0	0	0

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### DEFINE

**D**

1. Define Objective
2. Name Response Variables
3. Name Control Factors/Levels
4. Define/Document Held-Constant Variables
5. Name Nuisance Variables/Strategies
6. Design Study

DESIGN ORDER	RUN ORDER	A - A Diameter	B - B Diameter	C - Misalignment
1	11	-	-	-
2	6	+	-	-
3	9	-	+	-
4	1	+	+	-
5	12	-	-	+
6	7	+	-	+
7	4	-	+	+
8	8	+	+	+
9	3	0	0	0
10	2	0	0	0
11	5	0	0	0
12	10	0	0	0

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### DEFINE

**D**

1. Define Objective
2. Name Response Variables
3. Name Control Factors/Levels
4. Define/Document Held-Constant Variables
5. Name Nuisance Variables/Strategies
6. Design Study

DESIGN ORDER	RUN ORDER	A - A Diameter	B - B Diameter	C - Misalignment
4	1	+	+	-
10	2	0	0	0
9	3	0	0	0
7	4	-	+	+
11	5	0	0	0
2	6	+	-	-
6	7	+	-	+
8	8	+	+	+
3	9	-	+	-
12	10	0	0	0
1	11	-	-	-
5	12	-	-	+

111

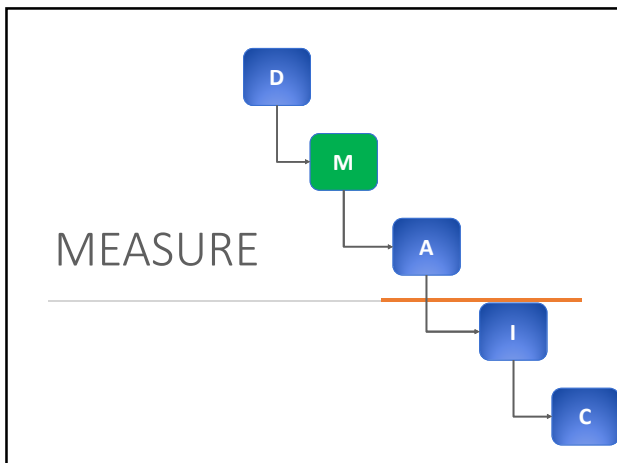
### DEFINE

**D**

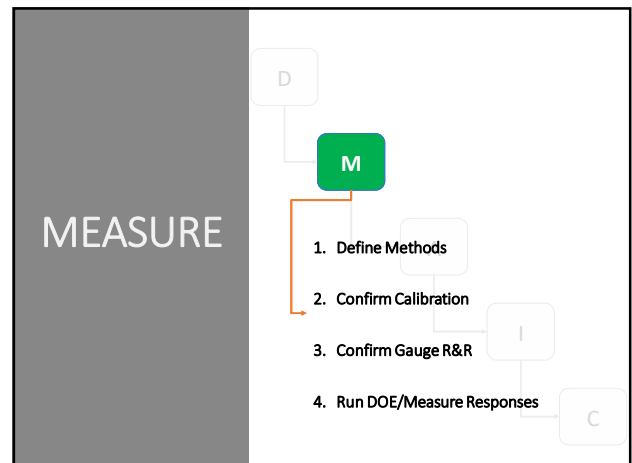
1. Define Objective
2. Name Response Variables
3. Name Control Factors/Levels
4. Define/Document Held-Constant Variables
5. Name Nuisance Variables/Strategies
6. Design Study

DESIGN ORDER	RUN ORDER	A - A Diameter	B - B Diameter	C - Misalignment
4	1	0.13	0.15	0.0
10	2	0.00	0.00	0.3
9	3	0.00	0.00	0.3
7	4	-0.13	0.15	0.6
11	5	0.00	0.00	0.3
2	6	0.13	-0.15	0.0
6	7	0.13	-0.15	0.6
8	8	0.13	0.15	0.6
3	9	-0.13	0.15	0.0
12	10	0.00	0.00	0.3
1	11	-0.13	-0.15	0.0
5	12	-0.13	-0.15	0.6

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# MEASURE

Factors:

- A Diameter – Calipers (0.01 mm)
- B Diameter – Calipers (0.01 mm)
- Misalignment – Dual Dial Indicators (0.1 mm)

Reponses:

- Defective Assembly - Visual Inspection

GOOD Assembly      DEFECTIVE Assembly

1. Define Methods
2. Confirm Calibration
3. Confirm Gauge R&R
4. Run DOE/Measure Responses

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# MEASURE

✓ CALIBRATION

Bias

True Value      Observed Mean

1. Define Methods
2. Confirm Calibration
3. Confirm Gauge R&R
4. Run DOE/Measure Responses

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# MEASURE

✓ REPRODUCIBILITY

Measurement Systems Analysis for Measurement (mm)

Average Chart

Range Chart

✓ REPEATABILITY

1. Define Methods
2. Confirm Calibration
3. Confirm Gauge R&R
4. Run DOE/Measure Responses

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# MEASURE

DESIGN ORDER	RUN ORDER	A – A Diameter	B – B Diameter	C – Misalignment	% Defective
4	1	0.13	0.15	0.0	
10	2	0.00	0.00	0.3	
9	3	0.00	0.00	0.3	
7	4	-0.13	0.15	0.6	
11	5	0.00	0.00	0.3	
2	6	0.13	-0.15	0.0	
6	7	0.13	-0.15	0.6	
8	8	0.13	0.15	0.6	
3	9	-0.13	0.15	0.0	
12	10	0.00	0.00	0.3	
1	11	-0.13	-0.15	0.0	
5	12	-0.13	-0.15	0.6	

1. Define Methods
2. Confirm Calibration
3. Confirm Gauge R&R
4. Run DOE/Measure Responses

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# MEASURE

DESIGN ORDER	RUN ORDER	A – A Diameter	B – B Diameter	C – Misalignment	% Defective
4	1	0.13	0.15	0.0	19%
10	2	0.00	0.00	0.3	
9	3	0.00	0.00	0.3	
7	4	-0.13	0.15	0.6	
11	5	0.00	0.00	0.3	
2	6	0.13	-0.15	0.0	
6	7	0.13	-0.15	0.6	
8	8	0.13	0.15	0.6	
3	9	-0.13	0.15	0.0	
12	10	0.00	0.00	0.3	
1	11	-0.13	-0.15	0.0	
5	12	-0.13	-0.15	0.6	

1. Define Methods
2. Confirm Calibration
3. Confirm Gauge R&R
4. Run DOE/Measure Responses

creative liberties taken for dramatic effect

119

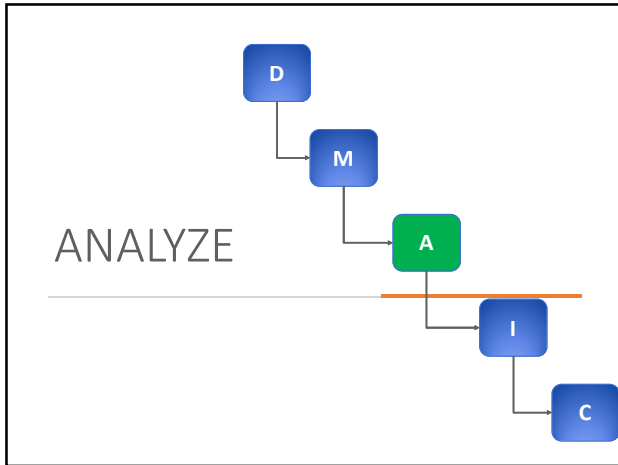
# MEASURE

DESIGN ORDER	RUN ORDER	A – A Diameter	B – B Diameter	C – Misalignment	% Defective
4	1	0.13	0.15	0.0	19%
10	2	0.00	0.00	0.3	49%
9	3	0.00	0.00	0.3	19%
7	4	-0.13	0.15	0.6	0%
11	5	0.00	0.00	0.3	19%
2	6	0.13	-0.15	0.0	49%
6	7	0.13	-0.15	0.6	0%
8	8	0.13	0.15	0.6	49%
3	9	-0.13	0.15	0.0	0%
12	10	0.00	0.00	0.3	0%
1	11	-0.13	-0.15	0.0	49%
5	12	-0.13	-0.15	0.6	19%

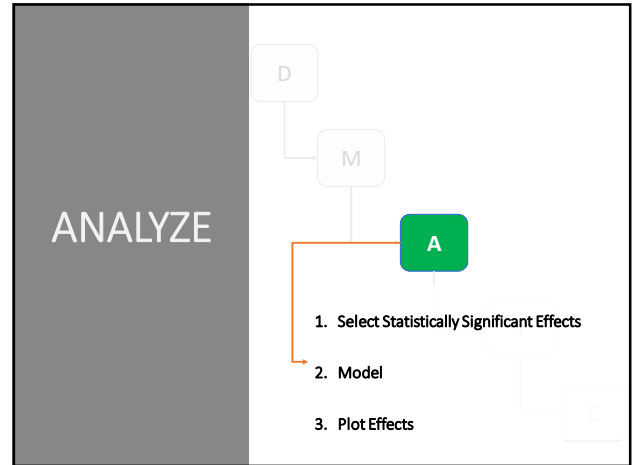
1. Define Methods
2. Confirm Calibration
3. Confirm Gauge R&R
4. Run DOE/Measure Responses

creative liberties taken for dramatic effect

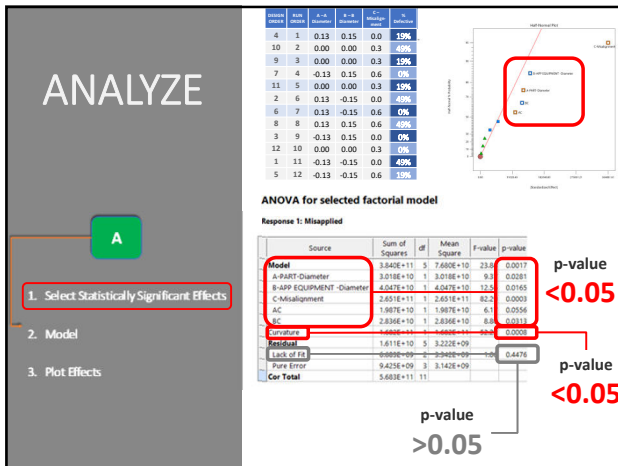
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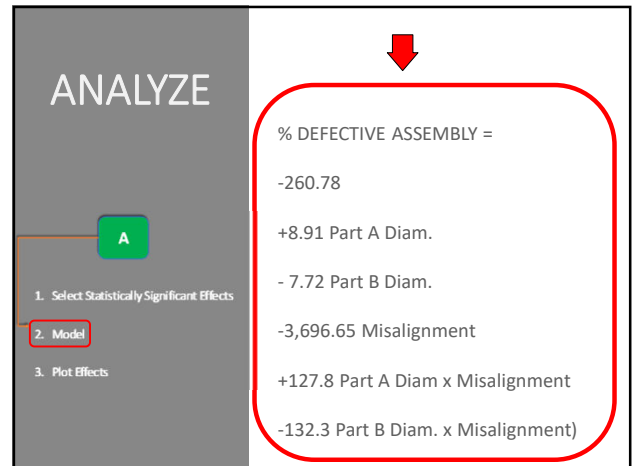
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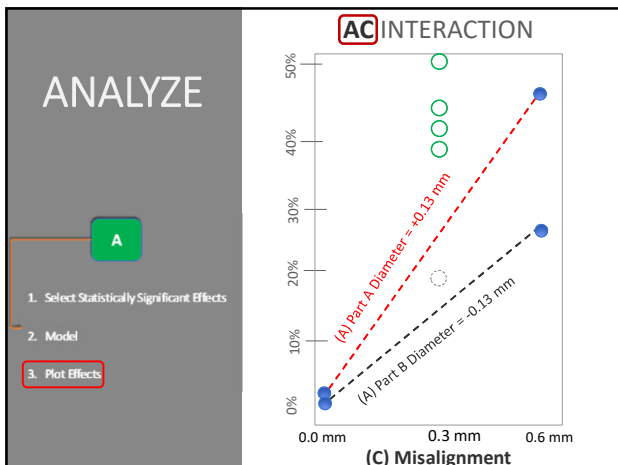
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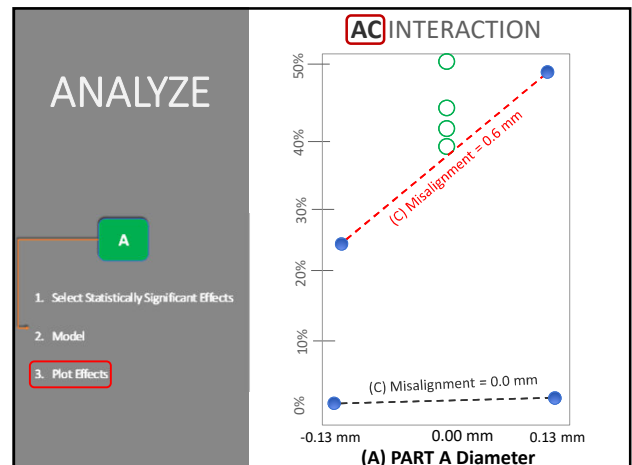
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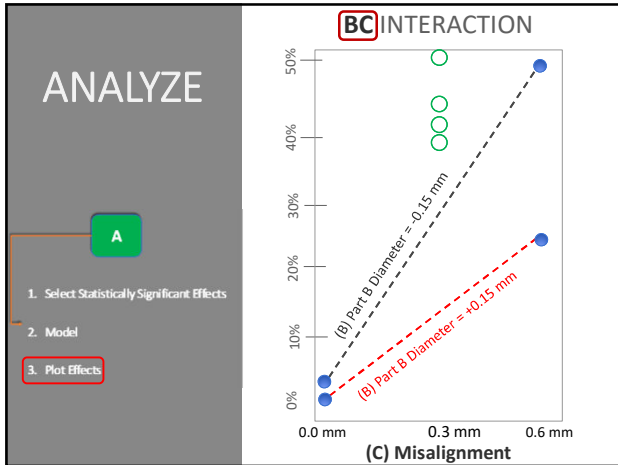
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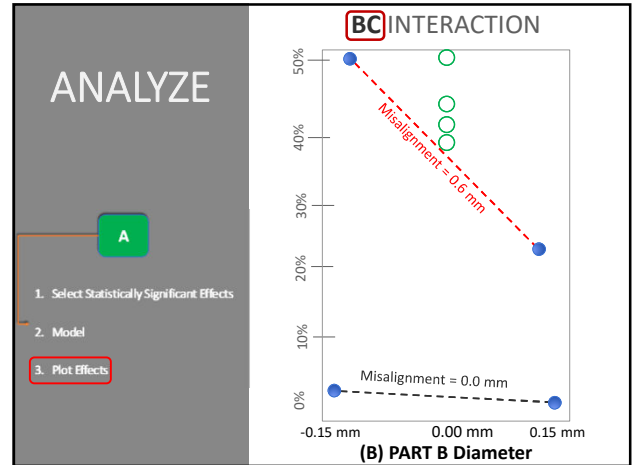
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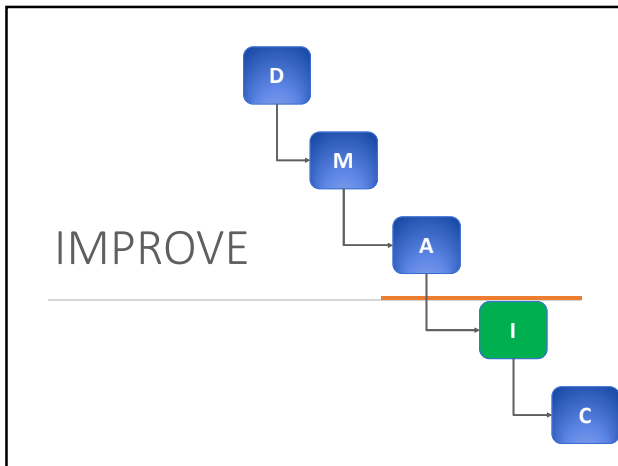
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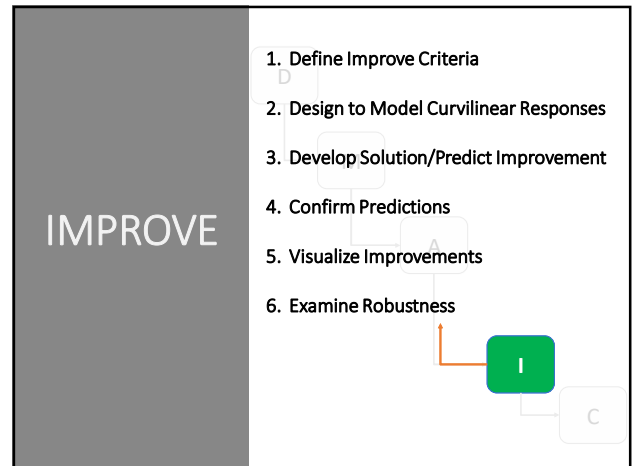
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### IMPROVE

- Define Improve Criteria
- Design to Model Curvilinear Responses
- Develop Solution/Predict Improvement
- Confirm Predictions
- Visualize Improvements
- Examine Robustness

Design parts A & B to:

- Minimize vulnerability to defective assemblies for misaligned components A & B during finish product manufacturing.

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### IMPROVE

- Define Improve Criteria
- Design to Model Curvilinear Responses
- Develop Solution/Predict Improvement
- Confirm Predictions
- Visualize Improvements
- Examine Robustness

File Version	22.0.6.0
Study Type	Response Surface
Design Type	I-optimal
Design Model	Quadratic

Factor	Name	Units	Type	SubType	Minimum	Maximum
A	A-Diameter	mm	Numeric	Continuous	-0.1300	0.1300
B	B-Diameter	mm from Nominal	Numeric	Continuous	-0.1500	0.1500
C	Misalignment	mm	Numeric	Continuous	0.0000	0.6000

Response	Name	Units	Observations	Minimum	Maximum	Mean	Std. Dev.
R1	Misapplications	PPM	30.00	0	652000	2.896E+05	1.935E+05
R2	Misapplications %	%	30.00	0.0	65.0	28.96	19.35

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# IMPROVE

1. Define Improve Criteria
2. Design to Model Curvilinear Responses
3. Develop Solution/Predict Improvement
4. Confirm Predictions
5. Visualize Improvements
6. Examine Robustness

K = 3,  $\alpha = 1.0$

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# IMPROVE

1. Define Improve Criteria
2. Design to Model Curvilinear Responses
3. Develop Solution/Predict Improvement
4. Confirm Predictions
5. Visualize Improvements
6. Examine Robustness

Std	Block	Run	Space Type	Factor 1 A-A Diameter mm	Factor 2 B-B Diameter mm from flange	Factor 3 C-Misalignment mm	Response 1 Reduced 11%
13	Block 1	1	Interior	0	0	0.1	23
1	Block 1	2	Factorial	-0.15	-0.15	0	0
12	Block 1	3	Factorial	-0.15	-0.15	0	0
9	Block 1	4	Factorial	0.15	-0.15	0	0
14	Block 1	5	Interior	0	0	0.1	20.944
2	Block 1	6	Factorial	0.15	-0.15	0.6	18.722
7	Block 1	7	Factorial	-0.15	-0.15	0	0
10	Block 1	8	Factorial	0.15	0.15	0	0
3	Block 1	9	Factorial	0.15	0.15	0.6	20.389
15	Block 1	10	Interior	0	0	0.1	18.191
5	Block 1	11	Factorial	-0.15	-0.15	0.6	44
4	Block 1	12	Factorial	-0.15	0.15	0	0
11	Block 1	13	Factorial	0.15	0.15	0	0
16	Block 1	14	Interior	0	0	0.1	20.944
6	Block 1	15	Factorial	-0.15	-0.15	0.6	0.111
8	Block 1	16	Factorial	0.15	-0.15	0.6	18.222
22	Block 2	17	Center	0	0	0.1	19.333
17	Block 2	18	CenterEdge	-0.15	0	0	0
26	Block 2	19	PlaneCent	0.15	0	0.1	9.333
23	Block 2	20	Center	0	0	0.1	0
29	Block 2	21	PlaneCent	0	0	0.6	37
28	Block 2	22	PlaneCent	0	0.15	0.1	9.333
18	Block 2	23	PlaneCent	0	0	0	0
24	Block 2	24	Center	0	0	0.1	16
19	Block 2	25	CenterEdge	-0.15	-0.15	0.1	4.333
20	Block 2	26	PlaneCent	0	-0.15	0.1	7
30	Block 2	27	PlaneCent	0	0	0.6	11.333
25	Block 2	28	Center	0	0	0.1	11.333
21	Block 2	29	PlaneCent	-0.15	0	0.1	4.667
27	Block 2	30	PlaneCent	0.15	0	0.1	11.333

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# IMPROVE

1. Define Improve Criteria
2. Design to Model Curvilinear Responses
3. Develop Solution/Predict Improvement
4. Confirm Predictions
5. Visualize Improvements
6. Examine Robustness

ANOVA for Reduced Quadratic model

Block	Mean	Standard Error	Sum of Squares	F	P
Block	19.37	0.00	10.76	0.000	0.999
A - Diameter	1.92	0.00	0.00	0.000	1.000
B - Diameter	0.00	0.00	0.00	0.000	1.000
C - Misalignment	0.00	0.00	0.00	0.000	1.000
AB	0.00	0.00	0.00	0.000	1.000
AC	1.75	1.75	10.50	0.000	0.000
BC	1.00	1.00	1.00	0.000	1.000
ABC	1.00	1.00	1.00	0.000	1.000
Error	1.00	0.00	1.00	0.000	1.000
Total	1.00	0.00	1.00	0.000	1.000
Correct Total	1.00	0.00	1.00	0.000	1.000

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# IMPROVE

1. Define Improve Criteria
2. Design to Model Curvilinear Responses
3. Develop Solution/Predict Improvement
4. Confirm Predictions
5. Visualize Improvements
6. Examine Robustness

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# IMPROVE

1. Define Improve Criteria
2. Design to Model Curvilinear Responses
3. Develop Solution/Predict Improvement
4. Confirm Predictions
5. Visualize Improvements
6. Examine Robustness

A: A-Diameter (mm)      B: B-Diameter (mm)

C: Misalignment (mm)      C: Misalignment (mm)

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# IMPROVE

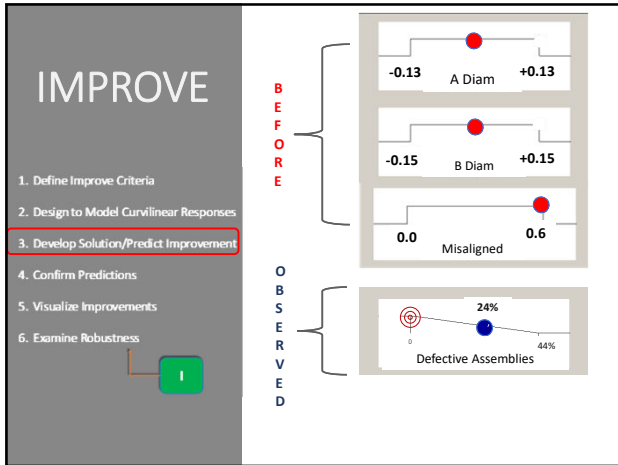
## MINIMIZE DEFECTIVE ASSEMBLIES

1. Define Improve Criteria
2. Design to Model Curvilinear Responses
3. Develop Solution/Predict Improvement
4. Confirm Predictions
5. Visualize Improvements
6. Examine Robustness

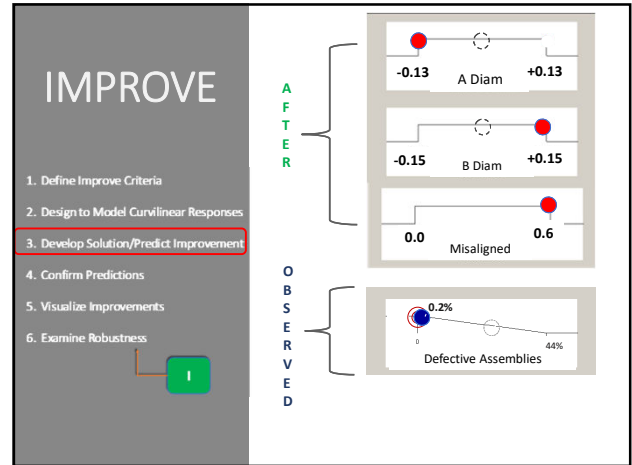
Desired Result

Defective Assemblies = 0.0 %

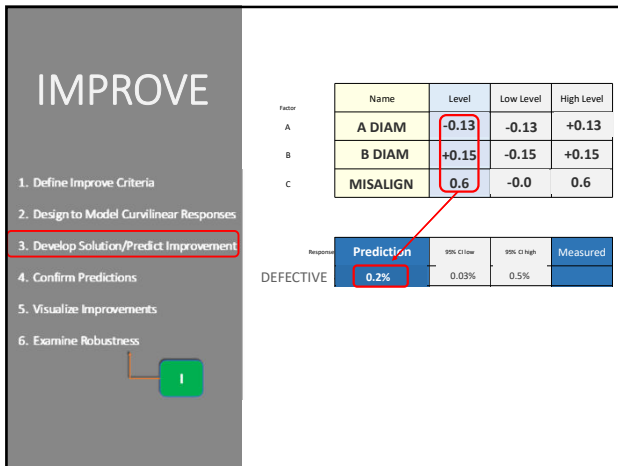
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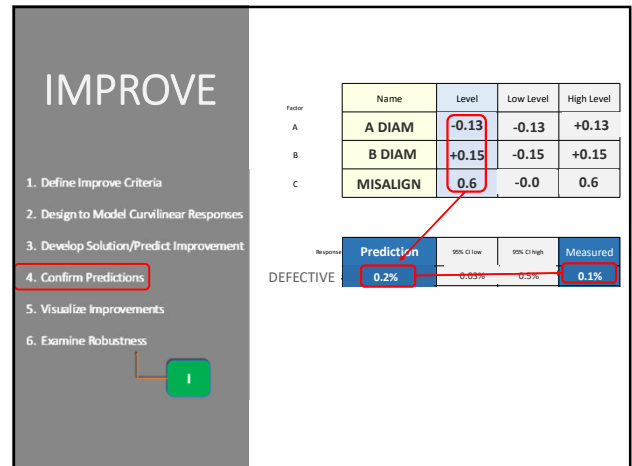
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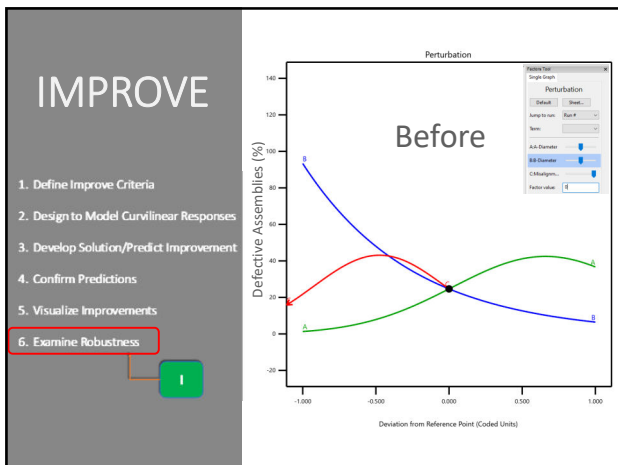
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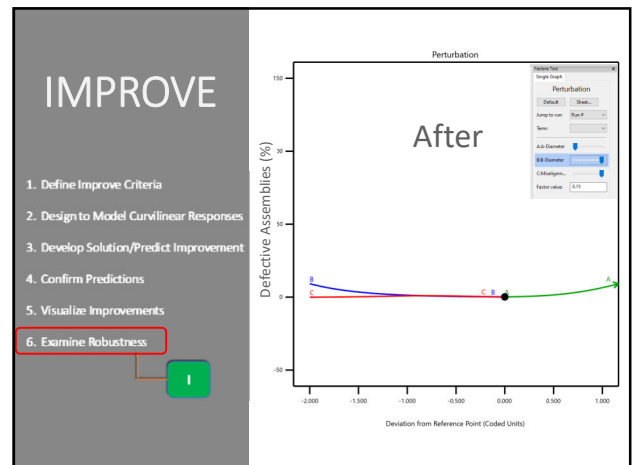
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142

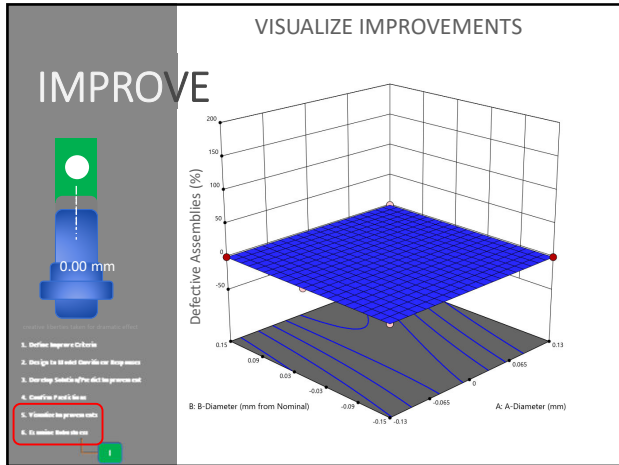


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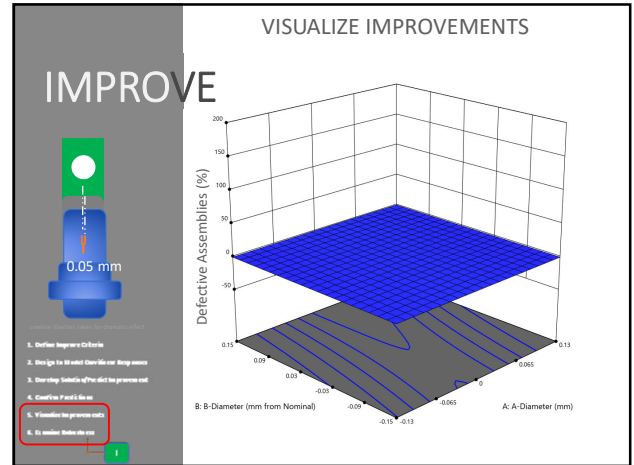


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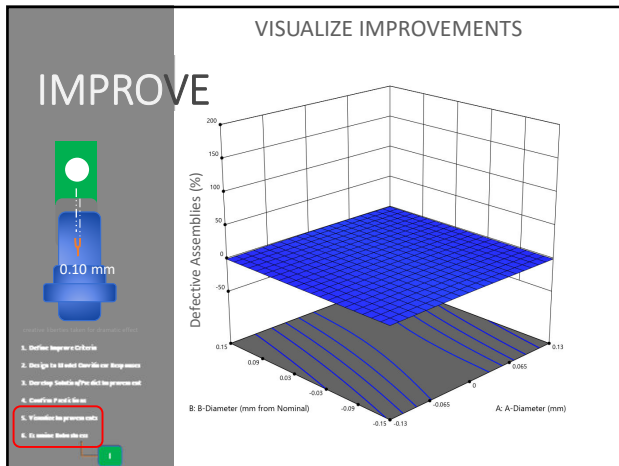




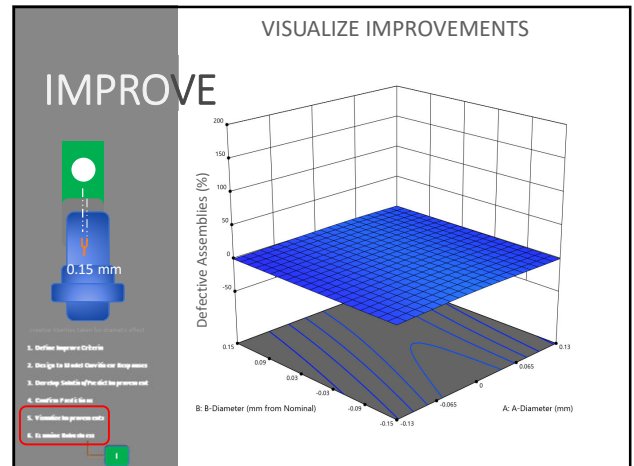
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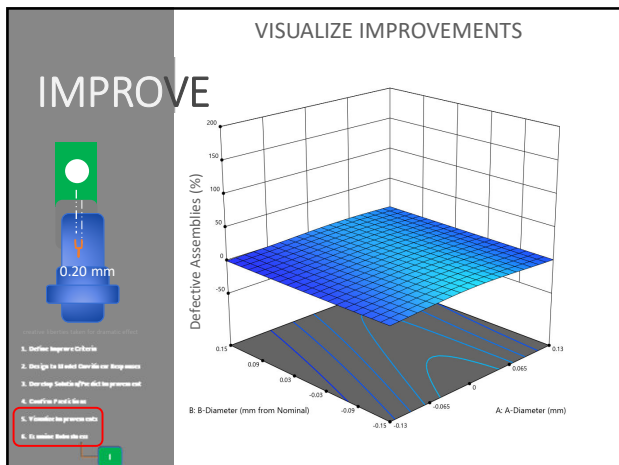
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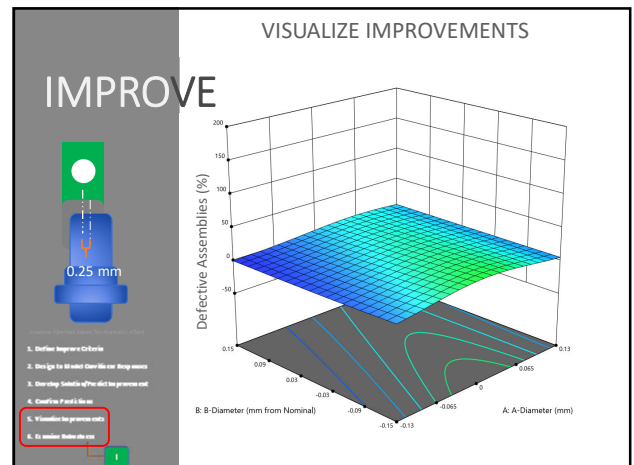
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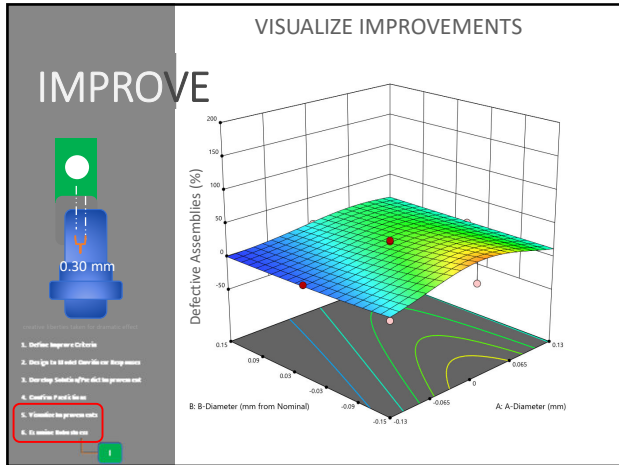
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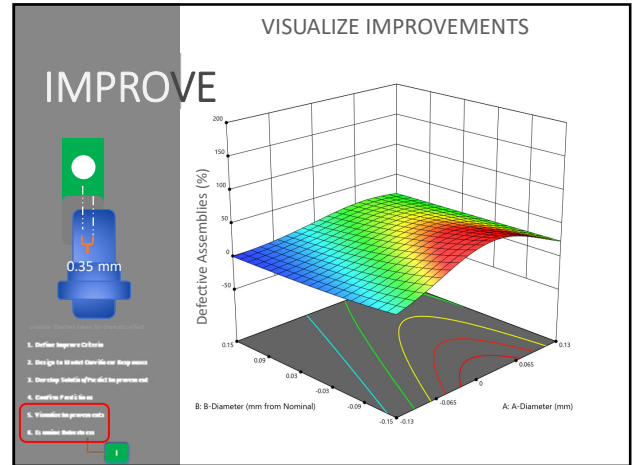
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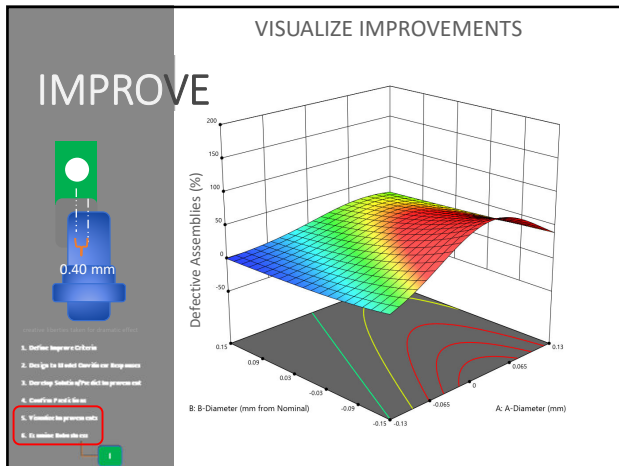
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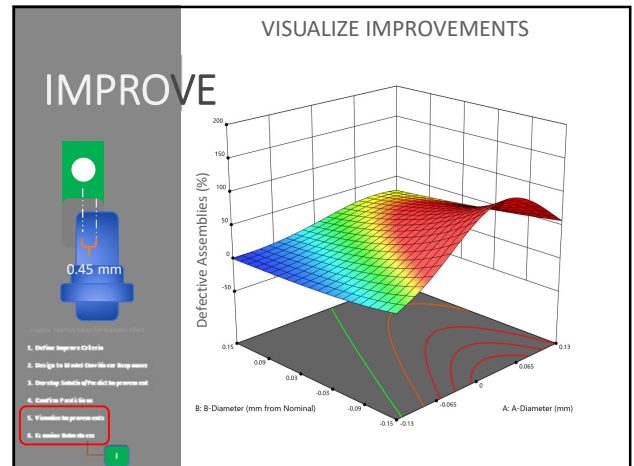
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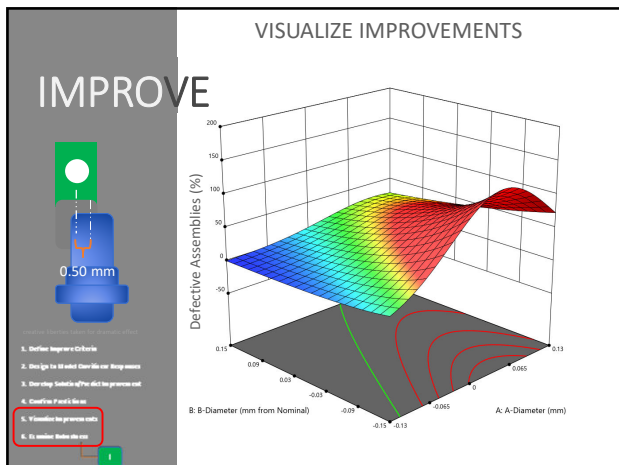
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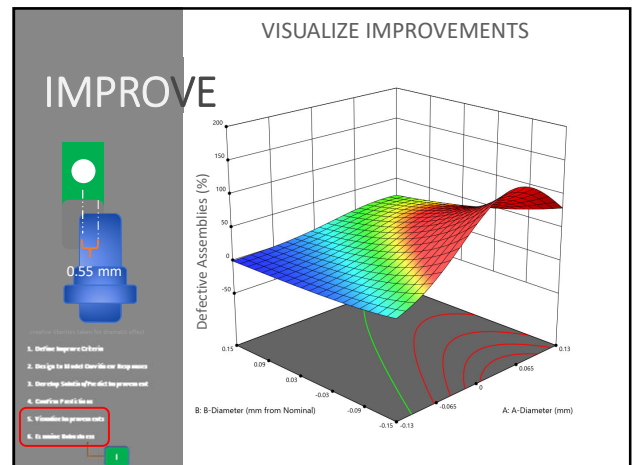
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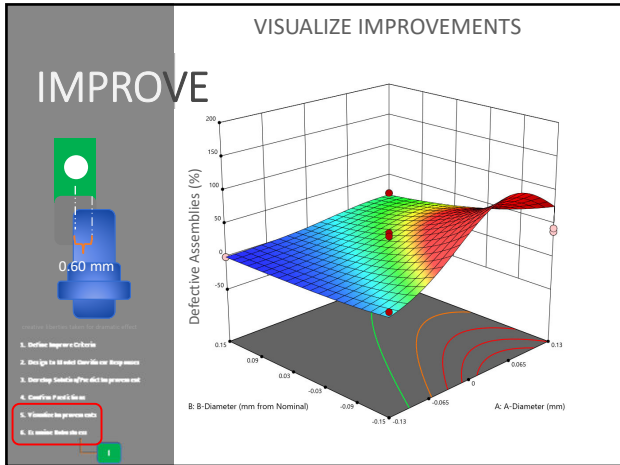
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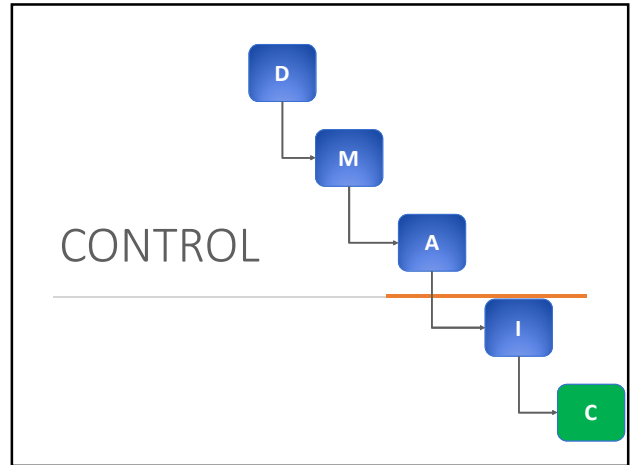
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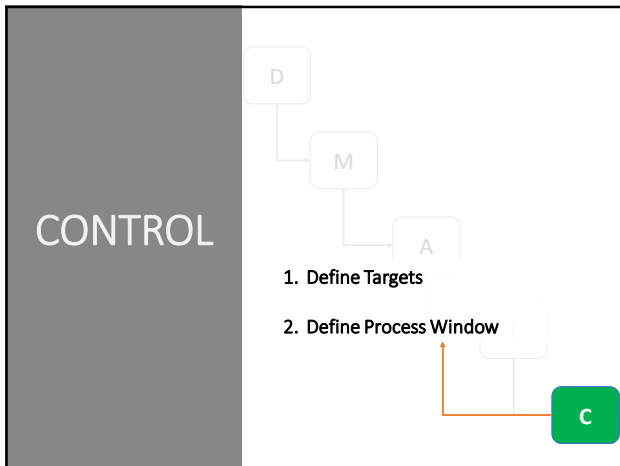
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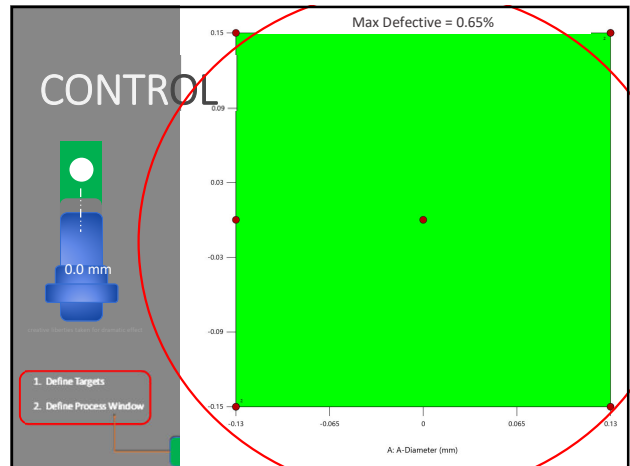
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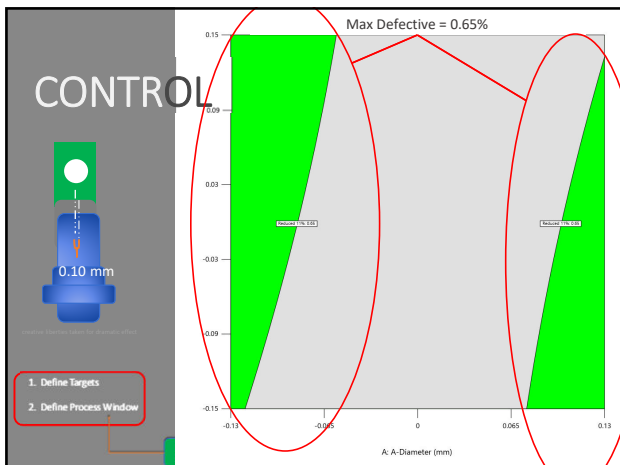
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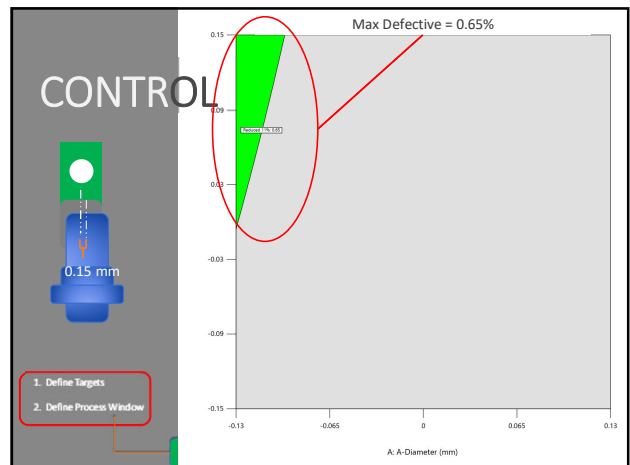
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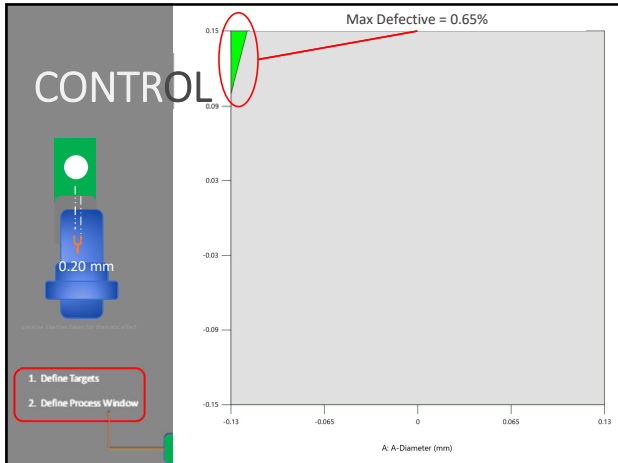
160



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# PROTOCOL SUMMARY

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## PROTOCOL

<p><b>D</b></p> <ol style="list-style-type: none"> <li>1. Define Objective</li> <li>2. Name Response Variables</li> <li>3. Name Control Factors/Levels</li> <li>4. Define/Document Held-Constant Variables</li> <li>5. Name Nuisance Variables/Strategies</li> <li>6. Design Study</li> </ol>	<p><b>M</b></p> <ol style="list-style-type: none"> <li>1. Define Methods</li> <li>2. Confirm Calibration</li> <li>3. Confirm Gauge R&amp;R</li> <li>4. Run Combos/Measure Responses</li> </ol>	<p><b>A</b></p> <ol style="list-style-type: none"> <li>1. Select Statistically Significant Effects</li> <li>2. Model</li> <li>3. Diagnose/Optimize Model</li> <li>4. Plot Effects</li> </ol>	<p><b>I</b></p> <ol style="list-style-type: none"> <li>1. Define Improve Criteria</li> <li>2. Develop Solution/Predict Improvement</li> <li>3. Confirm Predictions</li> <li>4. Visualize Improvements</li> <li>5. Examine Robustness</li> </ol>	<p><b>C</b></p> <ol style="list-style-type: none"> <li>1. Define Targets</li> <li>2. Define Process Window</li> </ol>
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# LESSONS FOR DERIVING MEANING FROM ANY DATA

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## LESSON 1

### 1. Define Your Objective(s)

- RANGE OF INTEREST
- CHARACTERIZE
- DISCOVER CAUSE AND EFFECT
- QUANTIFY CAUSE AND EFFECT
- PREDICT
- OPTIMIZE
- COMPARE AND SELECT

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## LESSON 2

### 2. Validate Measurement

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### 3. Distinguish Noise vs. Effects

LESSON 3

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### 4. Isolate Effects

LESSON 4

Day	Grade	RH	MPG
DAY 1	0%	90%	24
DAY 2	5%	70%	20
DAY 3	10%	50%	16

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### 5. Distinguish between actual factors vs. assumed factors

LESSON 5

- ASSUMED = PRESSURE
- ACTUAL = TURNS

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### 6. Consider Effects Conditional

LESSON 6

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### 7. View Relationships from Multiple Perspectives

LESSON 7

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### 8. Test Linearity

LESSON 8

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### 9. Confirm Predictions

Factor

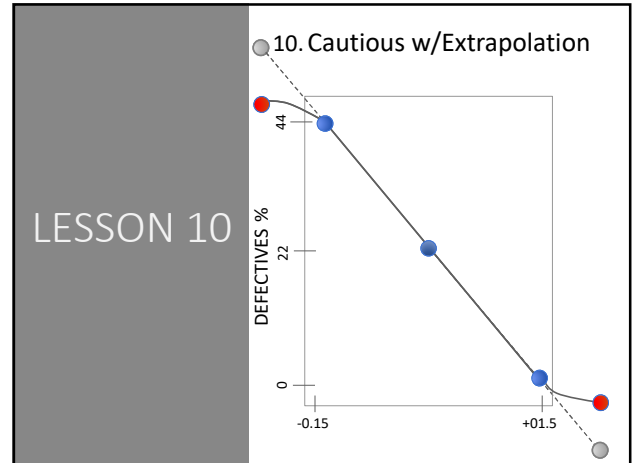
Name	Level	Low Level	High Level
A DIAM	-0.13	-0.13	+0.13
B DIAM	+0.15	-0.15	+0.15
MISALIGN	0.6	-0.0	0.6

Response

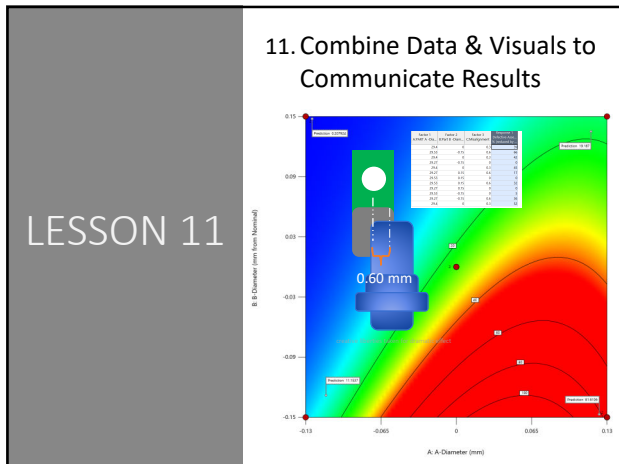
Prediction	95% CI Low	95% CI High	Measured
0.2%	0.023%	0.27%	0.1%

DEFFECTIVE

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THANK YOU!

HAPPY EXPERIMENTING!

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