Design of Experiments
Part 3

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DOE for Variation

Traditional DOE evaluates significant differences in the *average* output between levels.

good Black Belts *understand* the inputs that affect output average, but their primary goal is…

REDUCE VARIATION!

Injection Molding – Layout and Data

Three replications were run for each test combination as shown below:

Run \ Factor	Die Temp	Nozzle Temp	Shot Size	Inject Temp	Data Replication: Repl. 1	Repl. 2	Repl. 3
1	-1	-1	-1	-1	63	59	61
2	+1	-1	-1	+1	60	63	65
3	-1	+1	-1	+1	85	81	77
4	+1	+1	-1	-1	62	60	61
5	-1	-1	+1	+1	70	69	68
6	+1	-1	+1	-1	35	39	37
7	-1	+1	+1	-1	36	35	35
8	+1	+1	+1	+1	46	47	45

Data is Part Strength in Newtons

Injection Molding – Layout and Data

Three replications were run for each test combination as shown below:

Run \ Factor	Die Temp	Nozzle Temp	Shot Size	Inject Temp	Data Replication: Repl. 1	Repl. 2	Repl. 3	Measures of Variation: σ	σ2	ln(σ)
1	-1	-1	-1	-1	63	59	61	2.0	4.0	0.7
2	+1	-1	-1	+1	60	63	65	2.5	6.3	0.9
3	-1	+1	-1	+1	85	81	77	4.0	16.0	1.4
4	+1	+1	-1	-1	62	60	61	1.0	1.0	0.0
5	-1	-1	+1	+1	70	69	68	1.0	1.0	0.0
6	+1	-1	+1	-1	35	39	37	2.0	4.0	0.7
7	-1	+1	+1	-1	36	35	35	0.6	0.3	-0.5
8	+1	+1	+1	+1	46	47	45	1.0	1.0	0.0

We have all the information we need to calculate variation for our DOE. What metric should we use?

DOE for Variation

Standard deviation is not an appropriate metric for running a DOE, since σ (standard deviation of the sample) is a non-linear function. Also, using σ can produce confidence intervals that result in negative numbers– a situation that poorly represents reality.

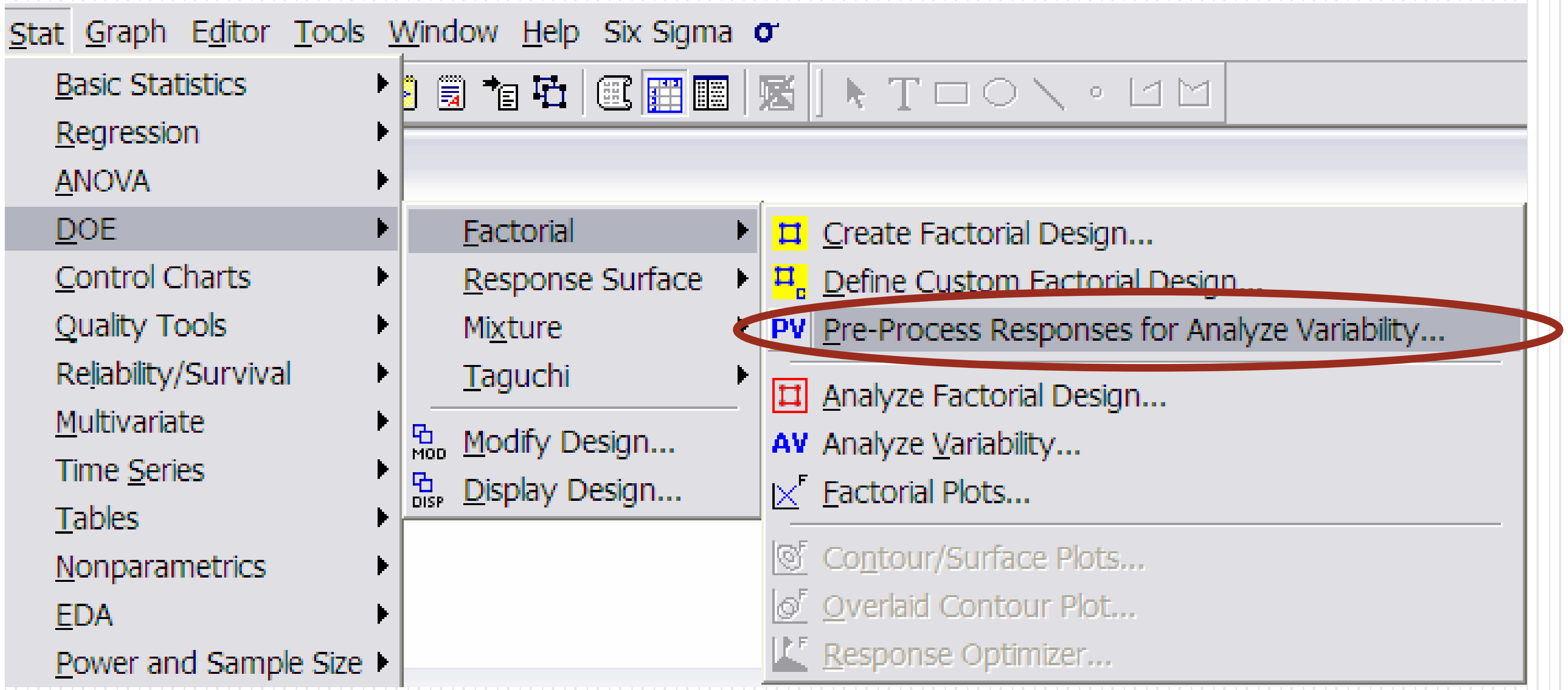
Variance has the advantage of being linear, but also results in a skewed distribution, since it's a squared value and cannot go below zero.

Ln(σ) (the natural log of the sample standard deviation) is actually one of the ***best measures*** for evaluating the significance of variation in a DOE, representing a compromise that, while not a linear function, reasonably represents the spread of the process variation within a distribution that is often very close to normal.

Measures of Variation		
σ	σ2	Ln(σ)
2.0	4.0	0.7
2.5	6.3	0.9
4.0	16.0	1.4
1.0	1.0	0.0
1.0	1.0	0.0
2.0	4.0	0.7
0.6	0.3	-0.5
1.0	1.0	0.0

DOE for Variation

Minitab can do this for us!

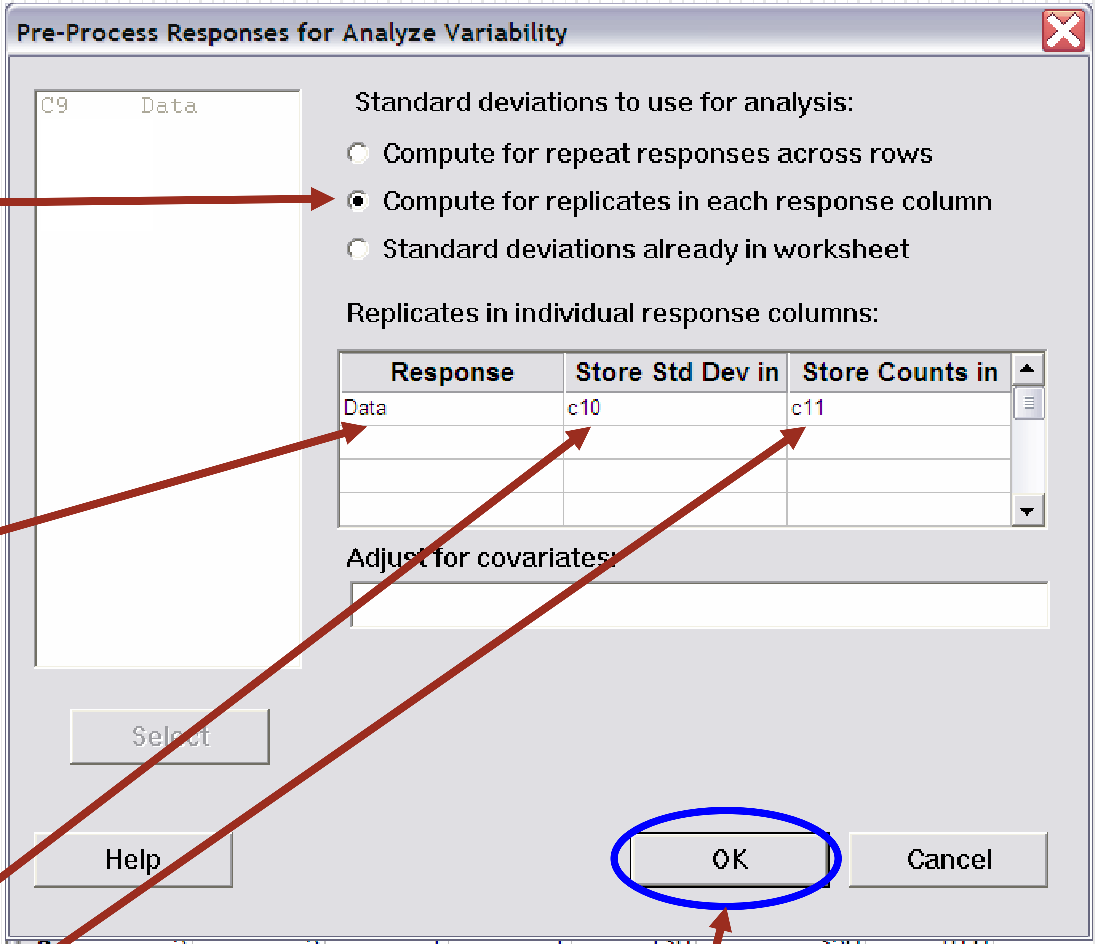


Stat > DOE > Factorial >

Pre-Process Responses for Analyze Variability…

DOE for Variation

- Select "Compute for replicates in each response column"
- Enter column with DOE output
- Select two unused columns to store σ and counts

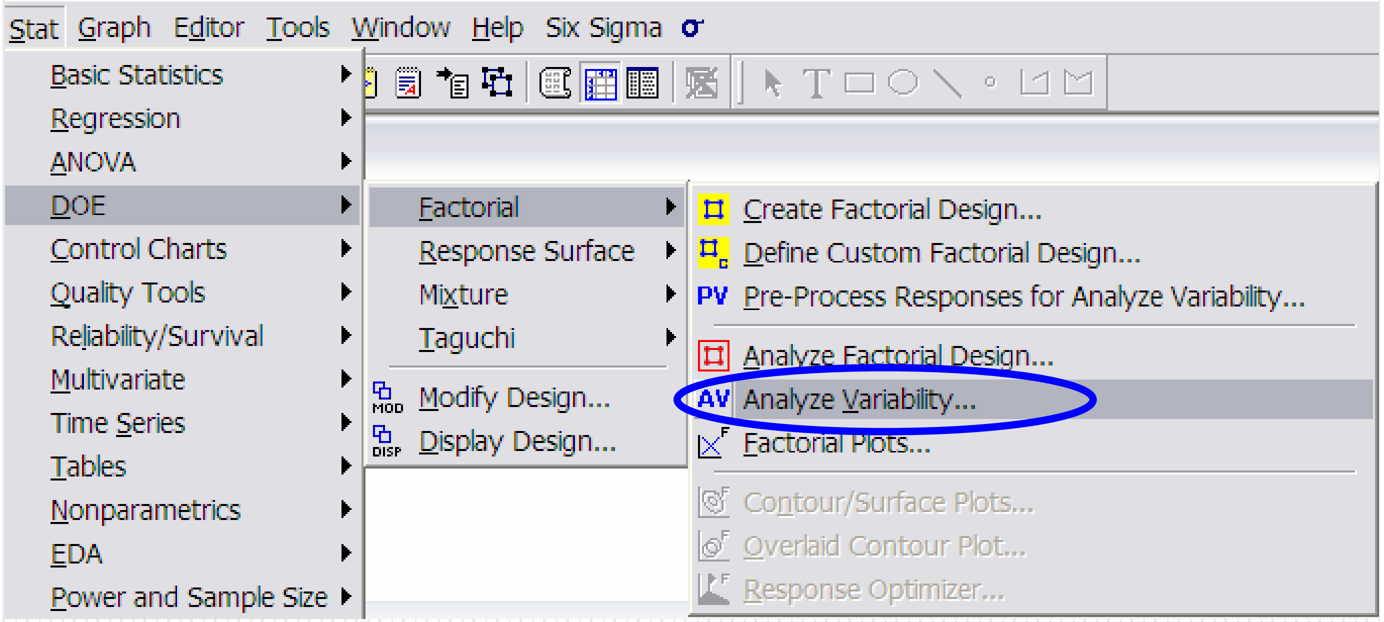


- Click "OK"

DOE for Variation

Minitab generated a column of standard deviations.

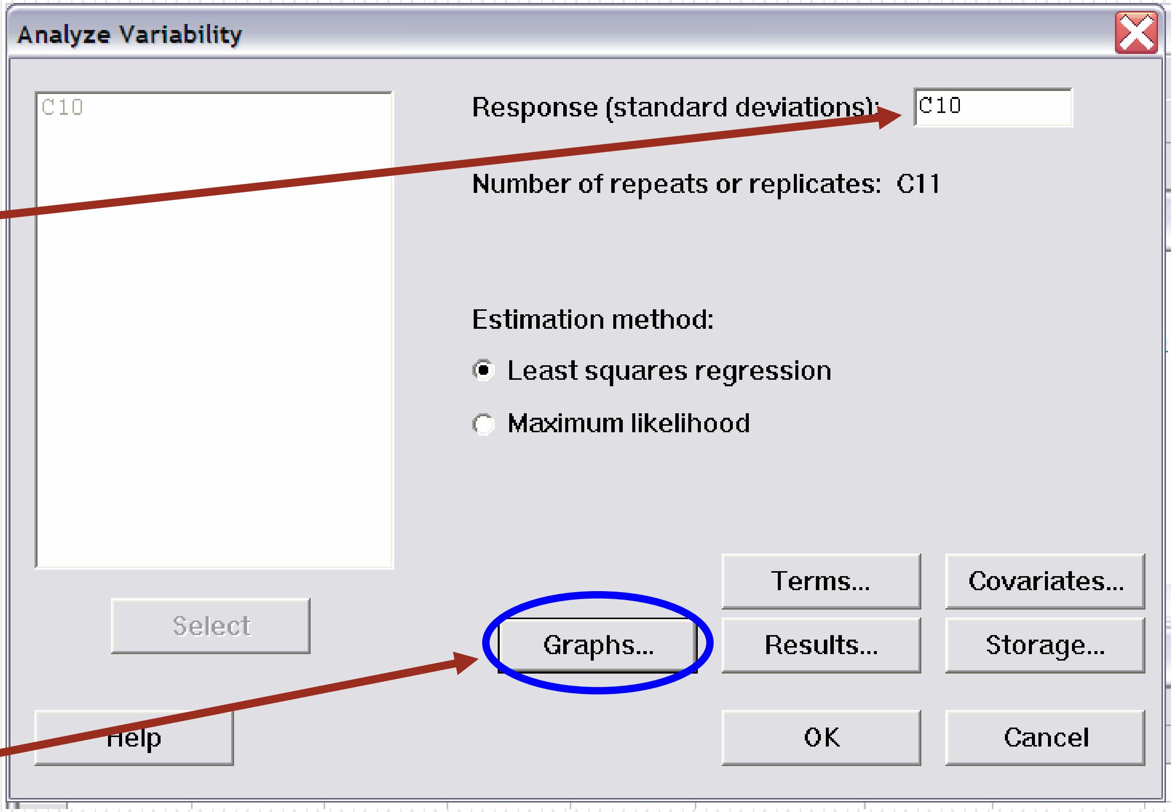
Now, let's use them!



Stat > DOE > Factorial > Analyze Variability…

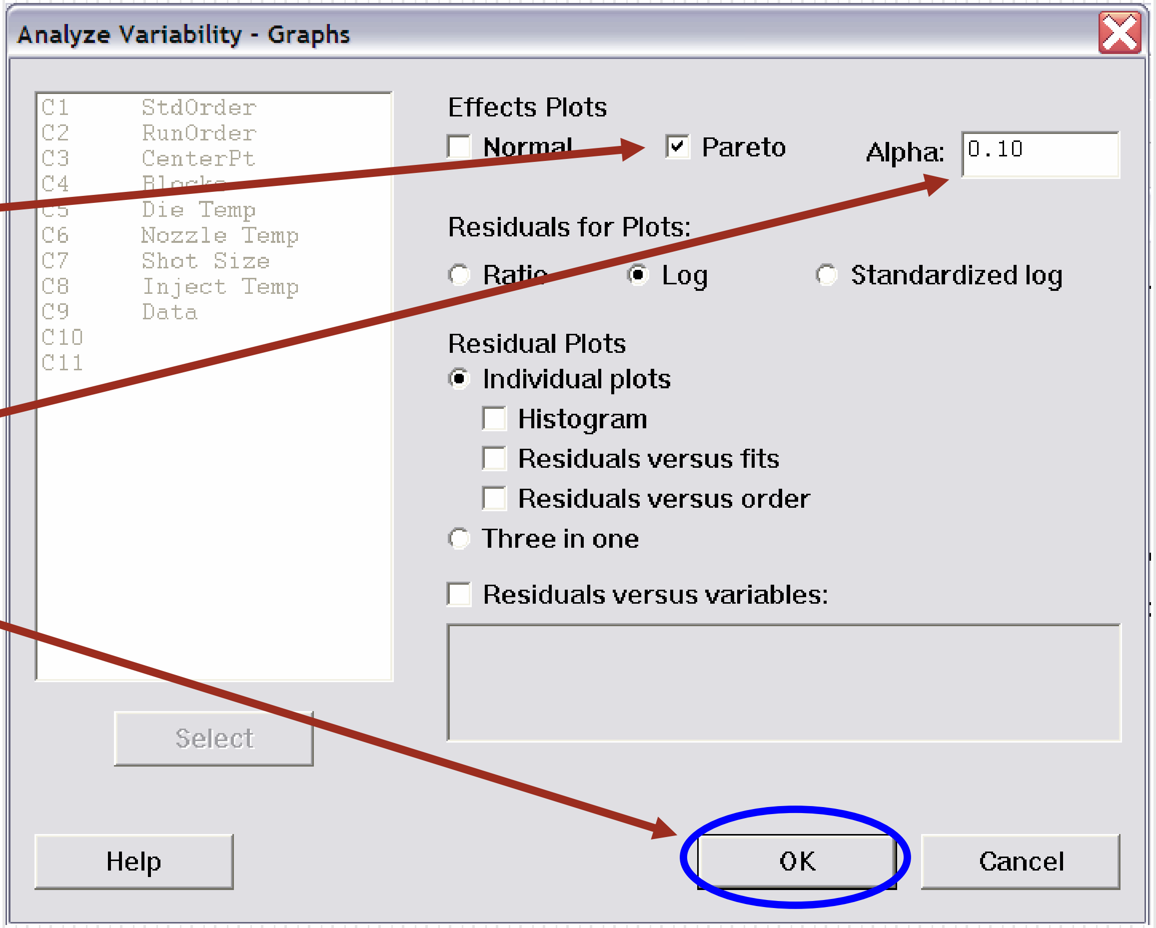
DOE for Variation

- For "Response (standard deviations):" select the column with standard deviation stored in it.
- Next, select Graphs



DOE for Variation

- Select "Pareto"
- Updated Alpha to "0.10"
- Click on "OK"



DOE for Variation

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Regression Estimated Coefficients for Natural Log of C10 (uncoded units)
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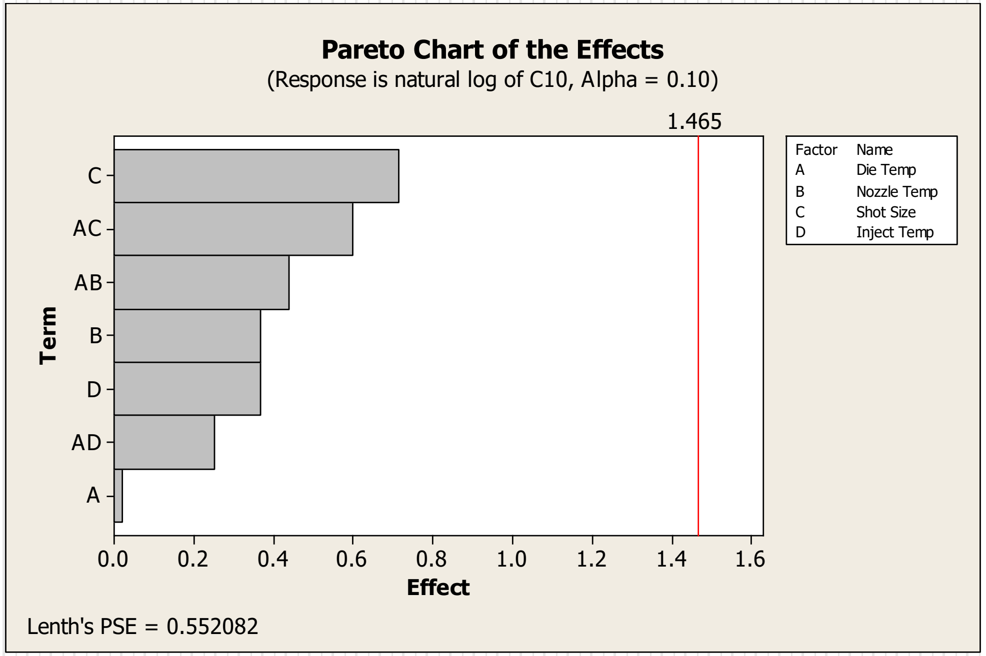


Minitab

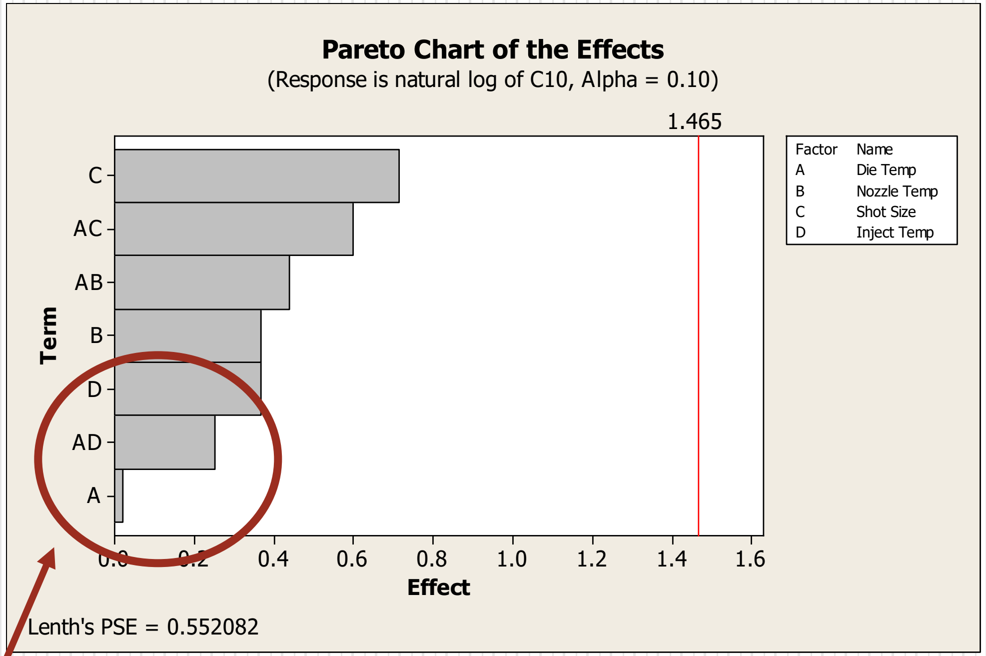
Session Window Output

Note that Minitab analyzes DOE variation using *ln(σ)*

Where are my p-values?

DOE for Variation

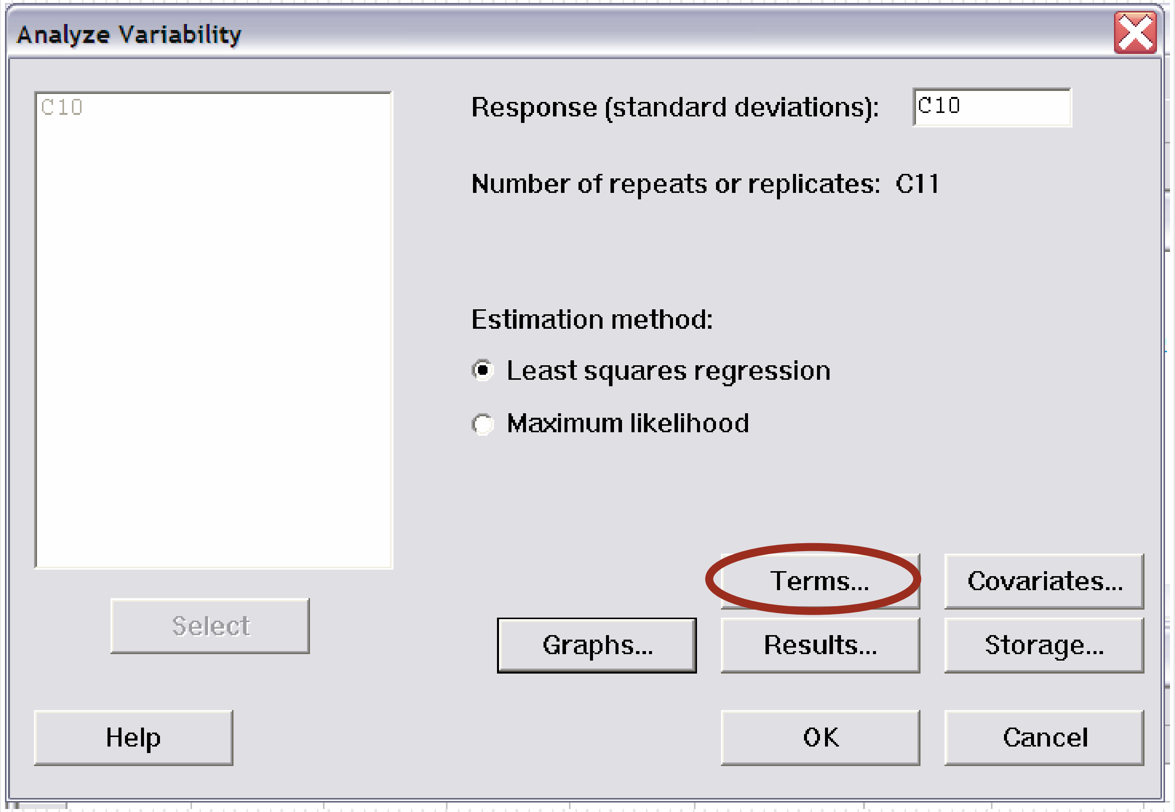
- We don't have enough data to be sure of our results, so p-values can't be generated.
- Let's give the computer a little more power!
- Note the bottom few effects on the pareto (those effects least likely to be significant)



- We'll de-select A, D, & AD

DOE for Variation

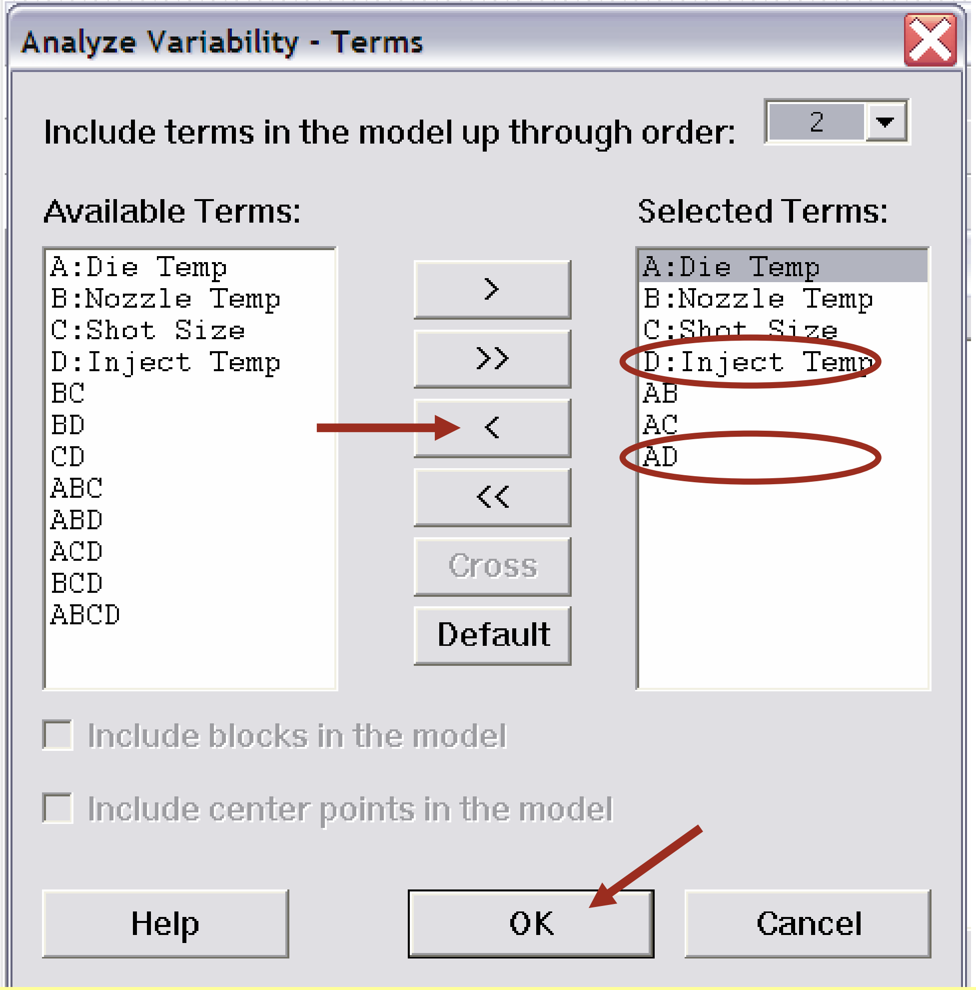
Stat > DOE > Factorial > Analyze Variability…



Select “Terms”

DOE for Variation

- We'll de-select D & AD, but not A. Why?
- Minitab needs A to calculate AB, AC, etc.
- By ignoring these factors, we tighten the parameters of the calculation, "focus" the math, and squeeze more power from the data.



For a better statistical understanding of this concept, check out Degrees of Freedom online, in Minitab, or in your statistics book.

DOE for Variation

Regression Estimated Effects and Coefficients for Natural Log of C10 (coded units)

Term	Effect	Ratio Effect	Coef	SE Coef	T	P
Constant			0.3933	0.1579	2.49	0.130
Die Temp	0.0215	1.0217	0.0107	0.1579	0.07	0.952
Nozzle Temp	-0.3681	0.6921	-0.1840	0.1579	-1.17	0.364
Shot Size	-0.7146	0.4894	-0.3573	0.1579	-2.26	0.152
Die Temp*Nozzle Temp	-0.4400	0.6441	-0.2200	0.1579	-1.39	0.298
Die Temp*Shot Size	0.5997	1.8217	0.2999	0.1579	1.90	0.198

R-Sq = 85.74%   R-Sq(adj) = 50.09%

Minitab Session Window

Cool! p-Values!

Now What?

DOE for Variation

Factor	Level		Mean	p-value	ln(s)	p-value
A: Die Temp.	-1	130º F	61.6	0.000	0.639	0.952
	+1	170º F	51.6		0.488	
B: Nozzle Temp.	-1	350º F	57.4	0.330	0.631	0.364
	+1	370º F	55.9		0.497	
C: Shot Size	-1	6.7 grams	66.4	0.000	0.867	0.152
	+1	10.0 grams	46.9		0.135	
D: Inject. Temp.	-1	700º F	48.6	0.000	0.332	0.298
	+1	900º F	64.6		0.756	
AD: Die Temp. x Inj. Press.	-1, -1	NA	48.3	0.007	0.254	0.832
	-1, +1	NA	49.0		0.916	
	+1, -1	NA	75.0		0.405	
	+1, +1	NA	54.3		0.564	

Not Mandatory, but a good idea!

One-stop summary of DOE for Average and Variation. Now, select your levels to minimize variation and maximize strength.

Predicting DOE Output

If I set my factors at the selected levels, what output would I expect from my process?

- Minitab does NOT automatically generate an equation for us like it did with Regression.

- HOWEVER, we can generate our own equation by pulling out the coefficients that we consider to be significant.

Regression Estimated Coefficients for Averages (uncoded units)

Term	Coef
Constant	-29.0081
Die Temp	0.243642
Inject Temp	0.117270
Shot Size	-1.57961
Die Temp*Inject Temp	-0.0008800

Minitab Session Window

Predicting DOE Output

Remember Y = mX + b?

in English:

Output = (some coefficient) x (some input factor) + Constant

With more than one input factor, the equation expands:

$$Y = m_1X_1 + m_2X_2 + m_3X_3 + \ldots + b$$

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Regression Estimated Coefficients for Averages (uncoded units)
Term                          Coef
Constant                  -29.0081
Die Temp                  0.243642
Inject Temp               0.117270
Shot Size                 -1.57961
Die Temp*Inject Temp    -0.0008800
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Minitab Session Window

Predicting DOE Output

First, insert your significant coefficients into an equation:

$$Y = 0.244X_1 + 0.117X_2 + (-1.580)X_3 + \ \ldots + (-29.01)$$

Next, insert your desired factor levels into the equation:

$$Y = 0.244(130) + 0.117(900) -1.580)(6.7) + (-29.01)$$

Regression Estimated Coefficients for Averages (uncoded units)

Term	Coef
Constant	-29.0081
Die Temp	0.243642
Inject Temp	0.117270
Shot Size	-1.57961
Die Temp*Inject Temp	-0.0008800

Minitab Session Window

Predicting DOE Output

Finally, solve your equation:

Y = 0.244(130) + 0.117(900) -1.580)(6.7) + … -29.01

Y = 97.4 Newtons

Note: Be sure to be consistent with your units (coded units with coded coefficients, uncoded with uncoded)

Regression Estimated Coefficients for Averages (uncoded units)

Term	Coef
Constant	-29.0081
Die Temp	0.243642
Inject Temp	0.117270
Shot Size	-1.57961
Die Temp*Inject Temp	-0.0008800

Minitab Session Window

Predicting DOE Output

Y = 0.244(130) + 0.117(900) -1.580)(6.7) + … -29.01

Y = 97.4 Newtons

The equation shows that if we set Die Temperature at 130ºF, Injection Temperature at 900ºF, and Shot Size at 6.7 grams, we should expect part strength to equal 97.4 Newtons. Great! Let's verify this!

Regression Estimated Coefficients for Averages (uncoded units)

Term	Coef
Constant	-29.0081
Die Temp	0.243642
Inject Temp	0.117270
Shot Size	-1.57961
Die Temp*Inject Temp	-0.0008800

Minitab Session Window

DOE for Variation

Remember:

- We'll have one equation to optimize the Average
- We'll have one equation to minimize the Variation
- Sometimes a single factor will have a positive impact on process average, but a *negative* impact on variation.

What do we do?

Ideally, minimize Variation first, then optimize for average

Fractional Factorials: 3-level factors

Fractional designs for factors at 3-levels have also been developed. For example, with four 3-level factors, A, B, C, D, a full factorial consists of 34 = 81 test combinations. A 1/9 fraction, 1/9 •34, consisting of nine test combinations is available.

Run	A	B	C	D
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

The factors will be confounded with interactions as in the 2-level fractionals, but in a more complex fashion.

Discovering Measurable Outputs

Process Description	Process Y	KPIV Critical Xs	DOE Response?
1. Accounts Payable	Time to Pay Invoice		No
		Time to Enter Data	Yes
		Data Entry Error Rate	Maybe
		Invoices not entered into System	No
2. On-site Tech Support	Cost to JCI		No
	Support Quality		No
	Number of call backs		No
		Time to get on site	Yes
		Time on site	No
		Customer Satisfaction Rating	Maybe

Discovering Measurable Outputs (Continued)

Process Description	Process Y	KPIV Critical Xs	DOE Response?
3. Predicting Energy Usage	Dollars Paid to Customer by JCI		No
	JCI Profit		No
		Estimated Usage/Actual Usage	Yes
4. Training	Skills use on Job		No
		Test Scores	Yes
		Satisfaction Ratings	Maybe
		Attendence	No
		Number of Departures before class ends	No

Training Project Scenario

- Finalize Improvements and Implement Controls
  - Finalize an equation to turn a new Satellite Launch into a "hit" as quickly as possible.
  - Map the new Satellite Launch process, minimize waste, optimize flow, minimize labor, minimize cycle time, etc.
  - Develop clear work instructions and controls for the new process. A control plan is required as part of the submission.
  - Present the final process to the Instructors, including proof of new process capability (old vs. new quality, time, labor, etc.)
  - Be prepared to put your money where your mouth is: Shoot Off Competition!

Training Project Scenario Cost Factors

- Each Launch cost $150 to repair
- Labor costs equals $1 per second person from start of first launch until final Launch is completed.
- Three attempts to "hit" the Orbit target for the appropriate Launch sequence. If you miss the target in three attempts, you incur a $1000 quality cost hit.
- If you fail to hit the target and your corrective actions do not follow the submitted control plan, $1000 warranty cost fine for faulty work

Summary

- Objectives
  - Fastest turn-around time (lowest labor costs)
  - Getting the correct output for the appropriate motor on the fewest attempts
  - Minimize quality costs and warranty costs
  - As always, HAVE FUN!