DGS Quality Assurance
www.dgs-qualityassurance.com

Define Measure Analyze Improve Control

Analytical Tests on SPC for Excel

Focus on Regression, DOE, and ANOVA

D Sexton CEng MIMechE

DGS Quality Assurance
www.dgs-qualityassurance.com

Forward

This presentation has been provided as a guide to assist with the understanding of DOE by using some examples within the context of "SPC for Excel version 5" ®(the software under test), by comparison with the more expensive Minitab 18®.

DOE is important within process engineering, as it is often considered the third step in data analysis after measurement system analysis (MSA) and statistical process control (SPC). It allows the most efficient analysis of any type of measurement data in establishing the cause and effect relationship for problem solving and/or process improvement (including investigating excessive common cause variation, or non random special cause on SPC charts). DOE also fits within the "improve" stage of the DMAIC process, currently being widely used in technical project work.

The focus of this presentation is a brief evaluation of the Regression, DOE & ANOVA modules within the software. It should be noted that the writer is not an expert in this software, and he is a mechanical engineer and not a professional statistician, so the analysis should be considered an evaluation of the software by a practical end user.

DGS Quality Assurance
www.dgs-qualityassurance.com

DOE in Process Problem Solving

Basic	Intermediate	Advanced
• Fishbone • Box Plot • Linear Regression • Hypothesis Tests (z-test, t-test, ANOVA, chi-square, HOV) • Process Map • Time Order Plots • Mistake Proofing • Multi-vari plot* • Force Fields* • Kaizen*	• DOE (full, fractional DOE) • Multi-variate Regression*	• Response Surface* • Taguchi (Inner/Outer Array)*

Problem Sophistication

Low → High

- complexity
- business impact
- risk
- data availability

Match Tool to Problem

DGS Quality Assurance
www.dgs-qualityassurance.com

Introduction

This presentation is not a guide on how to use "SPC for Excel". For those who are using the software they should refer to the website and user guide (which the writer has also used in order to make use of the software). Neither has this presentation been created to endorse (or not) the software. Like all products, this one has both advantages and disadvantages.

The writer has previously utilised the more common statistical tools in this software. These tools include, Pareto Analysis, I&MR charts, X Bar and Range charts, capability analysis and measurement systems analysis. All analysis, results, and graphs were mostly satisfactory.

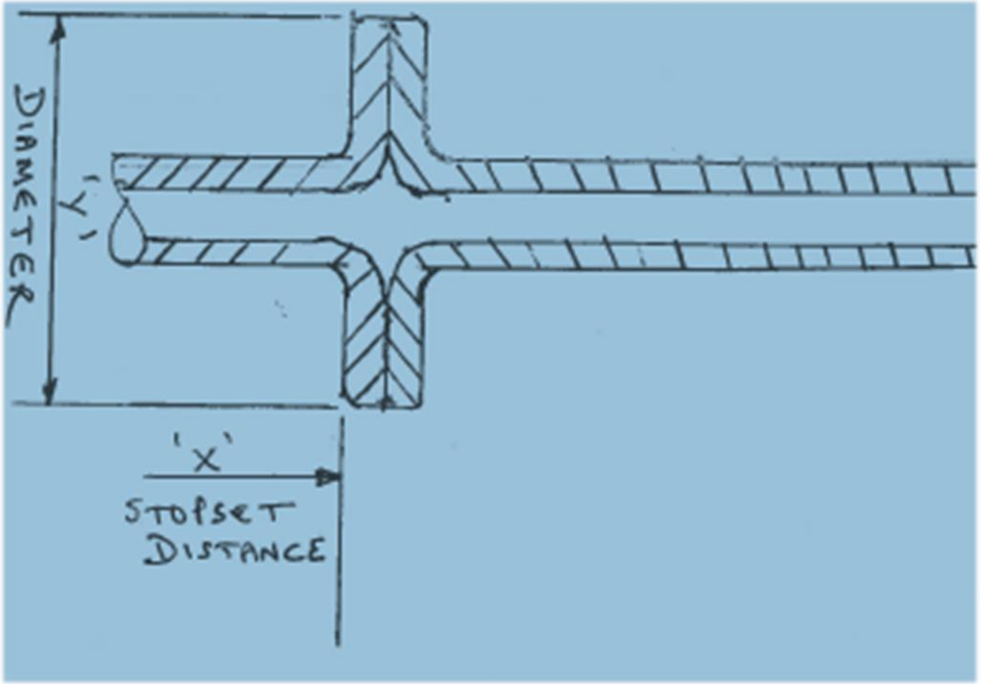
DOE is part of a very large collection of mathematical tools, so only three common types of analysis were studied. We begin with a simple linear regression model, then a three factor two-level matrix. This is a full factorial experimental trial, and utilises the DOE module within the software. Finally, we evaluated a two factor multi level experiment, utilising the ANOVA module.

The first two examples use data from previous projects carried out by the writer, while the third was previously published under the heading "The Analysis of Experimental Data" by Donald J Wheeler in "Quality Progress" magazine in 2014.

Forming Example

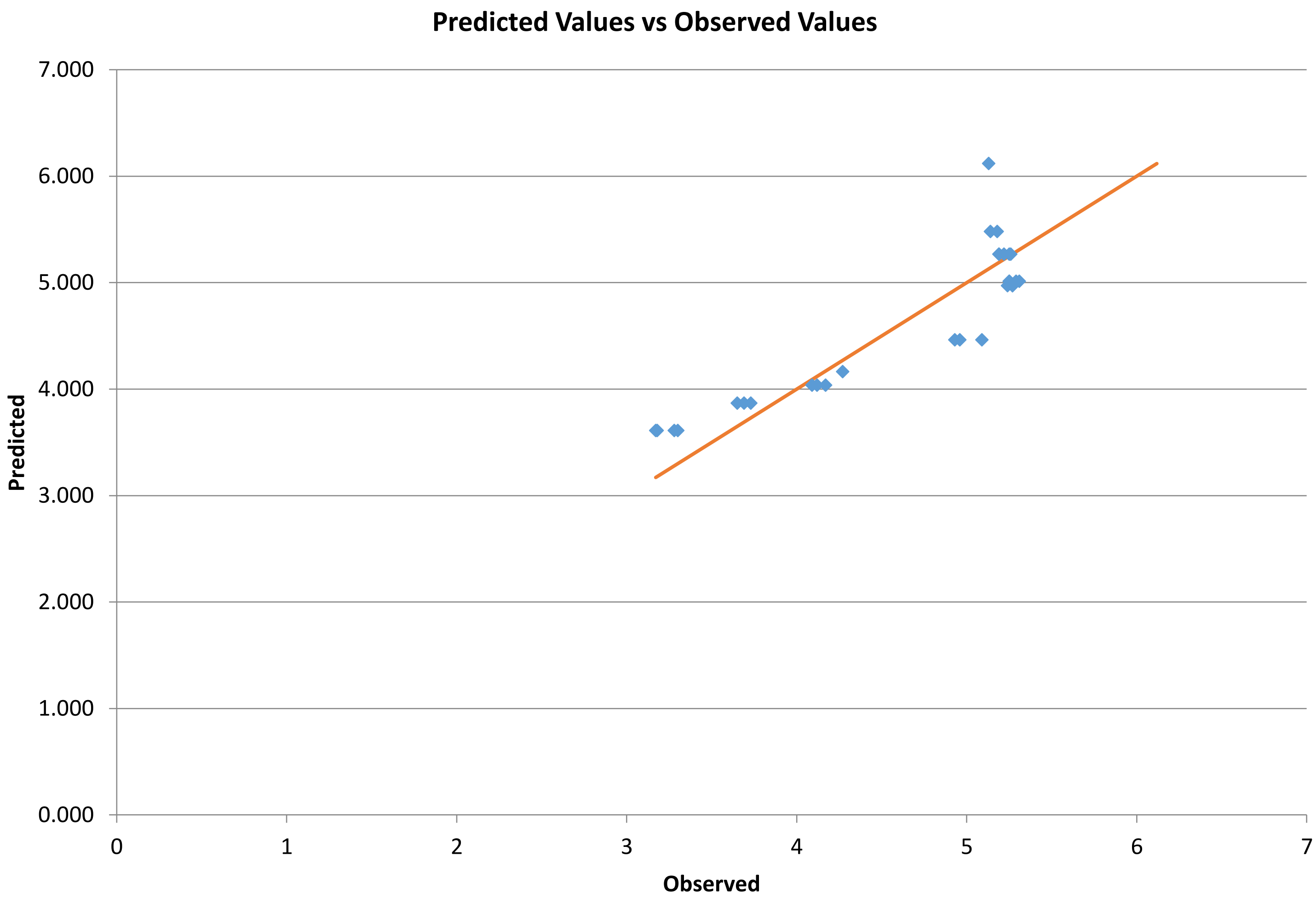
DGS Quality Assurance
www.dgs-qualityassurance.com

SPC FOR EXCEL

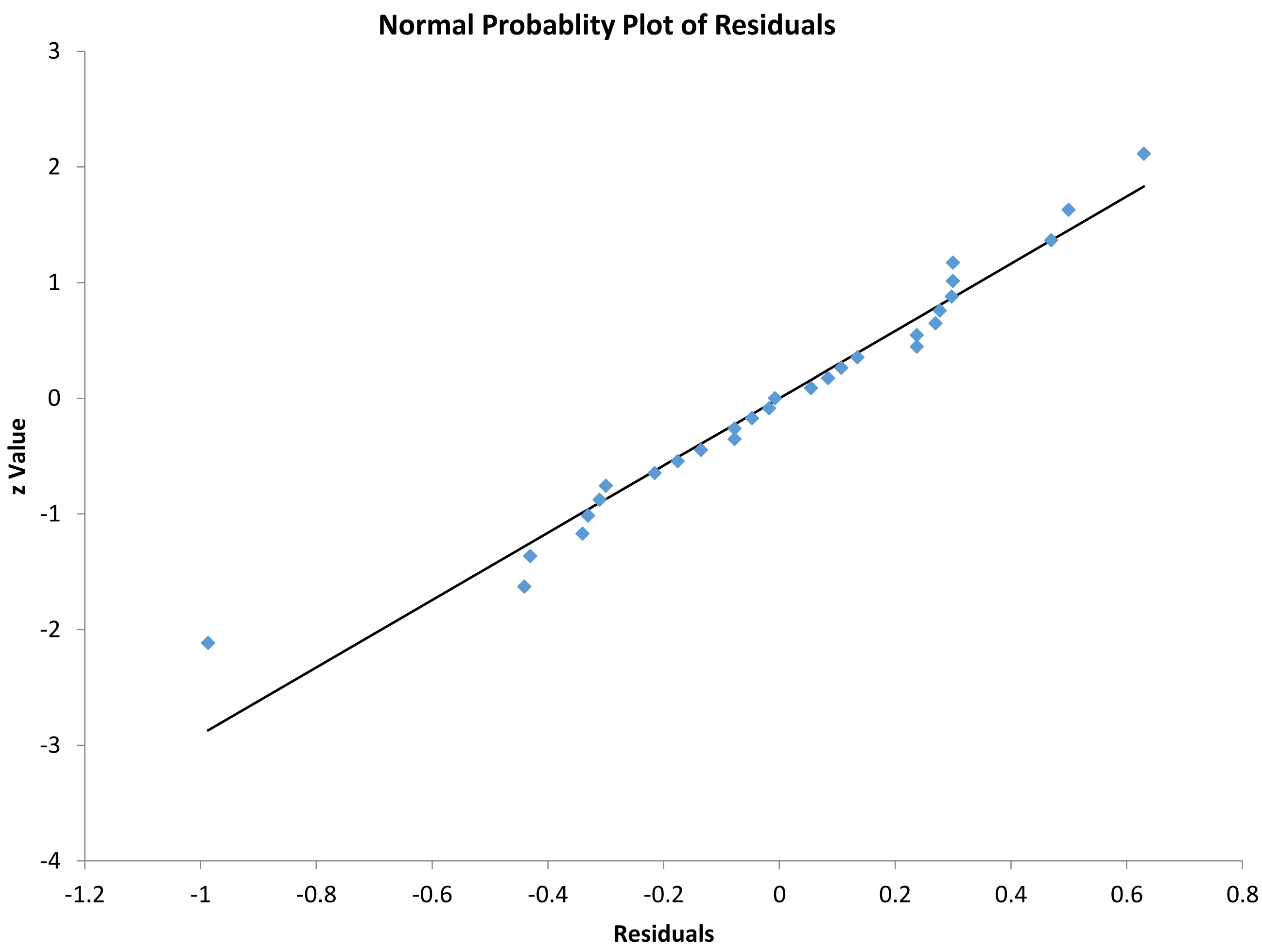


In this study, the “x” represents the stop-set distance, and “y” represents the formed diameter. Thirty pieces of material were used for the trial and between one (at -1.9mm) and five (at 0.7mm) pieces were formed at each setting. The plus and minus signs simply represent the direction in “x” from a starting point. The results were entered into columns in the software, and the program executed. The numerical and graphical results follow;.

Graphical Analysis



Graphical Analysis



DGS Quality Assurance
www.dgs-qualityassurance.com

Numerical Analysis

SPC for Excel

X	Y
2.7	5.11
2.7	5.13
1.2	5.18
1.2	5.14
0.7	5.22
0.7	5.19
0.7	5.19
0.7	5.25
0.7	5.26
0.1	5.29
0.1	5.25
0.1	5.31
0.1	5.25
0	5.24
0	5.27
0	5.27
-1.2	5.09
-1.2	4.93
-1.2	4.96
-1.9	4.27
-2.2	4.17
-2.2	4.09
-2.2	4.12
-2.6	3.69
-2.6	3.73
-2.6	3.65
-3.2	3.3
-3.2	3.28
-3.2	3.18
-3.2	3.17

ANOVA Table

	df	SS	MS	F	p value
Model	1	13.28	13.28	89.31	0.0000
Residual	28	4.162	0.149		
Total	29	17.44			

Predictors Table

	Coeff.	Standard Error	t Stat	p Value	95% Lower	95% Upper	VIF	Stand. Coeff
Intercept	4.910	0.0760	64.614	0.0000	4.754	5.065		
2.7	0.386	0.0409	9.450	0.0000	0.303	0.470		

Regression Statistics

R^2	76.13%
Adjusted R^2	75.28%
Mean	4.639
Standard Error	0.386
Coefficient of Variance	8.311
Observations	30
Durbin-Watson Statistic	0.230
PRESS	5.131
R^2 Prediction	70.58%

Numerical Analysis

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	13.2758	13.2758	89.31	0.000
Error	28	4.1622	0.1487		
Total	29	17.4380			

Model Summary

S	R-sq	R-sq(adj)
0.385552	76.13%	75.28%

The regression equation is Y(D) = 4.910 + 0.3864 X

Numerical Analysis

- The regression equation is Y(D) = 4.910 + 0.3864 X

OR

$$y = ax + b \ (+ \text{error})$$

so

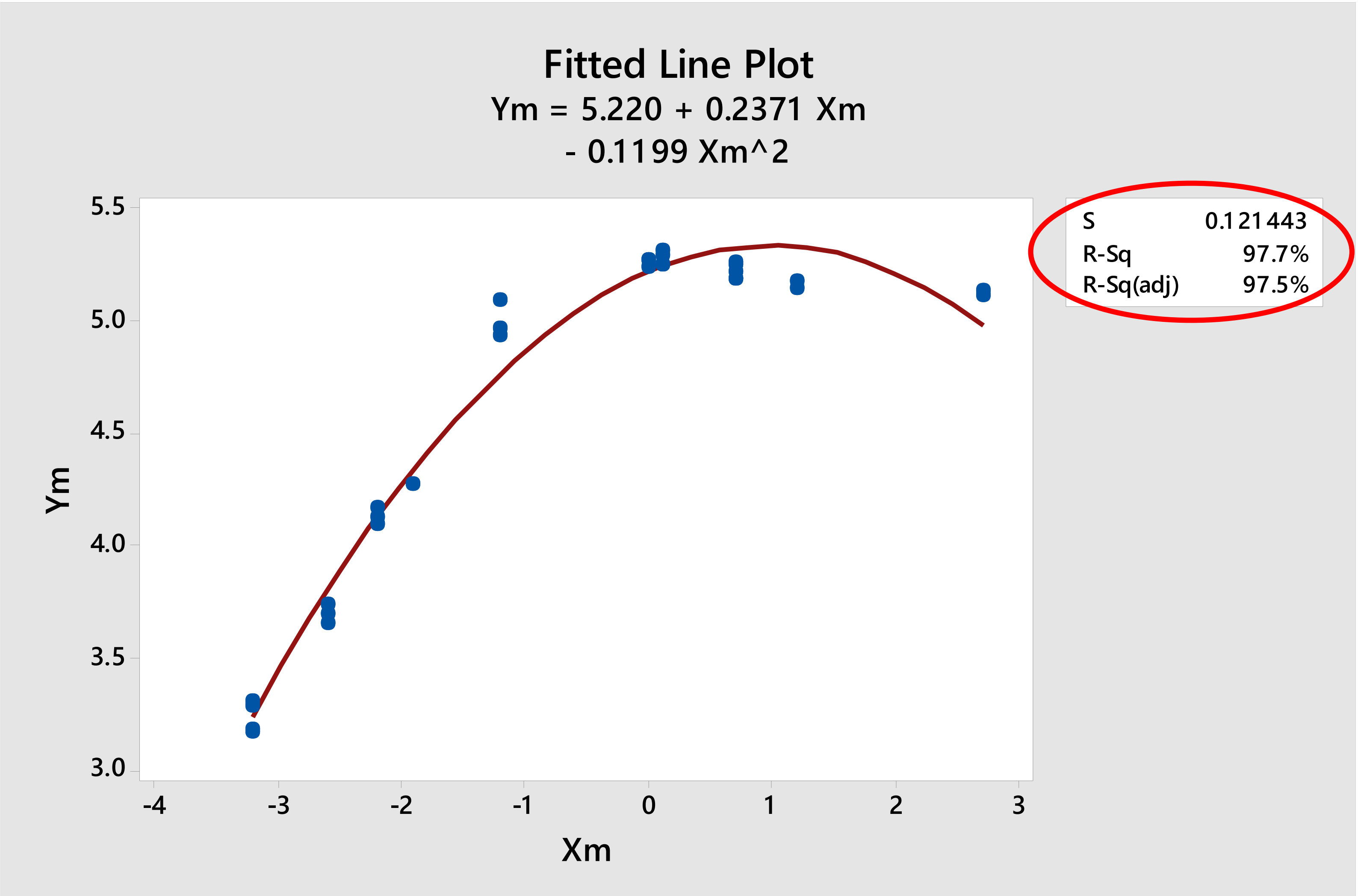
$$y = 0.386x + 4.910 + \varepsilon$$

Substituting x = 2.7 into the above equation to check the corresponding value of Y on the linear regression line (or line of best fit);

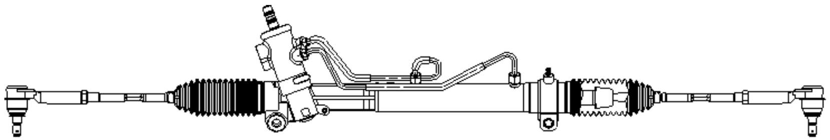
$y = (0.386 \times 2.7) + 4.91 = 5.95$ So when x = 2.7, y = 5.95

- The graphical analysis shows that the relationship between stop-set and diameter do not fit a straight line, so the linear model is less than ideal. We can plot the with a quadratic model in Minitab software, and this raises the coefficient of determination R^2 to 97.7%

Graphical Analysis



Steering Example



- Consider the data for a two level, three-factor experiment. Rack speed, Pinion speed, and hydraulic oil temperature are 100% tested in the functional testing machine to see the effects upon the returnability force of the steering rack (measured in Newton's). Again, we wish to know the extent of each factor on the returnability force and determine a mathematical relationship. Each of the factors has the levels defined below.

Factors	Level +	Level -
A Rack Speed	25.4 mm/sec	15.87 mm/sec
B Pinion Speed	40 RPM	28 RPM
C Oil Temperature	60°C	38°C

Numerical Analysis

Response Variables					
Force					

Factor Information

Factor	Name	Low Level	High Level
A	Rack Speed	15.87	25.4
B	Pinion Speed	28	40
C	Oil Temp	38	60

Actual Run Order	Standard Run Order	A	B	C	Force
1	2	25.4	28	38	235.47
2	4	25.4	40	38	241.83
3	3	15.87	40	38	224.95
4	8	25.4	40	60	214.81
5	7	15.87	40	60	205.07
6	5	15.87	28	60	189.94
7	1	15.87	28	38	223.75
8	6	25.4	28	60	212.76

Analysis Results for Force

Design Table

Standard Run Order	Mean	A	B	C	AB	AC	BC	ABC	Average
1	+	-	-	-	+	+	+	-	223.75
2	+	+	-	-	-	-	+	+	235.47
3	+	-	+	-	-	+	-	+	224.95
4	+	+	+	-	+	-	-	-	241.83
5	+	-	-	+	+	-	-	+	189.94
6	+	+	-	+	-	+	-	-	212.76
7	+	-	+	+	-	-	+	-	205.07
8	+	+	+	+	+	+	+	+	214.81
Sum +	1748.58	904.87	886.66	822.58	870.33	876.27	879.1	865.17	
Sum -	0	843.71	861.92	926	878.25	872.31	869.48	883.41	
Overall	1748.58	1748.58	1748.58	1748.58	1748.58	1748.58	1748.58	1748.58	
Difference	1748.58	61.16	24.74	-103.42	-7.92	3.96	9.62	-18.24	
Effect	218.6	15.29	6.185	-25.86	-1.980	0.990	2.405	-4.560	
SS		467.6	76.51	1337.0	7.841	1.960	11.57	41.59	
MSE	27.89								
F		16.76	-	47.93	-	-	-	-	
Fcrit	6.607891								

The significant effects are in bold in the effects row. These are larger than the minimum significant effect.

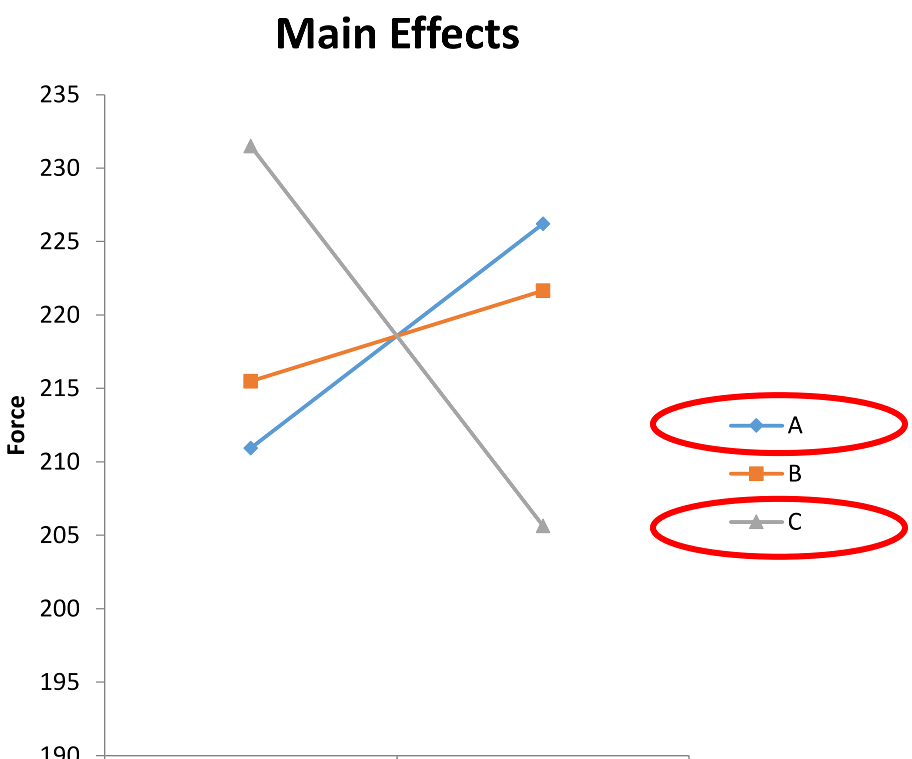
ANOVA Table Based on All Factors and Interactions

Source	SS	df	MS	F	p value	% Cont
A	467.6	1	467.6	N/A	N/A	24.05%
B	76.51	1	76.51	N/A	N/A	3.94%
C	1337.0	1	1337.0	N/A	N/A	68.77%
AB	7.841	1	7.841	N/A	N/A	0.40%
AC	1.960	1	1.960	N/A	N/A	0.10%
BC	11.57	1	11.57	N/A	N/A	0.60%
ABC	41.59	1	41.59	N/A	N/A	2.14%
Error	0.000	0				
Total	1944.0	7				

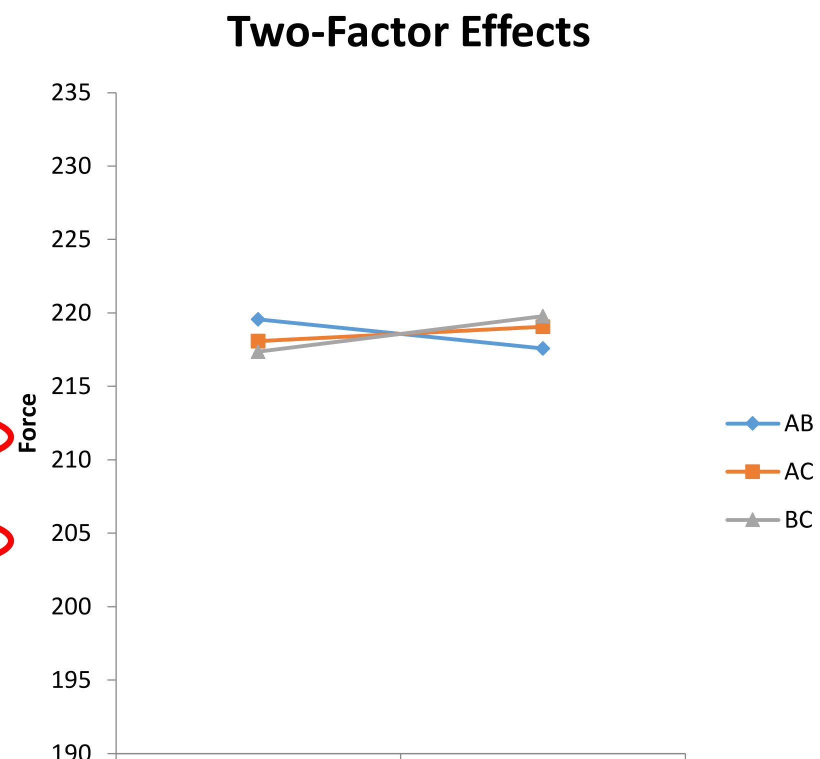
The significant effects cannot be estimated from the ANOVA since there was only 1 replication.

Each of the eight trials consisted of approximately 20 parts, so the eight results represent the group averages. I tried to enter the full data sets as multiple replications (starting with just one replication), but the software crashed (see conclusions). The “post hoc” analysis of the “within group” data is a requirement for in DOE, and can be done through the software.

Graphical Analysis

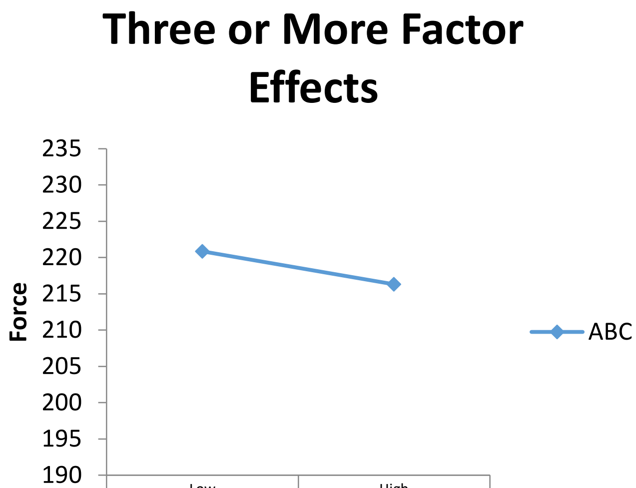


	Low	High
A	210.9275	226.2175
B	215.48	221.665
C	231.5	205.645

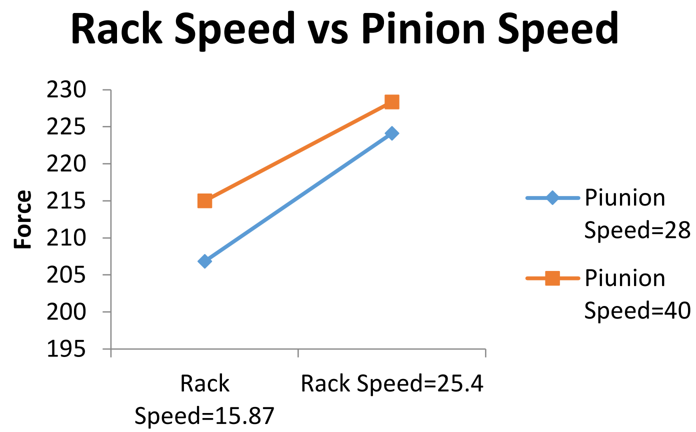


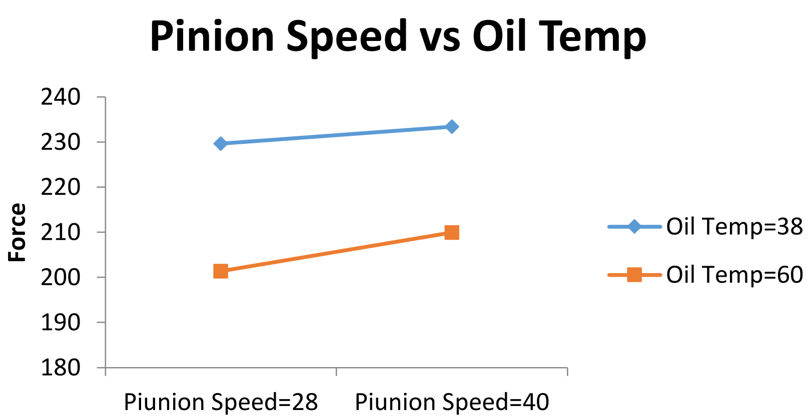
	Low	High
AB	219.5625	217.5825
AC	218.0775	219.0675
BC	217.37	219.775

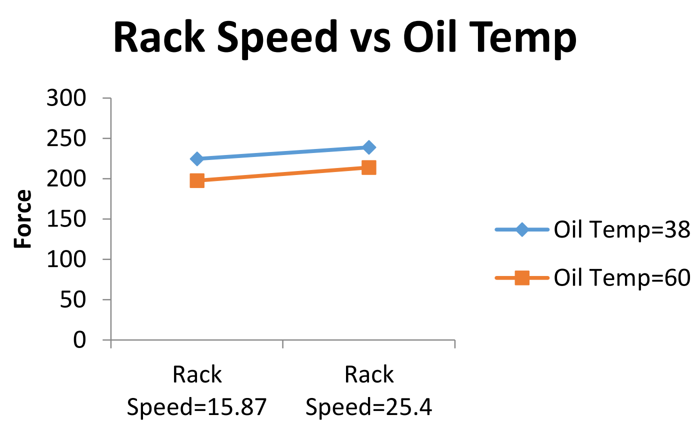
Graphical Analysis



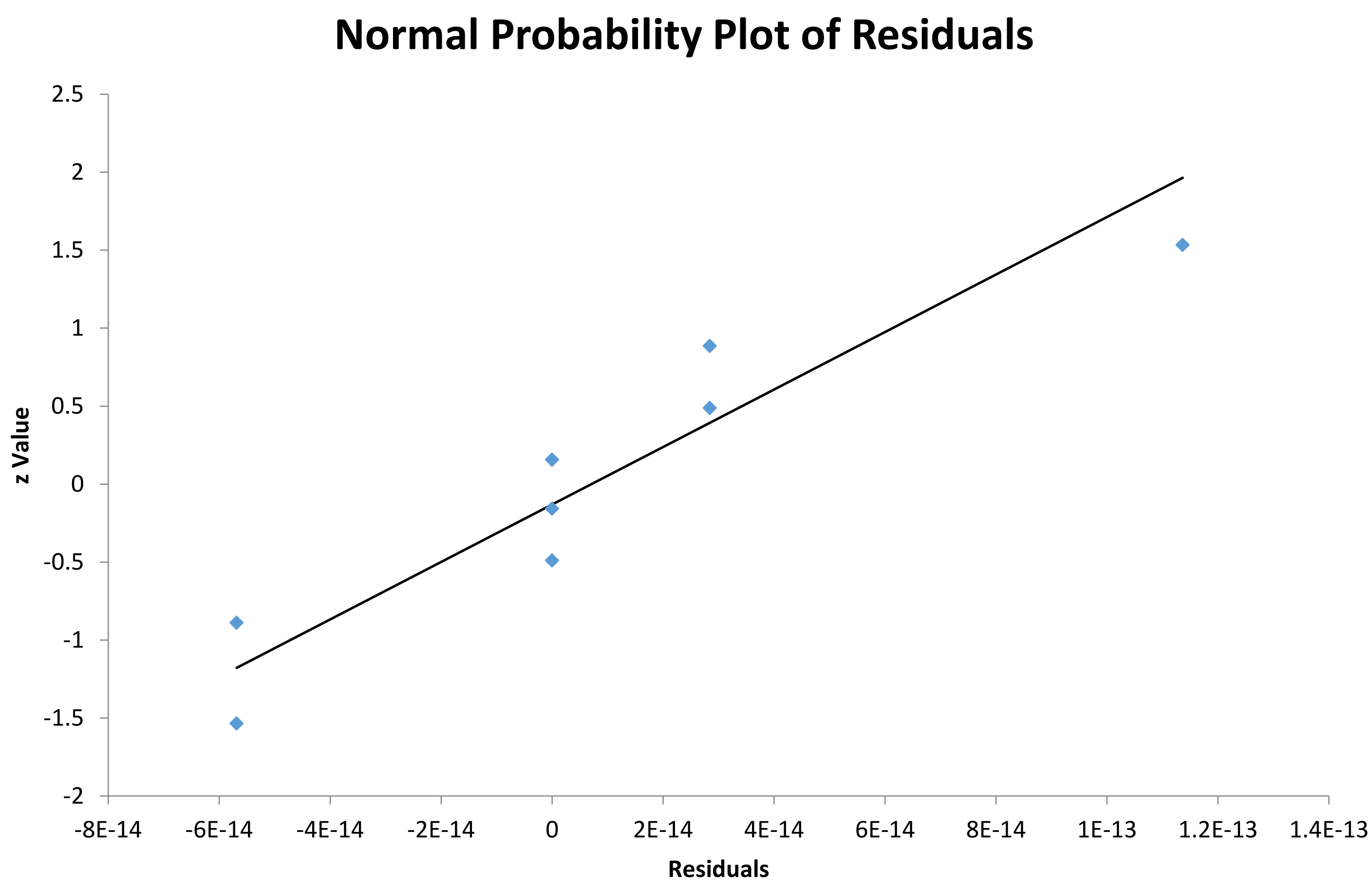
	Low	High
ABC	220.8525	216.2925







Graphical Analysis



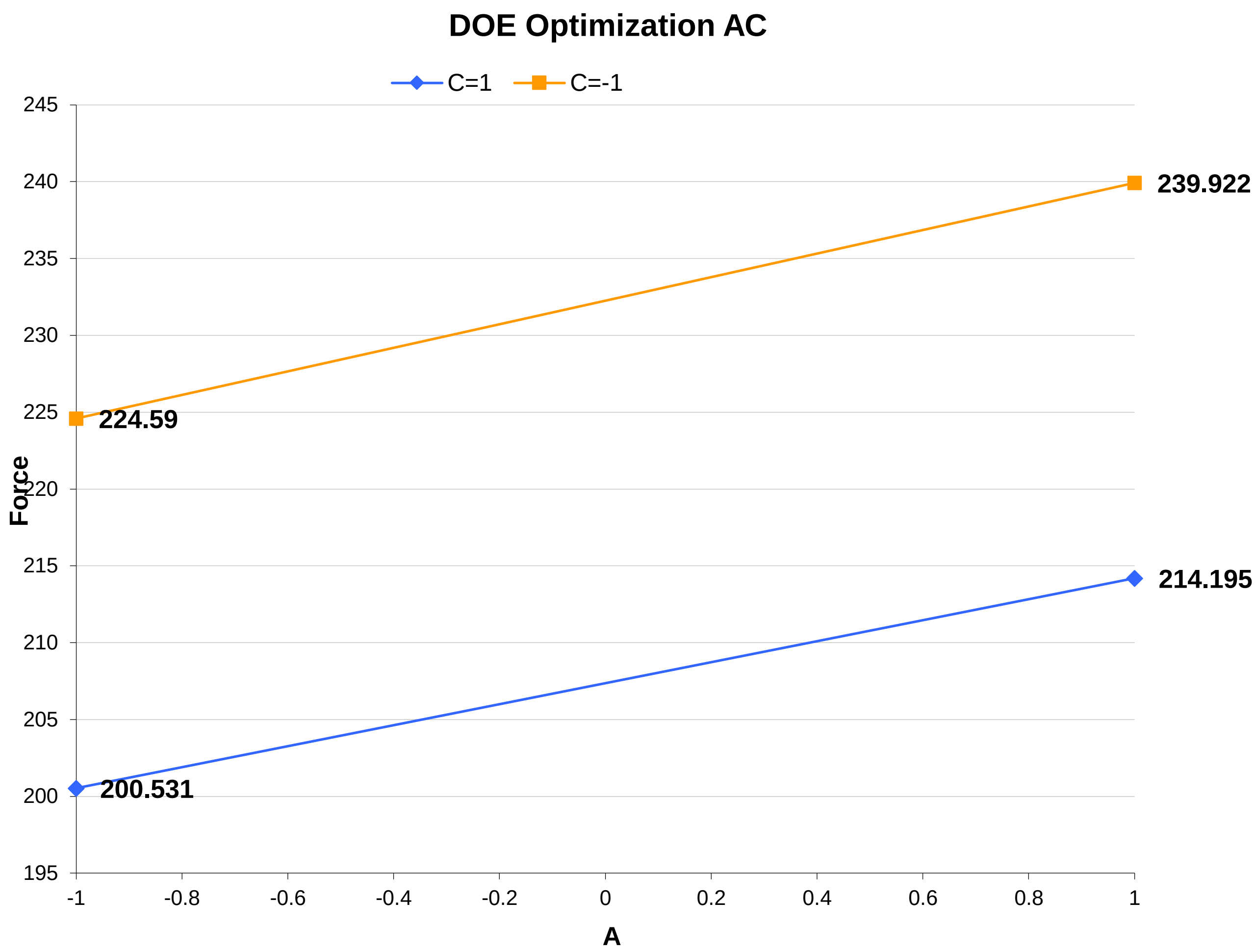
Graphical Analysis

Select X-Axis Factor

Select Series Factor

Select Values for Other Factors

B=0.40



Numerical Analysis

Regression Equation in Uncoded Units

Force = 490.4 - 9.759 A - 6.993 B - 7.076 C
+ 0.3206 A*B + 0.2559 A*C
+ 0.1678 B*C
- 0.007250 A*B*C

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	1943.99	277.71	*	*
Linear	3	1881.04	627.01	*	*
A	1	467.57	467.57	*	*
B	1	76.51	76.51	*	*
C	1	1336.96	1336.96	*	*
2-Way Interactions	3	21.37	7.12	*	*
A*B	1	7.84	7.84	*	*
A*C	1	1.96	1.96	*	*
B*C	1	11.57	11.57	*	*
3-Way Interactions	1	41.59	41.59	*	*
A*B*C	1	41.59	41.59	*	*
Error	0	*	*		
Total	7	1943.99			

Observations

- The major influence on this output was Oil temperature (C) and Rack Speed (A). The findings of the analysis were to a large extent partially predicted based on historical evidence. The one very important piece of information uncovered by the use of the unsaturated matrix, was that there was no significant interaction present. As this was only a two level per factor experiment, it assumes a linear cause and effect relationship.

- The software includes a process optimisation tool which is good for many applications. This function allows one to determine the ideal settings for independent variables in order to meet some desired output (say the minimum or maximum force) however the process optimiser is limited to the two level factor analysis available in the DOE module.

- The software has an ability to carry out a series of post hoc tests to check any assumptions. One example of this would be checking residual error for normality using tools such as the Anderson darling test among others. A normality test of residuals is a default tool within the DOE module. Another assumption of this type of analysis is that the "within group data" (the 20+ results per run on which the eight averages were based) are homogeneous. I was not able to test this via replication as it crashed out (this may be an issue with my PC rather than the software!), but it was possible to test this assumption by plotting all group data on I & MR charts.

www.dgs-qualityassurance.com

Donald Wheeler Example

- Two concentrations and five processing temperatures are examined for their effects upon the reflectivity of a certain coating. Three samples are coated and processed using each of the ten combinations of concentration and temperature. The first factor, concentration, has two levels (5 and 10), while the second factor, temperature, has five levels (75,100,125,150, and 175).

Concentration	5	5	5	5	5	10	10	10	10	10
Temperature	75	100	125	150	175	75	100	125	150	175
Measured	35	31	30	28	19	38	36	39	35	30
Reflectivity	39	37	31	20	18	46	44	32	47	38
	36	36	33	23	22	41	39	38	40	31
Averages	36.67	34.67	31.33	23.67	19.67	41.67	39.67	36.33	40.67	33.0
Ranges	4	6	3	8	4	8	8	7	12	8

DGS Quality Assurance
www.dgs-qualityassurance.com

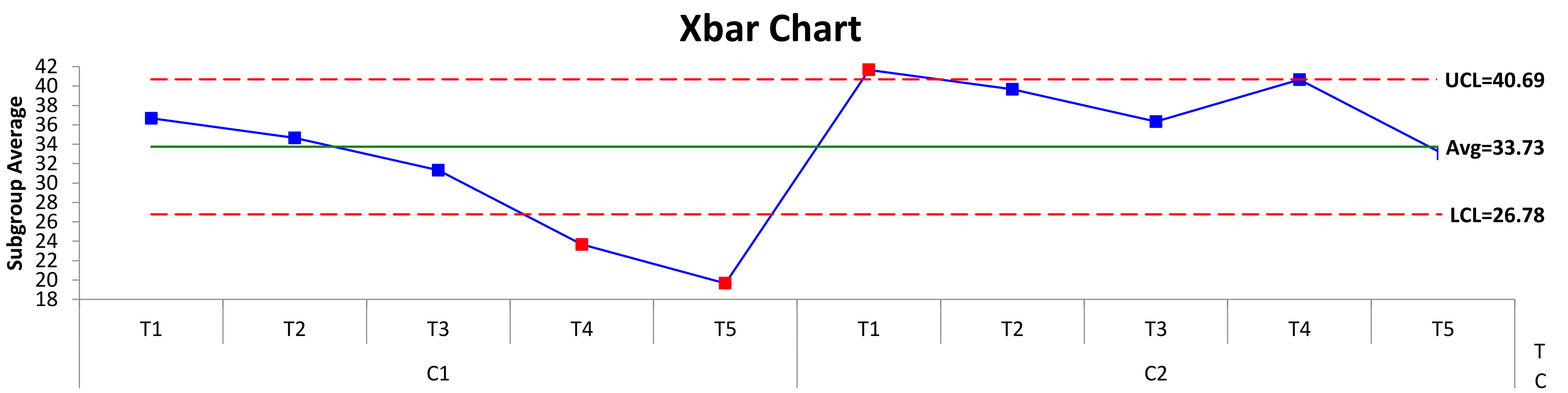
Background

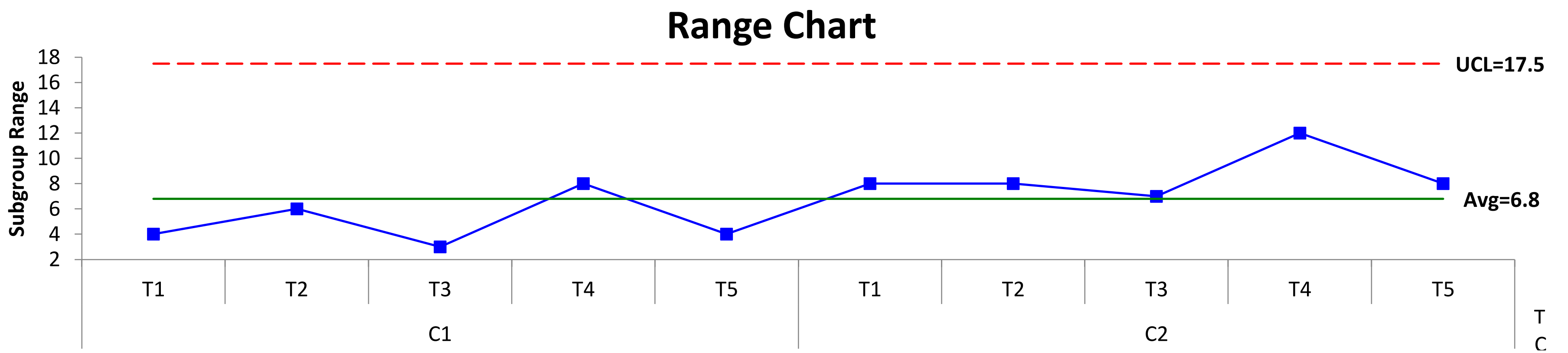
Initially this example was used to demonstrate the Analysis of Means and main effects (ANOME), but since most software dos not allow for the calculation of “detection limits” the questions raised can be solved using the ANOVA function in the software. The ANOVA module has a SPC chart function embedded as an output option which is convenient. The questions posed were:

- How does the concentration level affect the reflectivity?,
- How does the temperature affect the reflectivity?
- How does the interaction effect change the reflectivity?

Looking at the data, the writer was interested to see if the conclusions reached from a previous analysis of the same data is as he would have expected it (he had previously used both “normal excel” and his statistical calculator!). The ANOVA tab in the software offers several options for both numerical and graphical, so the writer has chosen the ones of most interest to him.

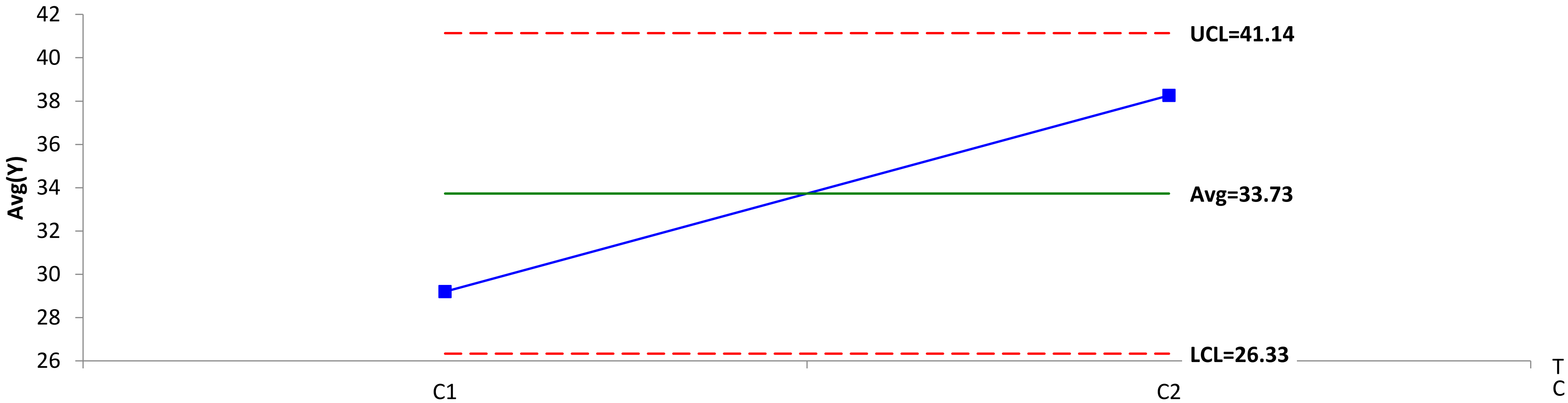
X Bar & Range Chart



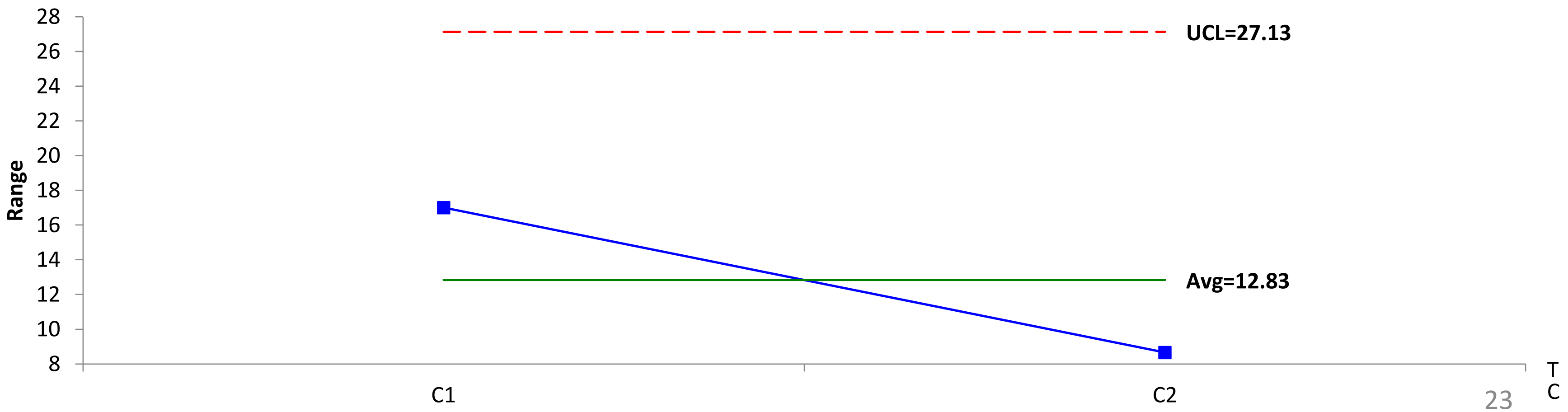


Graphical Analysis

Xbar Chart for Avg(Y)

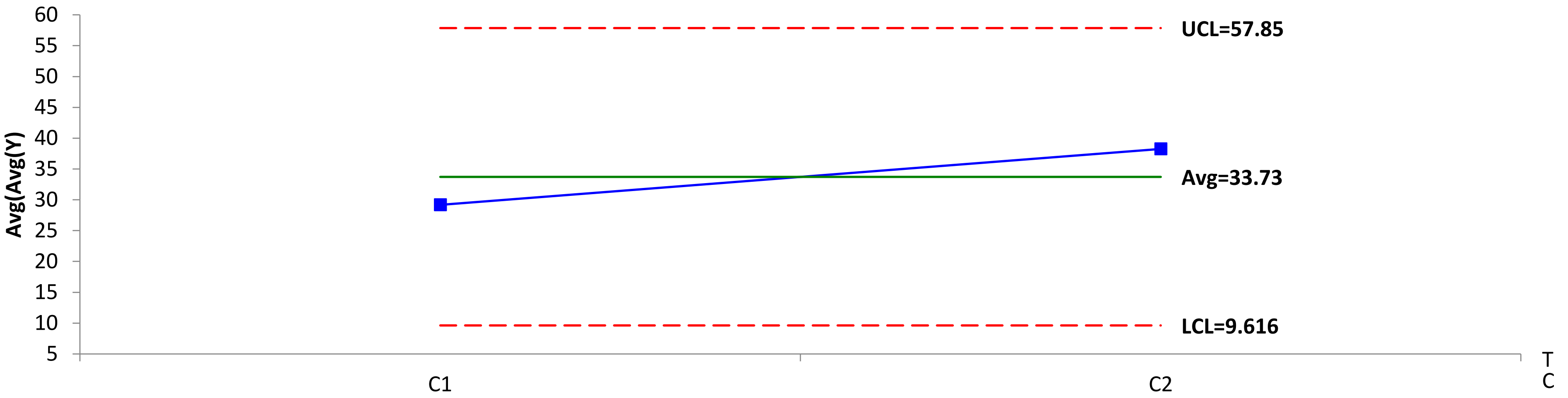


R Chart

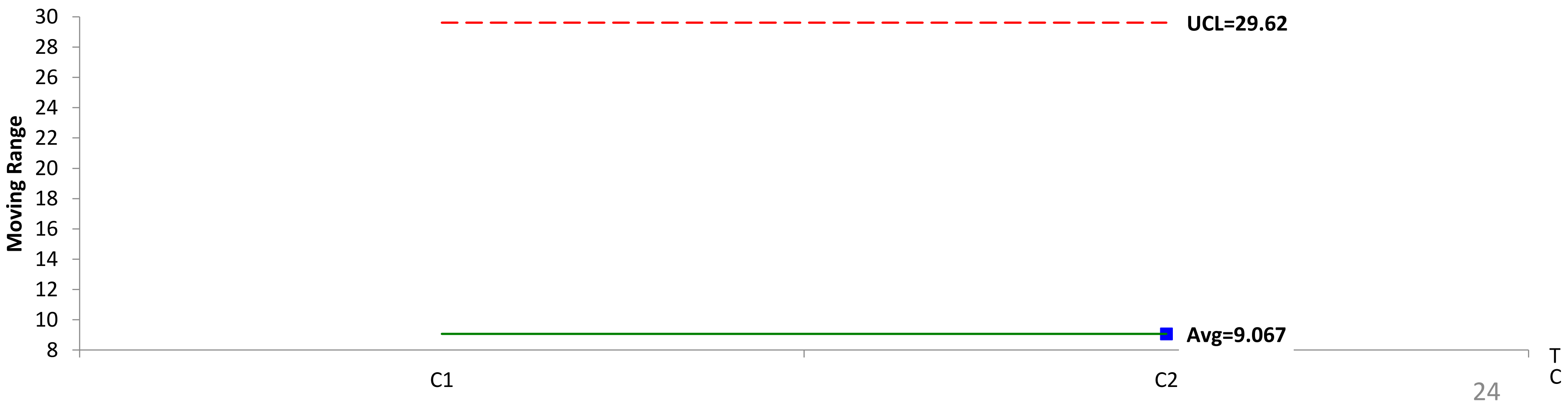


Graphical Analysis

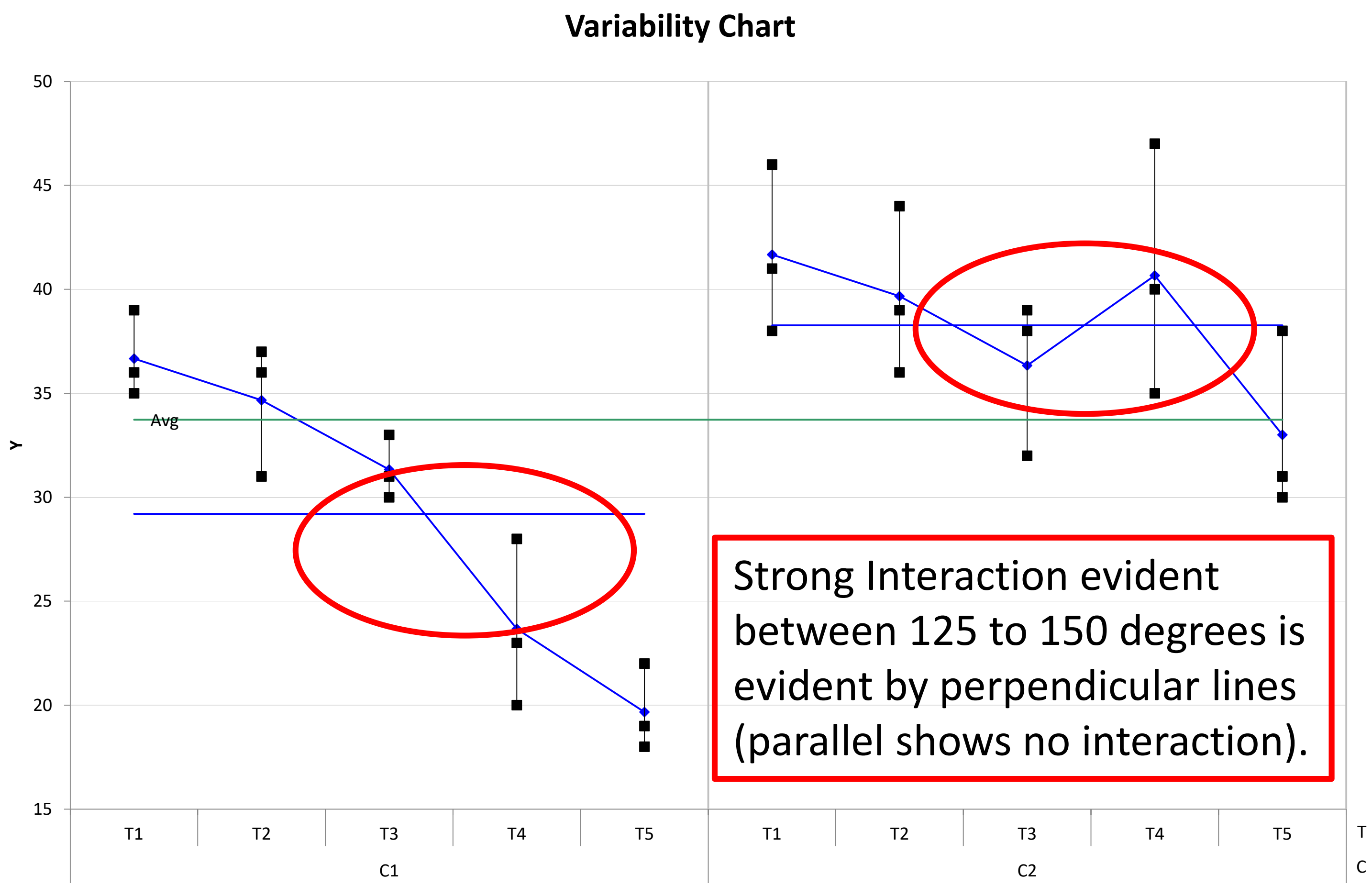
Individuals Chart for Avg(Avg(Y)



Moving Range Chart



Main Effects Analysis



Numerical Analysis

DGS Quality Assurance
www.dgs-qualityassurance.com

Crossed Design				
Fixed Factors				
Response:	Y			
Factors	Type	Levels		
C	Fixed	2	C1, C2	
T	Fixed	5	T1, T2, T3, T4, T5	
Reps:	3			
Std. Run No.	Actual Run No.	C	T	Y
1	1	C1	T1	35
2	2	C1	T1	39
3	3	C1	T1	36
4	4	C1	T2	31
5	5	C1	T2	37
6	6	C1	T2	36
7	7	C1	T3	30
8	8	C1	T3	31
9	9	C1	T3	33
10	10	C1	T4	28
11	11	C1	T4	20
12	12	C1	T4	23
13	13	C1	T5	19
14	14	C1	T5	18
15	15	C1	T5	22
16	16	C2	T1	38
17	17	C2	T1	46
18	18	C2	T1	41
19	19	C2	T2	36
20	20	C2	T2	44
21	21	C2	T2	39
22	22	C2	T3	39
23	23	C2	T3	32
24	24	C2	T3	38
25	25	C2	T4	35
26	26	C2	T4	47
27	27	C2	T4	40
28	28	C2	T5	30
29	29	C2	T5	38
30	30	C2	T5	31

Tukey's Test C

Family Conf. Int.=95%, Individual Conf. Int:=95%, q(a,f,p)=2.95

Comparisons	Diff. in Means	Critical Value	LCon	UCon	Sig Diff.?
C1 - C2	-9.067	2.850	-11.917	-6.217	Yes

There is evidence that some pairs of means are different.

ANOVA for Y (Crossed Design)

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	p Value
C	616.5	1	616.5	44.038	0.0000
T	591.2	4	147.8	10.557	0.0001
C*T	196.1	4	49.03	3.502	0.0253
Within	280.0	20	14.00		
Total	1683.9	29			

ANOVA for Model

Source	SS	df	MS	F	p value
Model	1403.9	9	156.0	11.142	0.0000

Average	33.73
Standard Deviation	3.742
Coefficient of Variation	11.09
R^2	83.37%
Adjusted R^2	75.89%

Modified Levene's Test for Equality of Variances: C

Treatment	Count	Variance	Std. Dev
C1	15	50.74286	7.123402
C2	15	25.49524	5.049281
F Levene	2.22		
F Critical	4.20		
p value	0.1471		

There is no evidence that the variances are different.

P Values show concentration, temperature and interaction factors are significant (<0.05)

95% Confidence Intervals for Treatment Means

Treatment	C	T	Mean	Stand. Err.	95% LCon	95% UCon
T1	C1	T1	36.67	2.160	32.16	41.17286
T2	C1	T2	34.67	2.160	30.16	39.17286
T3	C1	T3	31.33	2.160	26.83	35.83953
T4	C1	T4	23.67	2.160	19.16	28.17286
T5	C1	T5	19.67	2.160	15.16	24.17286
T6	C2	T1	41.67	2.160	37.16	46.17286
T7	C2	T2	39.67	2.160	35.16	44.17286
T8	C2	T3	36.33	2.160	31.83	40.83953
T9	C2	T4	40.67	2.160	36.16	45.17286
T10	C2	T5	33.00	2.160	28.49	37.5062

Observations

In relation to our questions;

- How does the concentration level affect the reflectivity?,
- *Moving from lower to higher concentration levels leads to significantly higher reflectivity*
- How does the temperature affect the reflectivity?
- *Moving from lower to higher temperature levels leads to significantly lower reflectivity*
- How does the interaction effect change the reflectivity?
- *There is only one point of interaction between the two concentration levels and it occurs between 125 and 150 degrees.*

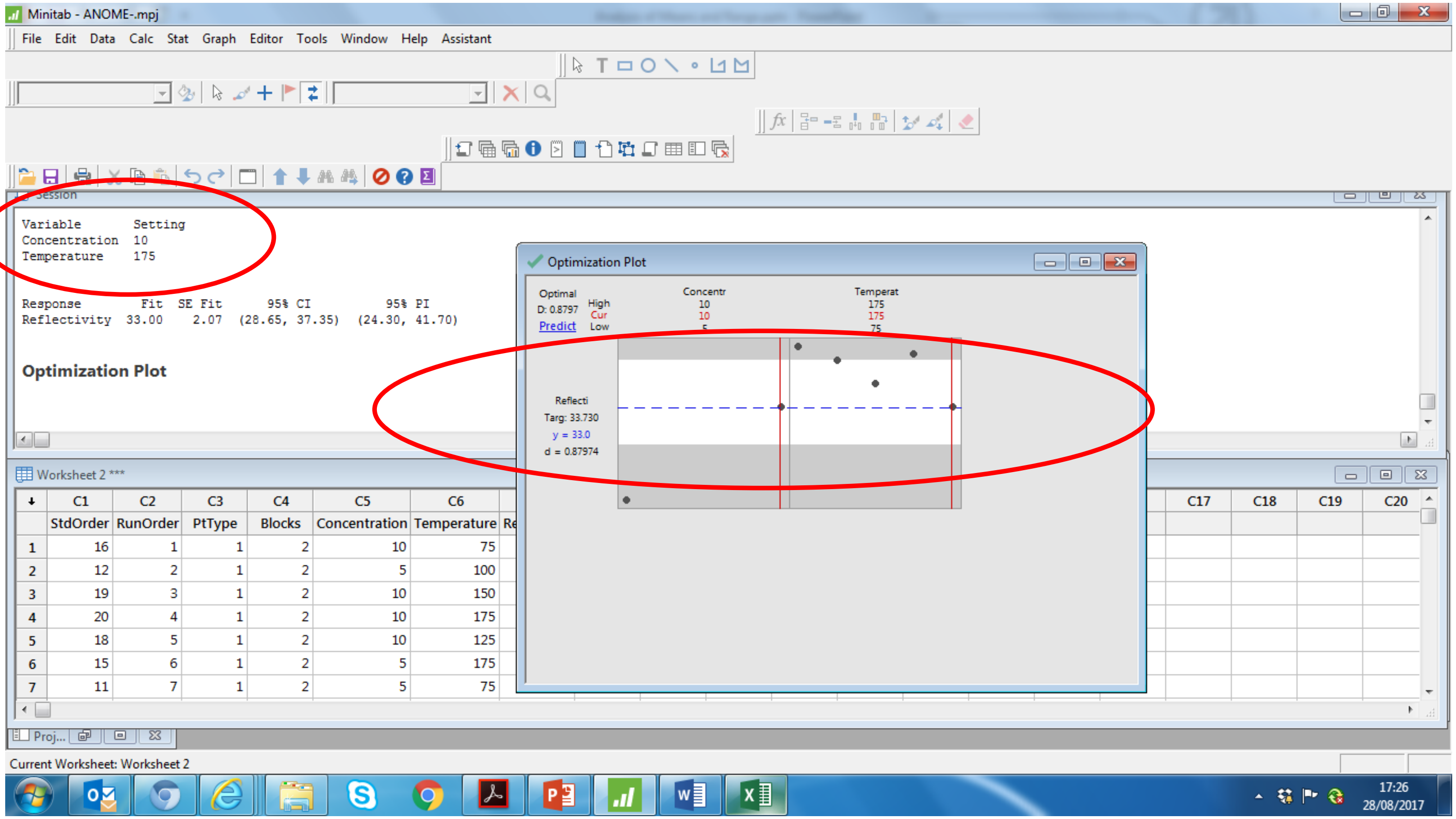
- *The p values show that both concentration and temperature are significant on reflectivity and interaction is also significant (shown on the graph between 125 and 150 degrees).*

Unlike Minitab, the software does not appear to have a process optimiser tool within the ANOVA module. It does have process optimiser within the DOE module, but one cannot do an analysis under DOE for this example, as one factor (temperature) had five levels.

DGS Quality Assurance
www.dgs-qualityassurance.com

Numerical Analysis

Minitab® 18



The ideal settings for achieving a reflectivity target of 33.73 +/- 6.076 is with concentration at 10, and temperature at 175. The delta value is 0.879. A value of 1 would be perfect, but natural variation does not allow “perfection”. This outcome may be obvious from the data in this simple example, but this is not the case in much more complicated examples with multiple multi level factors.

Conclusions

- This software only offers linear regression options (no non-linear options?).Looking at the graphical data of the example under study, one can see this is not a linear relationship, and by applying a quadratic model in Minitab, the coefficient of determination (R^2) was raised to 97.7%

- The DOE options include full factorial (up to 7 factors), fractional factorial (15 factors), and Plackett-Burman (27 factors). Other common arrays are not included (Taguchi three factor screening, Central Composite, Box Behnken etc..). With only two levels per factor, exploring non linear effects is not possible.

- Analysis via the ANOVA module was satisfactory for the example chosen, although the process optimiser function was not available .

- OVERALL A good addition to Microsoft Excel. There are some limitations on the DOE and ANOVA options as explained, but most of the modules are can be used without problems. The software has good advise and assistance via the website.