



A Walk-Through Taguchi Design of Experiment (DOE) Application

[Example: Plastic Injection Molding Process Study]

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Introduction

This brief report is prepared to show you the steps involved in the application of Design of Experiment (DOE) technique as standardized by Dr. Genichi Taguchi. Even though, the DOE techniques are presented in several different forms, the basic steps in application are quite common. To demonstrate the DOE application steps, we will make use of an example case study involving Plastic Injection process Study.

Case Study: A Plastic Injection Molding Process is use to produce an automobile engine cooling fan. Among the process defects, Short-Shots* were identified as critical to quality and cost. The purpose of the study was to reduce rejects due to Short-Shots.

To study process parameters factors affecting occurrence of Short-Shots, a Taguchi L-8 orthogonal array was used to layout six (Injection Pressure, Backpressure, Screw Speed, Spear Temperature, Manifold Temperature,..) among a large number of factors identified. Using weight of the molded component as an evaluation criterion (result) the test results were analyzed to identify the factors with significant influence and the optimum condition for the process.

* Short-shots are caused when there is not enough material entering the mold cavity during the fill process which generally results in dimensional shortages. Common corrective actions require that enough melt flow, pressure and hold time that allow proper filling of the cavity.



DOE Application Steps

Ia: Select Project and Form Team



Tasks you & your project to do:

- **Select a project** based on higher return on investment, or one that has most interest of your management
- **Identify a leader** for the project (In reality, a project responsible individual would initiate the project and seek management approval to pursue it. He/she naturally becomes the project leader)
- **Form team** by selecting people with interest in the project. It is a good idea to include people whose ideas would be valuable or those who would have to be involved in the implementation of improvement derived from the experimental study you undertake.
- **Appoint a facilitator.** Often, by default, the leader will be the facilitator for experiment planning discussions. A facilitator for experiment planning must be knowledgeable in DOE application process. If possible secure help from such individual who will remain impartial during discussion process. If you are the leader and you would conduct the planning discussions, you need to be extra careful to maintain objectivity while soliciting opinions and ideas from others.

Examples:

Project: Injection Molding Process

Leader: John Doe

Team Members: 9 members - project manager, process engineer, shift supervisor, equipment operator, and others.

Facilitator: the leader was knowledgeable in DOE and was willing to facilitate the discussions.

Ib: Conduct Experiment Planning Discussion



Experiment planning discussion is essential for successful study. It should be done with all team members during a meeting dedicated for the purpose. The findings from the meeting should be documented and, preferably, all decisions regarding the study are made by group consensus. You should prefer to complete planning in sessions during one single day (For detail discussions of experiment planning process, visit <http://nutek-us.com/wp-exptplanning.html>)

Tasks you & your project to do:

- **Define objective** in terms of a solution of the problem you are currently experiencing or which is the reason for launching the study.
- **Agree on a project title**
- **Identify quality characteristic** that measures how well your objective is satisfied (select evaluation criterion, define its units of measurement and direction of desirability of the result)
- **Select key factors and their levels** for the study (Factors for study should be selected from a long (*Paretoized*) list of factors identified by the team. Use of Ishikawa/Cause & effect type diagrams is strongly suggested.).
- **Determine interactions** of concern and select a few for study. (With a larger number of factors, possible interactions are also larger. Prior to experiments, only subject opinion of team members are available to select which ones to study.)
- **Identify noise factors** and evaluate possibility of incorporating their influence for *robust designs*.
- **Define scopes of experiment** by determining sample size for the study. It is a good idea for the team leader/facilitator to share with the group the total number of test and duration for the same.

Example:

Objective: Reduce rejects due to Short-Shots.

Title: An Experimental Study to Reduce Short-Shots in Cooling Fan Molding Process

Quality Characteristic: Weight of the part in ounce. Desirable performance - *Bigger is Better*.

From past experience, the team strongly felt that weight of production part bears a direct relationship with occurrence SHORT-SHOTS. Recent production parts measurement revealed that average weights of qualified parts fell on the higher side of the distribution while those with SHORT-SHOTS were on the lower end.

Factors & Levels: The top 6 from the list of 18 qualified and Paretoized factors were selected for the study. To keep the size of the experiment small and study as many factors as possible, all factors were studied at two extreme ranges of values (2 levels). These factors and their levels are shown next. (For complete process of discussions and determination of factors and their levels, follow steps outlined in <http://nutek-us.com/wp-exptplanning.html>)

(A long list of qualified factors, in descending order of importance to the project team)

1. Injection Pressure
2. Mold Closing Speed
3. Mold Pressure
4. Backpressure
5. Screw Speed
6. Spear Temperature
7. Manifold Temperature,
8. Mold Opening Speed
9. Mold Opening Time
10. Forward Screw Speed
11. Nozzle Heater On Time
12. Screw Retract Speed
13. Cooling Time
14. Holding Pressure Time
15. Ejection Speed
16. Coolant type (Water/Oil)
17. Room Temperature (Cold/Warm)
18. Operator skill level (New/Experienced)

Selected Factors and their Levels

Notation	Factor Description	Level 1	Level 2
A	Injection Pressure	1,800 psi	2,250 psi
B	Mold Closing Speed	Low (Not revealed)	Moderate
C	Mold Pressure	600 psi (4.1 MPA)	950 psi
D	Backpressure	950 psi	1,075 psi
E	Screw Speed	50 Sec.	65 Sec.
F	Spear Temperature	325 Deg. C	380 Deg. C

Interaction: Interaction between factors A & B (AxB) was selected for the study.

Noise factors: Among the factors identified, the last three factors in the above list were considered uncontrollable, noise factors [Coolant type (Water/Oil), Room Temperature (Cold/Warm), and Operator skill level (New/Experienced)]. For the study undertake, noise factors were not incorporated in the experiment (no *outer array* used)

Scope of Experiment: Based on the number of factors (6 2-level factors and 1 interaction), the experiment was expected to run 8 separate trial conditions (Using an L-8 array for the design). It was agreed that each trial condition would be run 4 separate times. Average of weights from each batch will be considered as the representative result for each batch. Thus, there would be $8 \times 4 = 32$ results for analysis. This information helped the project team procure and schedule the test equipment.

IIa: Design Experiment (Layout/Test Plan)

Designing experiment is a relatively simple task in the hands of the personal knowledgeable in the Taguchi experimental design technique. Once the planning session is completed, you will have all information necessary to complete the experiment design.



Tasks you & your project to do:

- **Select orthogonal array** and assign factors (For your starting experiments, use of L-8, L-12 or L-9 is recommended)
- **Produce test plan** (Print out trial conditions)
- **Establish order of running tests** (Which trial condition should be run when? It is never a good idea to run experiments in their natural sequence, unless you are forced to do because of the availability of man/machine)

Example:

Orthogonal array: Because there are only 6 2-level factors and one interaction is selected (from $6 \times 5 / 2 = 15$ possible two-factor interactions among 6 2-level factors), an L-8 array is used to design the experiment as shown below. [Qualitek-4 software for automatic design and analysis of Taguchi experiments is used for this example study. For more information about Qualitek-4, visit: <http://nutek-us.com/wp-q4w.html>)

	1	2	3	4	5	6	7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	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

Inner Array

*Orthogonal Array (L-8)
Used for Experiment*

Factor and Interaction Placement in L-8 Array

Inner Array Design

Array Type: **L-8**

Use <ctrl> + <arrows> to move

	Factors	Level 1	Level 2
1	A:Injection Press	1800 psi	2250 psi
2	B:Mold Closing Sp	Low	Moderate
3	INTER COLS 1 x 2	*INTER*	-----
4	C:Mold Pressure	600 psi	950 psi
5	D:Back Pressure	950 psi	1075 psi
6	E:Screw Speed	50 Sec.	65 Sec.
7	F:Spear Temperatu	325 Deg.	380 Deg. C

Test Plan: The experimental trial conditions are generated by Qualitek-4 software as shown below.

Description of 8 Trial Conditions

Trial Condition 1 (Random order for running this Trial is 6)

Factors	Level Description	Level #
A:Injection Press	1800 psi	1
B:Mold Closing Sp	Low	1
C:Mold Pressure	600 psi	1
D:Back Pressure	950 psi	1
E:Screw Speed	50 Sec.	1
F:Spear Temperatu	325 Deg.	1

Trial Condition 2 (Random order for running this Trial is 4)

Factors	Level Description	Level #
A:Injection Press	1800 psi	1
B:Mold Closing Sp	Low	1
C:Mold Pressure	950 psi	2
D:Back Pressure	1075 psi	2
E:Screw Speed	65 Sec.	2
F:Spear Temperatu	380 Deg. C	2

Trial Condition 3 (Random order for running this Trial is 5)		
Factors	Level Description	Level #
A:Injection Press	1800 psi	1
B:Mold Closing Sp	Moderate	2
C:Mold Pressure	600 psi	1
D:Back Pressure	950 psi	1
E:Screw Speed	65 Sec.	2
F:Spear Temperatu	380 Deg. C	2

Trial Condition 4 (Random order for running this Trial is 2)		
Factors	Level Description	Level #
A:Injection Press	1800 psi	1
B:Mold Closing Sp	Moderate	2
C:Mold Pressure	950 psi	2
D:Back Pressure	1075 psi	2
E:Screw Speed	50 Sec.	1
F:Spear Temperatu	325 Deg.	1

Trial Condition 5 (Random order for running this Trial is 7)		
Factors	Level Description	Level #
A:Injection Press	2250 psi	2
B:Mold Closing Sp	Low	1
C:Mold Pressure	600 psi	1
D:Back Pressure	1075 psi	2
E:Screw Speed	50 Sec.	1
F:Spear Temperatu	380 Deg. C	2

Trial Condition 6 (Random order for running this Trial is 3)		
Factors	Level Description	Level #
A:Injection Press	2250 psi	2
B:Mold Closing Sp	Low	1
C:Mold Pressure	950 psi	2
D:Back Pressure	950 psi	1
E:Screw Speed	65 Sec.	2
F:Spear Temperatu	325 Deg.	1

Trial Condition 7 (Random order for running this Trial is 8)

Factors	Level Description	Level #
A:Injection Press	2250 psi	2
B:Mold Closing Sp	Moderate	2
C:Mold Pressure	600 psi	1
D:Back Pressure	1075 psi	2
E:Screw Speed	65 Sec.	2
F:Spear Temperatu	325 Deg.	1

Trial Condition 8 (Random order for running this Trial is 1)

Factors	Level Description	Level #
A:Injection Press	2250 psi	2
B:Mold Closing Sp	Moderate	2
C:Mold Pressure	950 psi	2
D:Back Pressure	950 psi	1
E:Screw Speed	50 Sec.	1
F:Spear Temperatu	380 Deg. C	2

Order/Sequence of Tests: The eight trial conditions are tested by selecting the trial conditions in random order (Prescribed by software) as shown with each trial condition above.

IIb: Carry Out Planned Experiments and Collect Results

For experiment to produce beneficial output, they must be conducted in manner that matches the production environment. The best way to run the experiment is to do the same things done for production process. Should you need to carry out experiments under laboratory environment, assure that the tests are field/production relevant.

While the above considerations hold true for any kind of tests, there are a few special considerations that are required for DOE studies.



Tasks you & your project to do:

- Review and **define order of running tests** (which test to run first and how it is determined)
- **Create data collection sheet** (Prepare table reflecting experiment design and proper placement of results)
- Provide **instruction for data collection** and handling (Describe instruments, units of measure and any processing of data required before submitting for analysis)

Example:

Test Order: The sequence of carrying out the trial conditions were maintained as prescribed by the software (Shown earlier)

Data Collection Sheet: Based on L-8 array design and one evaluation criteria (result) for 4 samples in each trial condition, the following data collection sheet was prepared and used for the experiments.

Data Collection Sheet

Trial Condition	Results (Weight in Ounce)			
#	Sample 1	Sample 2	Sample 3	Sample 4
1				
2				
3				
4				
5				
6				
7				
8				

Data Collection Instruction: The team was asked to maintain the order of running the tests and document data in the table above. The results were to be obtained by weighing each cleaned sample using a scale that shows digital display of weight in ounces.

IIIa: Analyze Results



Minimum analyses of DOE results involve calculation for three items: main Effect, ANOVA, and Optimum. As a matter of fact, for simplest form of analysis, ANOVA can be excluded, in which case only the arithmetic type calculations (+, -, x and div.) suffice.

Since routine analysis is repetitive and non-value added, it is nicely handled by software with the Taguchi experiment design and analysis.

Tasks you & your project to do:

- Calculate factor average effects and express main effects (Graphical presentations always preferred) which show the trend of influence of factor to the result.
- Perform analysis of variance (ANOVA) which reflects the relative influence of factors to the variation of result.
- Determine optimum condition based on the main effects and factors found to have significant influence.

Example:

Standard Analysis (using Average of Results)

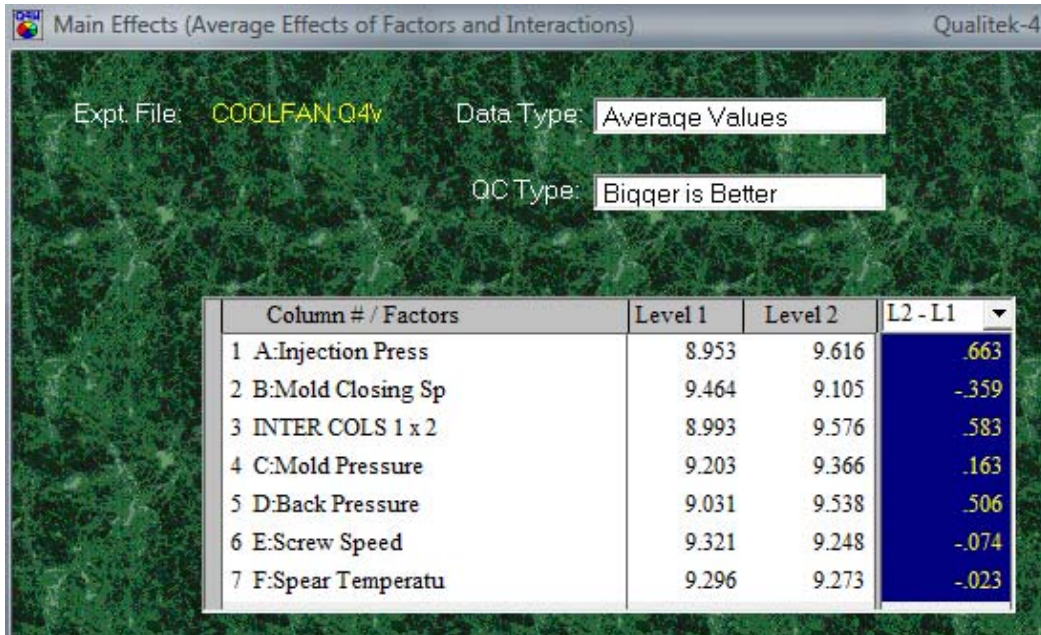
The planned experiments for the example case were completed by the team and the results were recorded (8x 4 results as shown below) for analysis. [Some *parameters and results are altered for this report.*]

	1	2	3	4	5	6	7	1	2	3	4	Averages	
1	1	1	1	1	1	1	1	8.52	8.76	8.45	8.49	8.555	
2	1	1	1	2	2	2	2	9.1	9.12	9.06	9.23	9.127	
3	1	2	2	1	1	2	2	8.72	8.76	8.56	8.69	8.682	
4	1	2	2	2	2	1	1	9.43	9.46	9.33	9.57	9.447	
5	2	1	2	1	2	1	2	10.34	10.08	10.25	10.4	10.285	
6	2	1	2	2	1	2	1	9.83	10.03	9.92	9.78	9.89	
7	2	2	1	1	2	2	1	9.35	9.65	9.06	9.11	9.292	
8	2	2	1	2	1	1	2	9.12	8.73	8.93	9.22	9	
	Inner Array							Results				9.285	Grand Avg.

When there are multiple samples (multiple columns of results) tested in each trial condition, the results can be analyzed THREE different ways: Standard analysis (Average of results, most common), Analysis using Standard deviation, and Analysis using S/N ratios. To keep this report brief, only analysis using AVERAGE will be presented in details first. Then, to show variation reduction and cost savings, S/N analysis will be briefly shown.

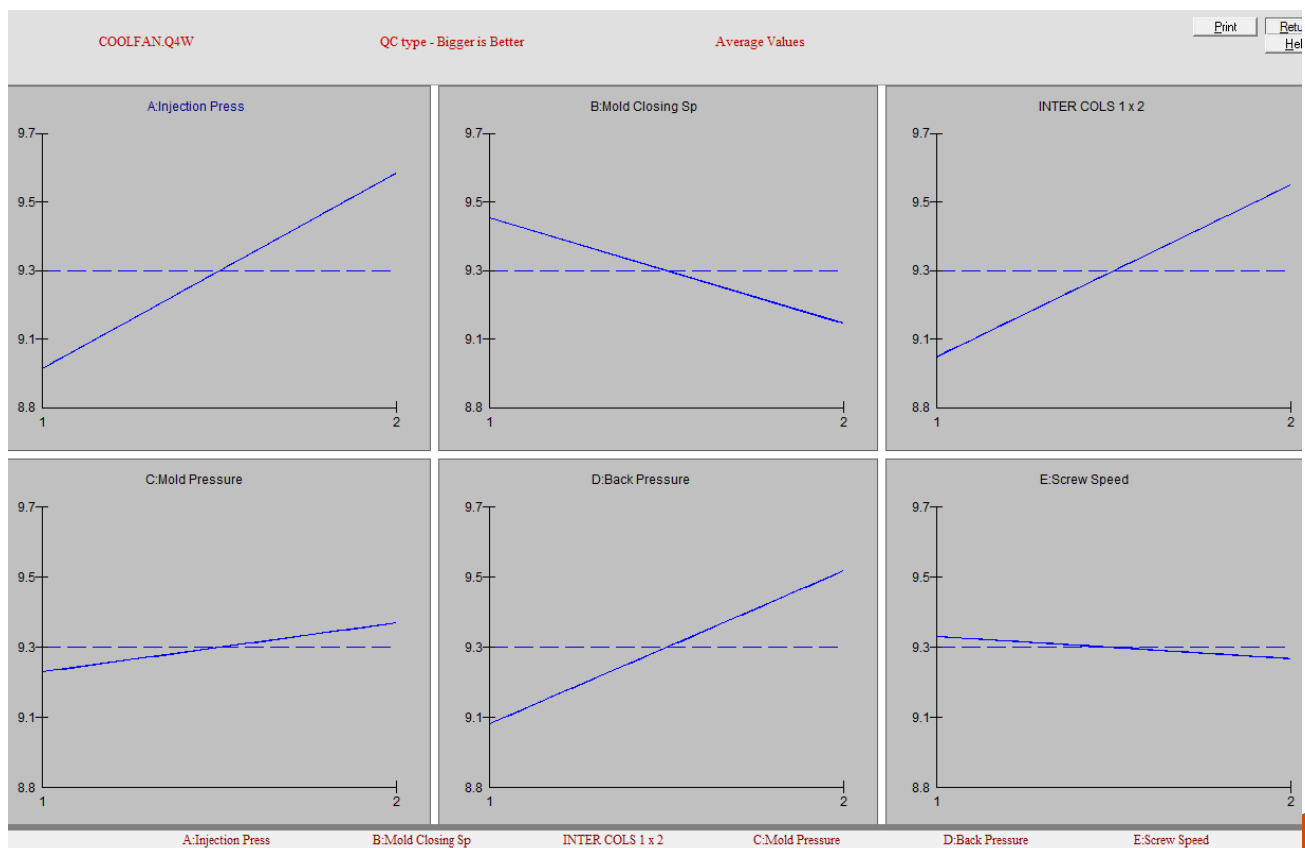
Average Effects: Calculation of factor average effects, including the column reserved for interaction (AxB in column 3) are shown in screen shot below. Note that the magnitude of the values in the last column (L2 – L1) indicates the influence of the factors. The plots of the main effects (average factor effects) are shown next.

Calculated Factor Average Effects



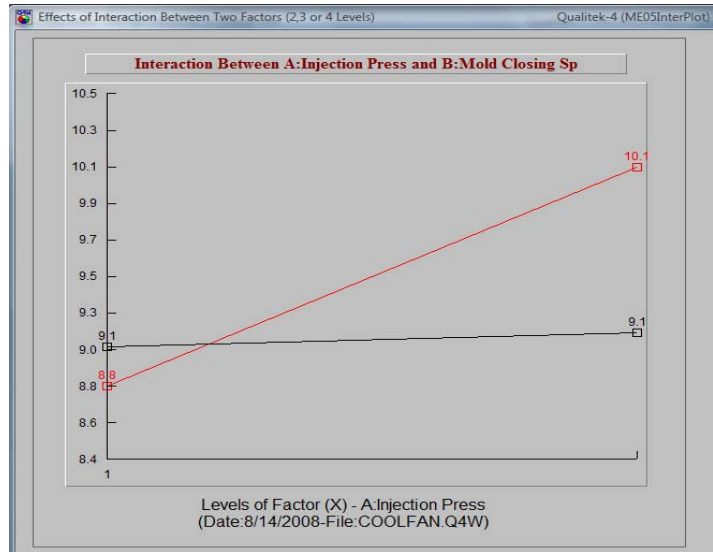
Plot of Trend of Factor Influence (main effects or Column Effects)

By reserving column 3 of the array, interaction between factors A & B was captured.



Plot of Interaction between Factors A and B

The interaction plot (not the effects of column 3) between these two factors, as shown below, is used to make correction for the levels of these two factors due to presence of interaction. Based on the Quality Characteristic (Bigger is better), the plot shows that the desirable factor level combination is A2B1.



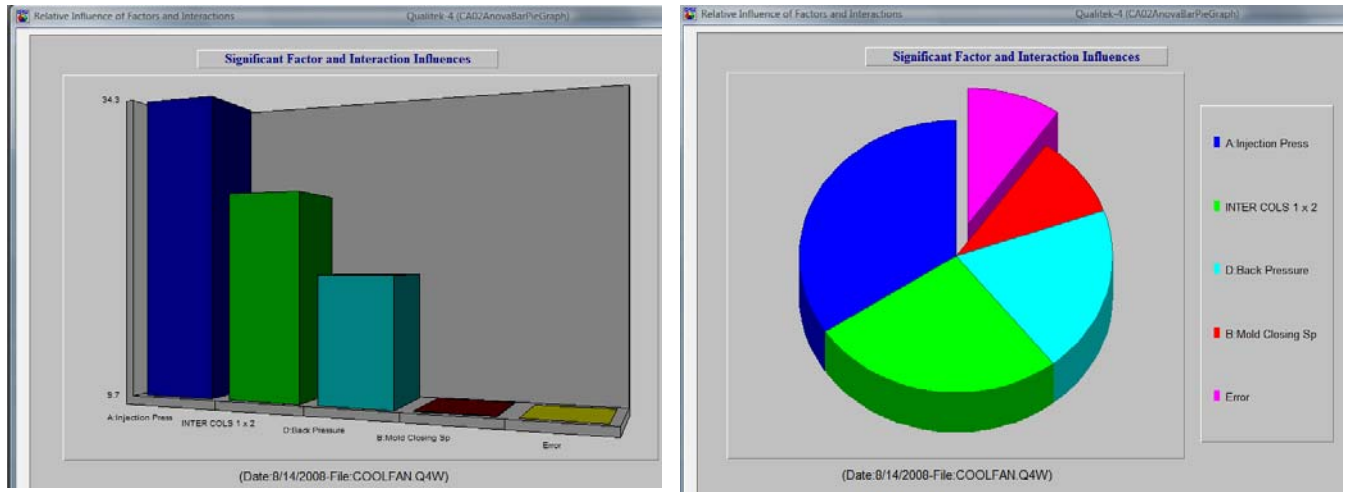
ANOVA: ANOVA offers information about relative influence of the factors and interaction to the variation of results based on their significance. It also allows identification of insignificant factors from the significant ones. Pooled (insignificant factors ignored) ANOVA for the example case study is shown below.

ANOVA Table Qualitek-4 (CA01AnovaScreen)

Expt. File: COOLFAN.Q4v Data Type: Average Values QC Type: Bigger is Better

Col # / Factor	DOF (f)	Sum of Sqrs. (S)	Variance (V)	F - Ratio (F)	Pure Sum (S')	Percent P (%)
1 A:Injection Press	1	3.524	3.524	110.531	3.492	34.309
2 B:Mold Closing Sp	1	1.029	1.029	32.293	.997	9.802
3 INTER COLS 1 x 2	1	2.714	2.714	85.134	2.682	26.354
4 C:Mold Pressure	(1)	(.211)		POOLED	(CL=99.43%)	
5 D:Back Pressure	1	2.05	2.05	64.297	2.018	19.827
6 E:Screw Speed	(1)	(.043)		POOLED	(CL=83.72%)	
7 F:Spear Temperatu	(1)	(.004)		POOLED	(CL= *NC*)	
Other/ Error	27	.86	.031			9.708
Total:	31	10.179				100.00%

The relative influences of significant factor & interaction are also shown as Bar Graph and Pie Diagram below.



Optimum Condition: From factor average effects and interaction considerations, the most desirable factor combination (Optimum condition) for highest expected weight are as shown in the screen shot below (Optimum: A2 B1 D2, Expected Performance = 10.338 oz). Note that, as customary, the insignificant factors are not included in the optimum condition or the expected performance. This means that the levels of the factors found insignificant can be set to any level or determined from considerations other than this DOE results.

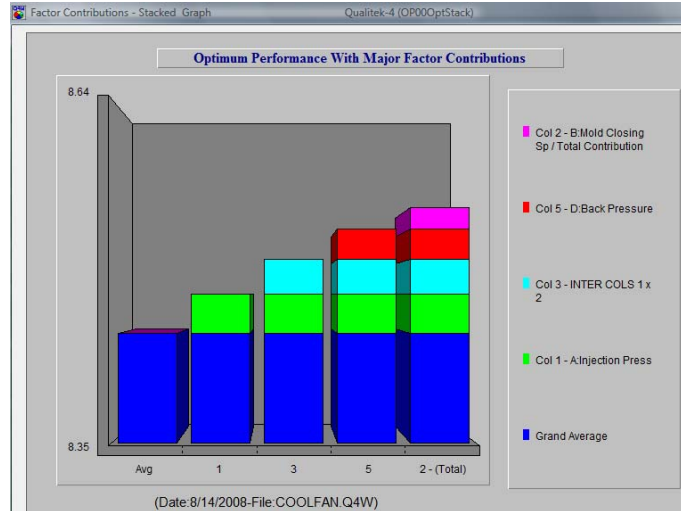
Optimum Conditions and Performance

Expt. File: COOLFAN.Q4W Data Type: Average Values

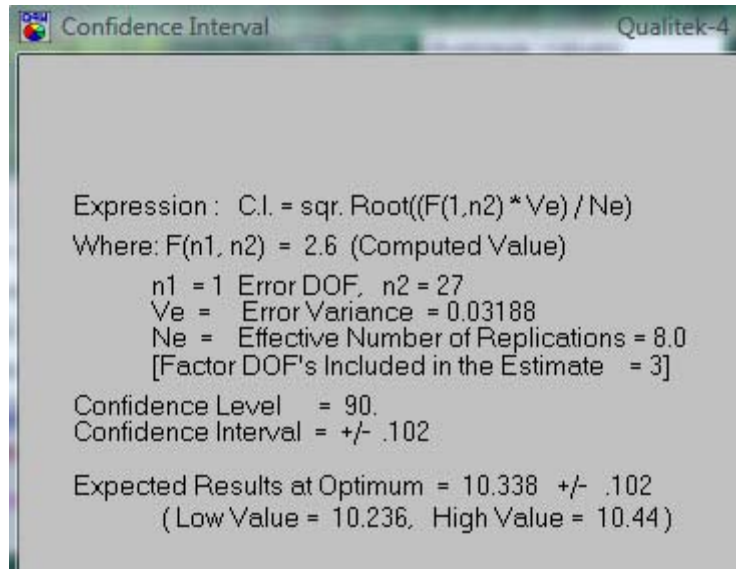
QC Type: Bigger is Better

Column # / Factor	Level Description	Level	Contribution
1 A:Injection Press	2250 psi	2	.331
2 B:Mold Closing Sp	Low	1	.179
3 INTER COLS 1 x 2	-----	2	.291
5 D:Back Pressure	1075 psi	2	.253
Total Contribution From All Factors.....			1.054
Current Grand Average Of Performance...			9.284
Expected Result At Optimum Condition...			10.338

The Stacked Diagram below shows how the average performance is increased from contributions of individual significant factor.



For confirmation of predicted performance at the optimum condition, confidence interval (C.I.) at a confidence level (say 90%) serves as boundaries within which the performance is expected to fall. The calculated C.I. at 90% confidence level is shown below.



Range of Expected performance:
10.236 - 10.44.

Analysis Using S/N Ratios

In support of Standard analysis, the results were also analyzed using Signal-to-Noise ratios. The S/N ratios of the results used for analysis are shown below.

Conditions	Sample# 1	Sample# 2	Sample# 3	Sample# 4	Sample# 5	Sample# 6	S/N Ratio
Trial# 1	8.52	8.76	8.45	8.49			18.641
Trial# 2	9.1	9.12	9.06	9.23			19.206
Trial# 3	8.72	8.76	8.56	8.69			18.771
Trial# 4	9.43	9.46	9.33	9.57			19.505
Trial# 5	10.34	10.08	10.25	10.47			20.241
Trial# 6	9.83	10.03	9.92	9.78			19.902
Trial# 7	9.35	9.65	9.06	9.11			19.354
Trial# 8	9.12	8.73	8.93	9.22			19.079
							19.337

The S/N analysis also identified the same significant factor. As expected, the relative influences are also of the same order of importance (not expected to be same as from Standard analysis). ANOVA and the plots of the relative influences are shown below (Bar Graph & Pie Diagram)

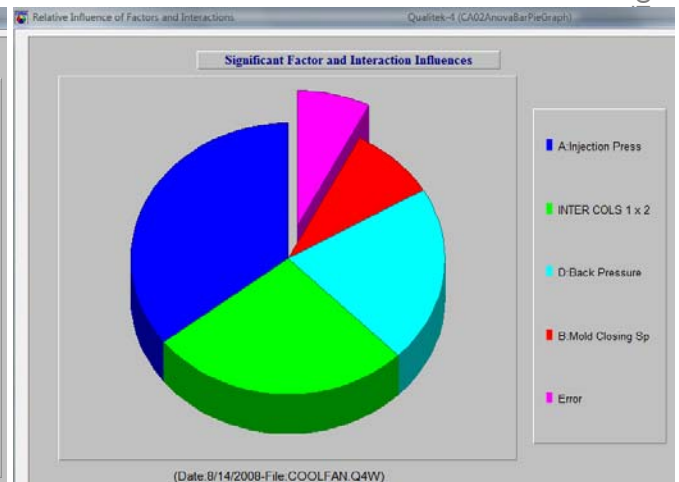
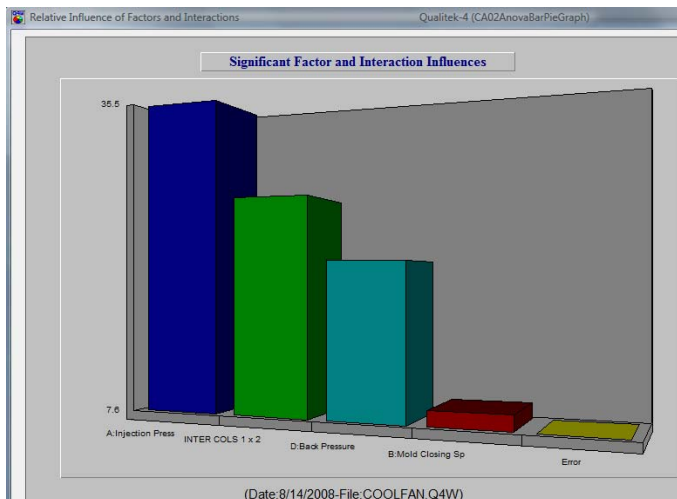
ANOVA

ANOVA Table Qualitek-4 (CA01AnovaScreen)

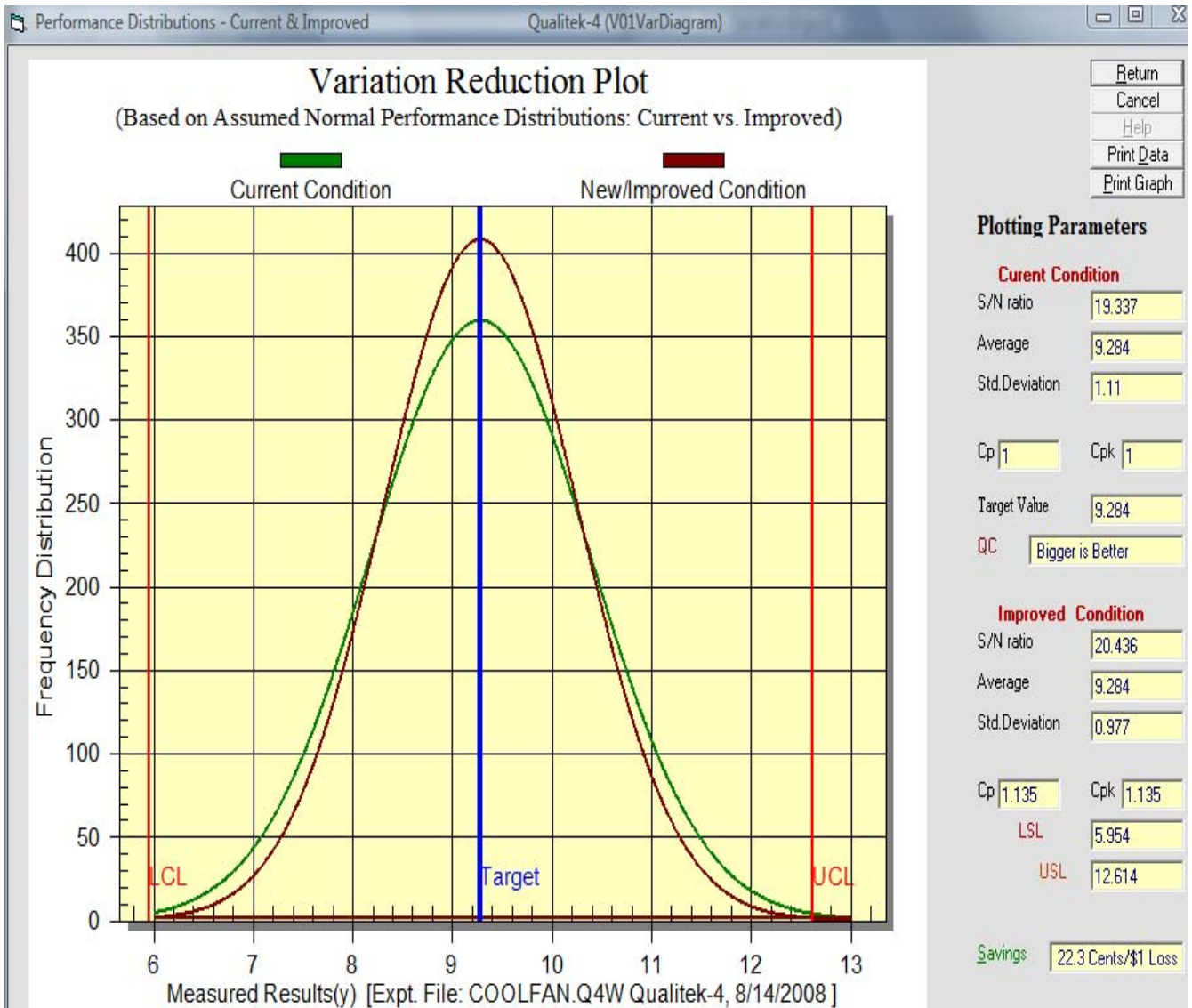
Expt. File: COOLFAN.Q4W Data Type: S/N Ratio
QC Type: Bigger is Better

Col # / Factor	DOF (F)	Sum of Sqrs. (S)	Variance (V)	F - Ratio (F)	Pure Sum (S')	Percent P(%)
1 A:Injection Press	1	.751	.751	33.784	.729	35.543
2 B:Mold Closing Sp	1	.205	.205	9.229	.183	8.921
3 INTER COLS 1 x 2	1	.572	.572	25.711	.55	26.791
4 C:Mold Pressure	(1)	(.058)		POOLED	(CL=95.15%)	
5 D:Back Pressure	1	.457	.457	20.538	.434	21.183
6 E:Screw Speed	(1)	(.006)		POOLED	(CL=100%)	
7 F:Speer Temperatu	(1)	(.001)		POOLED	(CL= *NC*)	
Other Error	3	.066	.022			7.562
Total:	7	2.053				100.00%

Bar and Pie Graphs



One of the major benefits of S/N analysis is that it readily leads to plot of performance distributions and calculations of cost savings using the Taguchi Loss function. Based on the variation plot (Generated by Qualitek-4 based on certain assumptions) shown below, the new design (optimum condition) is expected to improve Cpk from 1.00 to 1.135 and result in 22.3% cost savings.



IIIb: Observation Summary



Tasks you & your project to do:

- Identify significant factors in order of their influence on variability
- Predict expected performance from optimum condition
- Determine boundaries of expected performance for confirmation purposes (90% confidence interval desired)
- Estimate cost saving (Loss function) and improved capabilities (Cp & Cpk) expected from the new design (process parameter setting)

Example:

These items have already been identified in the previous step and are displayed in the software screen shots. They are again itemized below for the example case study.

Significant Factors: Three most significant factors are *A:Injection Pressure, B:Mold Closing Speed and D:Back Pressure.*

Expected Performance: 10.33 oz (weight) at optimum condition (A2 B1 D2)

Boundaries of Expected Performance: From calculation of confidence interval, the range of performance at the optimum condition is expected to be between 10.23 and 10.44 (oz, weight)

Cost Saving: Saving comes from reduced loss (waste) Based on *Loss Function*; the savings is estimated to be about 22 cents on every dollar lost before improved design is implemented.

IIIc: Validate Improvement



Tasks you & your project to do:

- **Test multiple samples** (as many as number of samples per trial or more) at the **optimum condition** (set process parameter to improved condition indentified).
- **Confirm prediction** by comparing the average performance with the predicted range.
- **Present findings** with all and prepare reports.

Confirmation of findings from analysis of results is a necessary step for completion of any DOE study. Before accepting predicted optimum condition, it is essential that the predicted performance at the optimum be confirmed by running a number of samples in that condition. To confirm predicted performance, mean (average) of the actual test results is compared with the confidence interval calculated for the expected performance.

Example:

Test Results at Optimum Condition: Results of samples tested at optimum condition were:

10.45, 10.29, 9.95, 10.31, and 10.30, Average = 10.16 oz (weight)

Confirm Prediction: The average of performance (10.26) fell within the predicted performance range (10.23 and 10.44). Predicted improvement **CONFIRMED**.

Report Findings: (**This report**)

References:

1. Injection Pressure: http://www.ides.com/articles/processing/070306_kulkarni.asp
2. A PLASTIC INJECTION MOLDING PROCESS CHARACTERISATION *USING* ...: <http://eprints.utm.my/1913/1/JTDIS41A01.pdf>
3. Study to learn the technique: <http://nutek-us.com/wp-free.html>
4. Training Topics on Taguchi DOE: <http://Nutek-us.com/wp-sem.html>



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