Using Design of Experiments to Optimize Processes

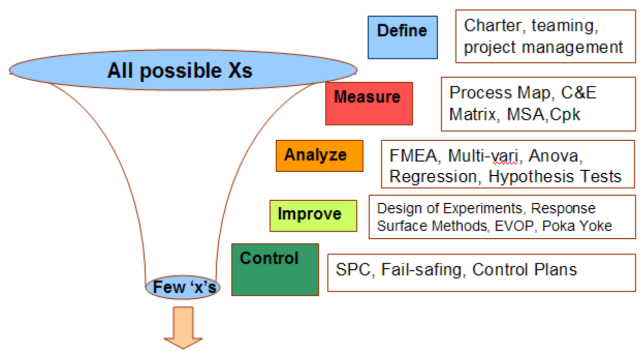
(Published in Quality World September 2007)

By Hemant Urdhwareshe,
Director, Institute of Quality and Reliability,

In the earlier articles on Six Sigma, we have discussed about:

- Basic Concepts
- Organizing for Six Sigma
- Identifying, Selecting and Defining Projects
- Mapping the process and converting practical problem in to Statistical Problem
- Measurement Systems Capability
- Initial Process Capability
- Various tools to analyze data to separate the important relationships between input factors (Xs) and Response or Output Factors (Ys)

If we look at the Six Sigma Roadmap, it can be visualized as a funnel to reduce variation and to identify the few Xs that have maximum impact on the Y. We can then control these few Xs to assure the desired response Y.



We will discuss about one of the most important and frequently used tools in Improve phase: Design of Experiment. We will not go in the details of statistical analysis, but will limit our discussion to understand the basic philosophy and power of this tool.

Conventional approach to experimentation

If we want to evaluate effects of various factors on output, we usually vary One Factor At a Time. This is called “OFAT” approach! However, in OFAT, we will not know interaction of various factors with each other. Interaction means effect of a factor depends on setting of the other factor(s).

Experts have therefore recommended Statistically Designed Experiments (SDE). Popularly, this technique is called “Design of Experiments’. The primary benefit of DOE is we *Test Less and Learn More*!
‘

Experiments are denoted as L^F where F is number of factors and L is no. of levels. For example, If there are 3 factors and each factor has 2 levels, the experiment is 2^3. This experiment has 2x2x2 or 8 runs. This is called a single “replicate” of the experiment. Similarly, if there are 5 factors each having 3 levels, the experiment is 3^5. This experiment has 3x3x3x3x3 or 243 runs!!! We can easily see that the number of runs or trials rapidly increase as factors and levels

Factors	Levels	Runs
2	2	4
3	2	8
4	2	16
5	2	32
6	2	64
7	2	128
8	2	256
9	2	512
10	2	1024

increase (see table shown here). Due to the large number of runs, most of the experimentation is done with 2 levels for each factor. If there are k factors, each having two levels, we will have 2^k number of runs in the experiment. This is a "single replicate" of the experiment. We can repeat the complete experiment to improve precision in the experiment.

		Levels	
	Factors	-	+
1	**Cooking method**	Ordinary	Pressure Cooker
2	**Heating Method**	Stove	LPG

Let us consider a very simple example to illustrate the procedure. Our objective is to minimize cooking time for rice! We want to evaluate effect of cooking method and heating method on cooking time! *Cooking Method (CM)* is the first factor and its levels are ordinary vessel and Pressure Cooker. It is customary to denote these levels as - and +. The + level is expected to improve response. Thus ordinary vessel is - level and Pressure Cooker is + level. Similarly, there are 2 levels for heating method (HM): Stove at -1 and LPG at +1 level.

If we run the experiment and collect data, we get cooking time as shown in the table shown. We changed the levels of both the factors but we can calculate effects of each factor and interaction between the factors!

Cooking Method	Heating Method	Time
-	-	25
+	-	15
-	+	18
+	+	9

We can now calculate the Main effects of the two factors as:

Cooking Method	Heating Method	Result
-	-	25
+	-	15
-	+	18
+	+	9

Total =40, Average 20,

Total = 27, Average 13.5

Main effect of a factor:

Average at (+) high level– Average at low (-) level

$$\frac{27}{2}-\frac{40}{2}=-\frac{13}{2}=-6.5$$

The effect of Heating Method is to reduce cooking time by 6.5 minutes.

Average at High (+) level – Average at Low (-) level. As shown in the figure, we can see that effect of Heating Method is to reduce cooking time by 6.5 minutes.

Similarly, we can find out effect of Cooking Method. For this refer to the next figure. Thus

Cooking Method	Heating Method	Result
-	-	25
+	-	15
-	+	18
+	+	9

Total =43, Average 21.5

Total =24, Average 12

Main effect of a factor:

Average at (+)high level– Average at low (-) level

$$\frac{24}{2}-\frac{43}{2}=-\frac{19}{2}=-9.5$$

Effect of Cooking Method is to reduce cooking time by 9.5 minutes.

time reduces by 9.5 min if we shift from low level to high level i.e. from stove to LPG. Interestingly, we can calculation *interactions between the two facotrs* as well. For this, refer to the table that shows added column for interaction. Signs of interaction levels can be obtained by multiplying the signs of the levels. We can now see these effects graphically.

Cooking Method	Heating Method	Interaction	Result
-	-	+	25
+	-	-	15
-	+	-	18
+	+	+	9

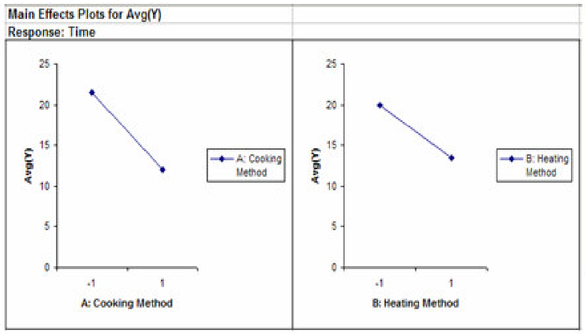
Total =34, Average 17,

Total = 33, Average 16.5

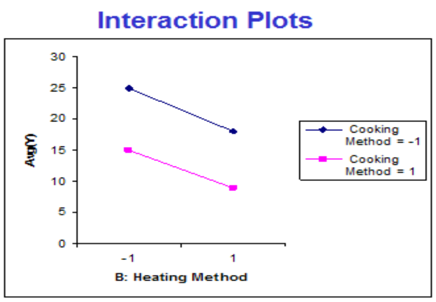
$$\frac{(25+9)}{2}-\frac{(18+15)}{2}=\frac{34-33}{2}=+0.5$$

The interaction effect of X1 and is to increase cooking time by 0.5 minutes.

The graphs show the relative magnitude of the effects. The interaction plot is also shown. It shows the effect of Heating Method separately when the cooking method is at low level and high level. If there was interaction, the effects would be different at these two levels. If effect is same at both levels, lines would be parallel. Thus presence of interaction can be easily identified with non-parallel lines. In this case, the interaction is very small. We will not perform more statistical calculations. However, there are many softwares such as Minitab or SigmaXL that can perform calculations to assess whether these effects are ststisticly significant or not.



Main effects plot show graphically the effects. We can see that effect of Cooking Method is larger than Heating Method.

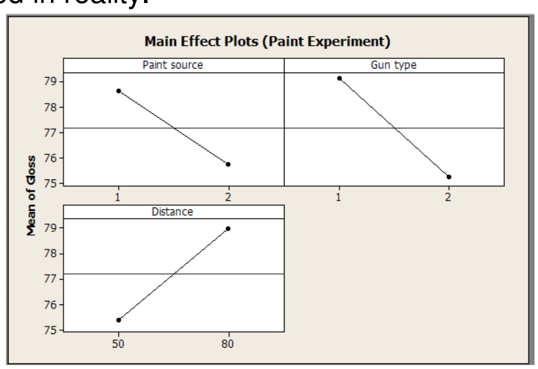


Parallel lines indicate no interaction.
If lines are not parallel, interaction is present.

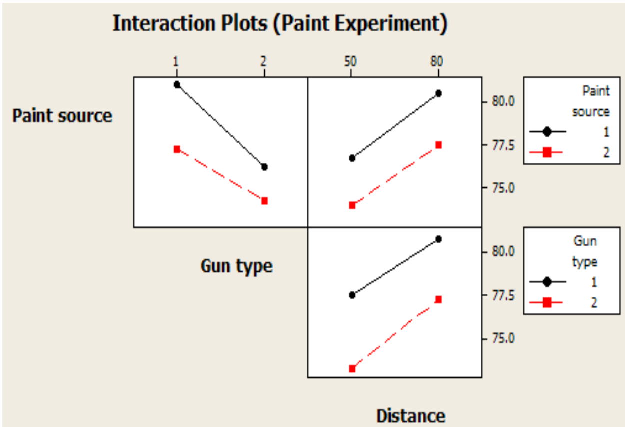
When we run trials with each possible "treatment", it is called Full Factorial Experiment. Statisticians have designed *Fractional Factorial Experiments (FFE)* to reduce number of runs when we have to conduct experiments with large number of factors. In these experiments, we compromise on some loss of information to save cost and efforts for experiment.

	Factor	Low Level	High Level
1	Paint Source	1	2
2	Gun Type	1	2
3	Distance	50 cm	80 cm

Having discussed the basic principles of designed experiments, let us see how this can be applied in reality. Let us recall the painting example. Our objective is to improve paint gloss (shine) so the customers have better preference for our machines. After working through Define, Measure and Analyze phases, the Six Sigma Team has identified three factors with 2 levels each as shown in the table here. This is a 2-level & 3-factor experiment of 2^3 experiment with 8 runs if we run it once. For better precision in the experiment, the team decides to run it twice. In other words, they decided to run the experiment with 2 replications. Data was collected and analyzed in Minitab software. The main effects are shown graphically. We can see that all three factors are important. We will get best results when we use paint source 1, Gun type 1 and distance 80. We can actually try increasing the distance to see whether gloss improves further. However, remember that increasing distance of paint gun may increase loss of paint!



Interaction plots from Minitab are also shown here. We can see that there is some interaction between Paint Source and Gun Type. This is evident because the lines are not parallel. There is little interaction between Gun type-distance and Paint Source-Distance. Please observe that the lines are nearly parallel.



Thus, in the Designed Experiments, we can change settings of all factors at the same time but still can find effects of each factor separately. In addition, we can estimate interaction effects.

Statisticians have created standard designs for experimentation depending upon number of factors and levels. Usually Six Sigma Belts and other professionals use softwares such as Minitab to design and analyze experiments. Many additional features are available to estimate settings of factors that will result in most optimum response and also to minimize variation.

About Author:

Hemant Urdhwareshe is Director, Institute of Quality and Reliability, Pune. He is

- *Qimpro Foundation Silver Standard 2003 Award Winner*
- *First ASQ Certified Six Sigma Black Belt in India*
- *ASQ Certified Quality Engineer, Quality Manager and Reliability Engineer.*

Email: hemant@world-class-quality.com *Phone: 020-25367952*

Visit: www.world-class-quality.com