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Industrial Statistics - A Competitive Necessity

Use of Experimental Design in Analytical Studies

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Improvement & Experiments

"We are, I think, in the right road of improvement, for we are making experiments."

Benjamin Franklin

1786

Types of Experiments

Very Informal

1. ***Trial-and-error methods***
   Introduce a change and see what happens

2. ***Running special lots or batches***
   Produced under controlled conditions

3. ***Pilot runs***
   Set up to produce a desired effect

4. ***One-factor experiment***
   Using a control chart to experiment on a process

5. ***Planned comparison of two methods***
   Background variables considered in plan

6. ***Experiment planned with two to four factors***
   Study separate effects and interactions

7. ***Experiment with 5 to 20 factors***
   Screening studies

8. ***Comprehensive experimental plan with many phases***
   Modeling, multiple factor levels, optimization

Very Formal

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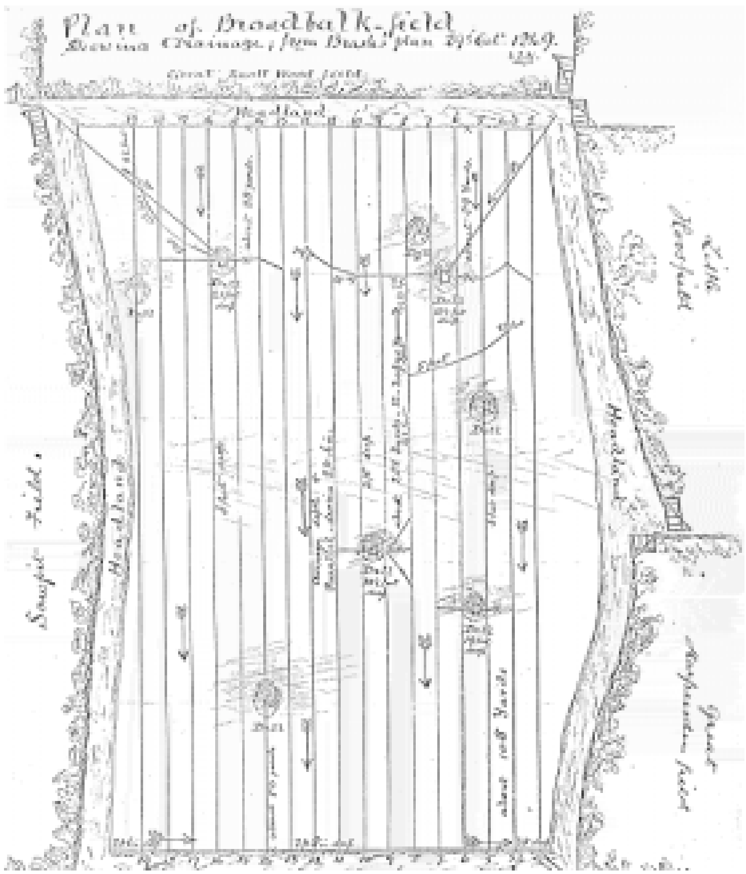
Rothamsted Experimental Station

Language of Experimental Design from Rothamsted



1844

Factors

Background Variables

Response variables

Experimental unit

Randomization

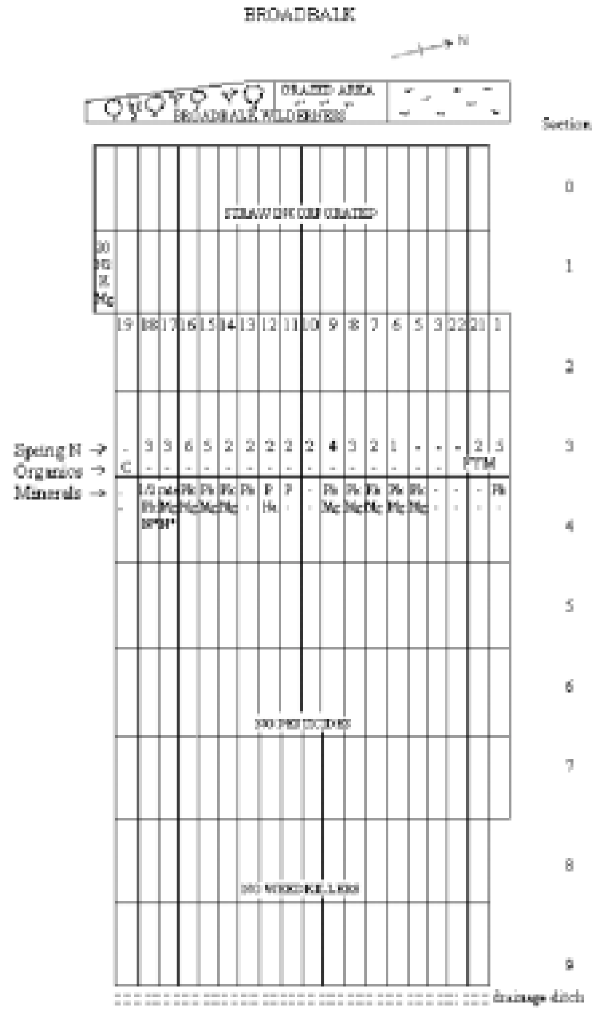
Replication

Blocks

Plots

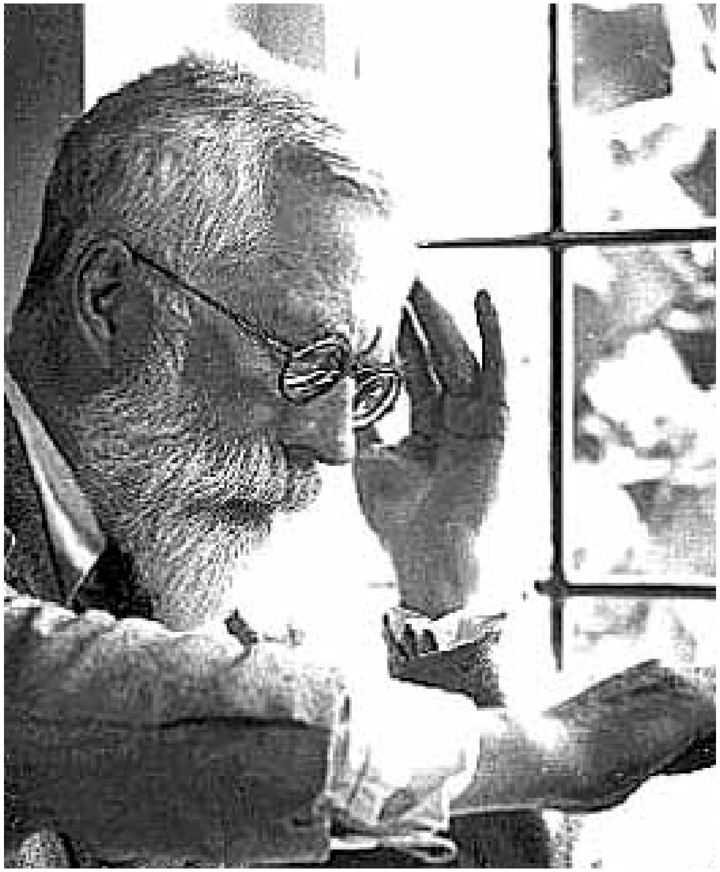
Subplots

Experimental Pattern



1994

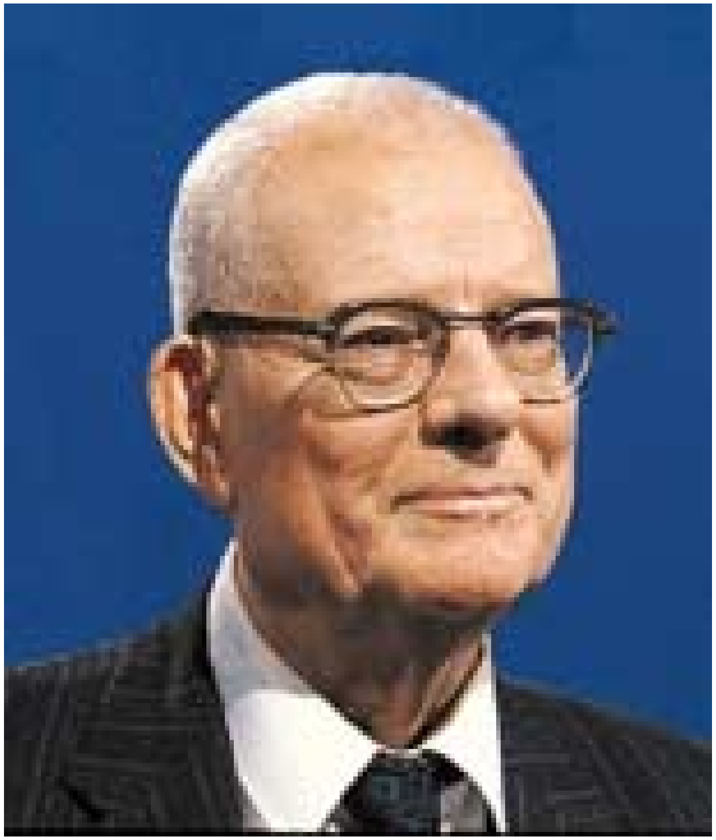
Principles (or Requisites) of a Good Experiment



Sir Ronald A. Fisher 1890-1962

1. Clearly defined objective
2. Effects of factors should not be obscured by other variables
3. Results should not be influenced by bias
4. Provide a measure of precision
5. Precision sufficient to accomplish its purpose

W. E. Deming's Two Types of Studies



Chapter 7 from *Some Theory of Sampling*, 1950

The aim of any experiment is to provide a rational basis for action

<u>Enumerative study</u>: an experiment in which action will be taken on the universe.

<u>Analytic study</u>: an experiment in which action will be taken on a cause system to improve performance in the future.

Two Types of Studies

Enumerative Studies:

Census

Inventory

Exit survey at polls

Acceptance sampling

Analytic Studies:

Selection of suppliers

Poll to determine strategy

Experiment to improve performance

Drug testing

Deming: *Statistical theory as taught in the books is valid and leads to operationally verifiable tests and criteria for an enumerative study. Not so with an analytic problem, as the conditions of the experiment will not be duplicated in the next trial. Unfortunately, most problems in industry are analytic.*

Important Aspects of Enumerative and Analytic Studies

	Type of Study	
Aspects of Study	**Enumerative**	**Analytic**
Aim	**Estimation**	**Prediction**
Method of Access	**Frame & Sample**	**Models of product or process**
Major Source of uncertainty	**Sampling Error**	**Extrapolation to the future**
Major Source of uncertainty quantifiable?	**Yes**	**No**
Environment of the study	**Static**	**Dynamic**
Role of the statistician	**Assess important effects**	**Support subject matter expert**
Role of the subject matter expert	**Define the universe approve the frame**	**Identify variables, levels: assess conditions in the future; assess degree of belief**

Estimation & Prediction in Various Types of Studies

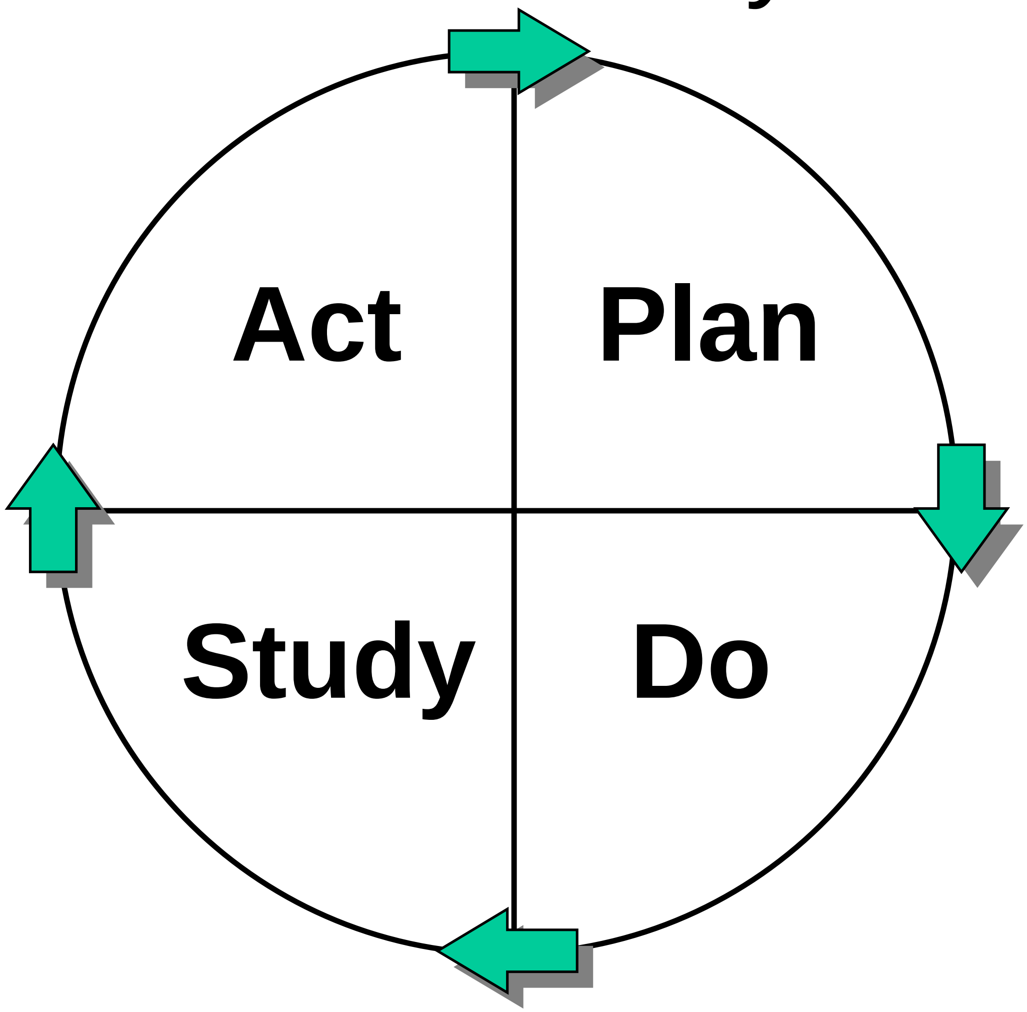
Leverage For Improvement	Application	Examples	Theory to support use of the standard error of prediction	Role of subject matter expert
Low	Estimation	Acceptance sampling		
↑	↑	Value inventory	Probability distribution in combination with a frame and sampling by random numbers	Approval of the frame and definition of the complete coverage
		Census	↓	↓
		Exit Poll of voters		
		Stable Process - no expected changes	Shewhart	Prediction that conditions will be relatively unchanged in the future.
		Stable process - minor changes	Shewhart Weaker justification	Prediction that The change will not interact with future conditions.
		Stable process – major changes	Shewhart Weaker justification	
		Poll 2-4 months before election	None	Reasonable simulation of the real thing
		Pilot plant studies	↓	↓
		Prototype testing		
		Accelerated life tests		
↓	↓	Low dose extrapolation		
High	Prediction			

Principles for Designing Analytic Studies

1. Well defined objective
2. Sequential approach
3. Partitioning variation
4. Degree of belief
5. Simplicity of execution

Framework for Planning Analytic Experiments

The PDSA Cycle



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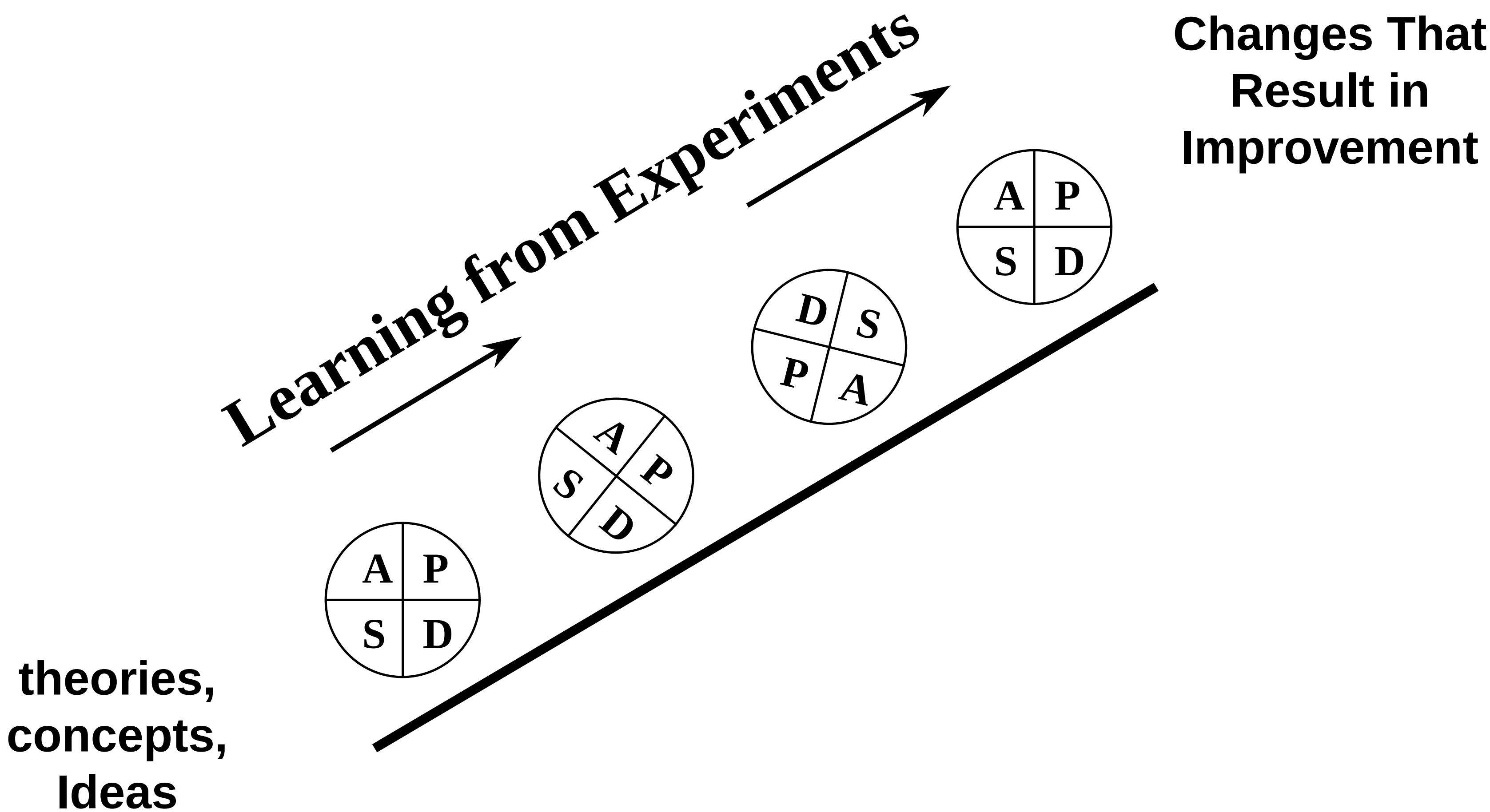
Sequential Use of the PDSA Cycle



Strategy for Sequential Experimentation

Current Knowledge of experimenters	Types of Experiments
Low knowledge	Fractional factorials (screening studies)
Moderate knowledge	Fractional factorials (study Interactions) Factorial studies (new levels, new factors)
High knowledge	Confirmatory studies, Optimization

Fisher's Tools for Experimentation

- **Experimental pattern**
- **Planned grouping**
- **Randomization**
- **Replication**

Using Experimental Tools to Attain the Properties of a Good Analytic Experiment

Experimental Tools

Property of Good Analytic Study	Experimental pattern	Planned grouping	Randomization	Replication
Well-defined objective	X			
Sequential approach	X	X		X
Partitioning variation	X	X	X	X
Degree of belief	X	X		X
Simplicity of execution	X		X	

Background Variables in an Analytic Study: **Planned Grouping**

Two Decisions to Make:

- How to control the background variables so that the effects are not distorted by them.
- How to use the background variables to establish a wide range of conditions for the study to increase the degree of belief or to aid in designing a robust product or process.

Three Methods to Deal with Background Variables:

1. Hold them constant in the study.
2. Measure them and adjust for their effects in data analysis.
3. Use planned grouping to set up blocks.

Planned Grouping

Objective: Run an experiment to compare three material suppliers and choose one for future contract.

Each of the three suppliers will submit four prototypes.

Background variables in the plant that could affect the response variables of interest:

Background variable	Levels of background variable
Machine	#7, #4
Operator	Joe, Susan, George
Gage	G-102, G-322
Saw Blade	20 blades available
Time (day-to-day)	Different days possible

What do we do with these variables when we conduct the study of the suppliers?

Planned Grouping in an Analytic Study

Objective: Run an experiment to compare three material suppliers. Each of the three suppliers will submit four prototypes.

B. Create four blocks with widely varying conditions based on these background variables:

	Block 1	**Block 2**	**Block 3**	**Block 4**
Machine	#7	#4	#7	#7
Operator	Joe	Susan	George	Joe
Gage	G-102	G-322	G-102	G-322
Saw Blade	Blade 1	Blade 2	Blade 3	Blade 4
Time	Day 1	Day 2	Day 3	Day 4

Example of Planned Grouping

Objective: Run an experiment to compare three material suppliers. Each of the three suppliers will submit four prototypes.

C. Evaluate one prototype from each supplier (A,B,C) in each block (random order within each block

Test	Block 1	Block 2	Block 3	Block 4
1	B	B	C	A
2	A	C	A	C
3	C	A	B	B

D. Analyze supplier difference within each block;
evaluate consistency of differences across blocks

Randomization

- **Not a requirement in an analytic study** (judgment sampling usually preferred)
  - Helps prevent variation due to nuisance variables from being confused with the variation due to the factors or due to the background variables.
  - Sometimes useful a several different levels or phases of an experiment
  - Guideline: Use when not prohibitive

When to use randomization

- Experiments conducted when the important response variables have not been brought into a state of statistical control.
- Experiments that will be conducted by many different operators and technicians
- Experiments in which the variation due to nuisance variables is expected to be large relative to the magnitude of effects of important factors
- Formal experiments in which results must be evaluated by others (such as customers or senior staff) for action to be taken

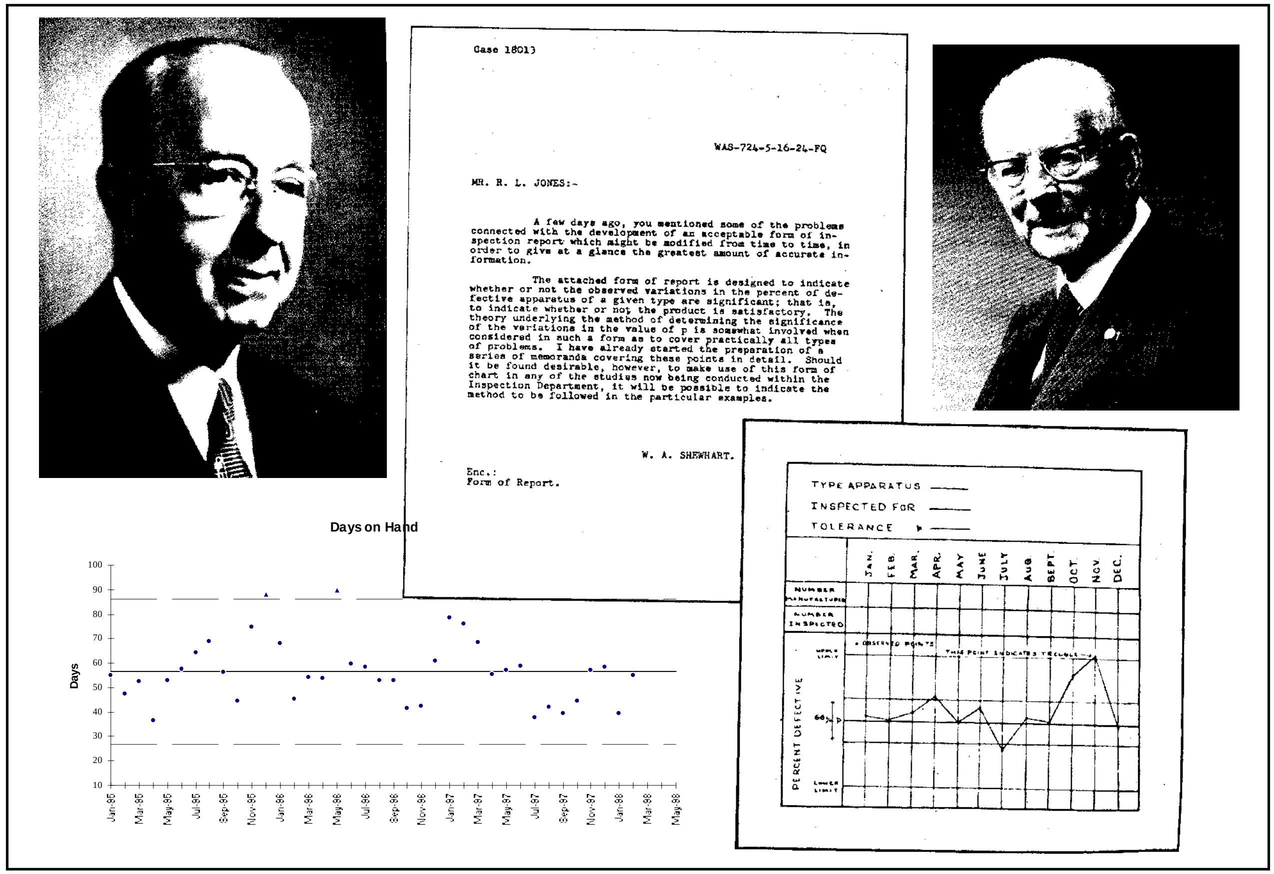
Replication

- **Repeating particular aspects of an experiment**
- **Different types of replication including:**
  - **Repeated measurements of experimental units**
  - **Multiple experimental units for each combination of factors**
  - **Partial replication of the experimental pattern**
  - **Complete replication of the experimental pattern**

Analyzing Data from Analytic Studies

Shewhart/Deming View of Variation

Variation is Due to Common Causes and Special Causes



Analysis of Data from Analytic Studies
Three Basic Principles

1. The analysis of data, the interpretation of the results, and the actions that are taken as a result of the study will be led by **experts in the relevant subject matter**.
2. The conditions of the study will be different from the conditions under which the results will be used. **An assessment of the magnitude of this difference and its impact** by experts in the subject matter should be an integral part of the interpretation of the results of the experiment.
3. Methods for the **analysis of data should be graphical**, with minimum aggregation of the data before initial display. The aim of the graphics is to visually partition the data among the sources of variation present in the study.

Analysis of Analytic Experiments

Provide a Basis for Action

The aim of the analysis is to give the experts in the subject matter the best possible chance to take the right action

1. **Plot the data in the order in which the tests were conducted,** identifying the presence of special causes in the data.
2. **Rearrange the graph to study background variables** (batches of raw material, measurement, operators, and environmental conditions).
3. **Use graphical displays to assess how much of the variation in the data can be explained by factors in the study.**
4. **Summarize the results of the study with graphical displays.**

One Factor Experiment: Chemical Process

Factor:

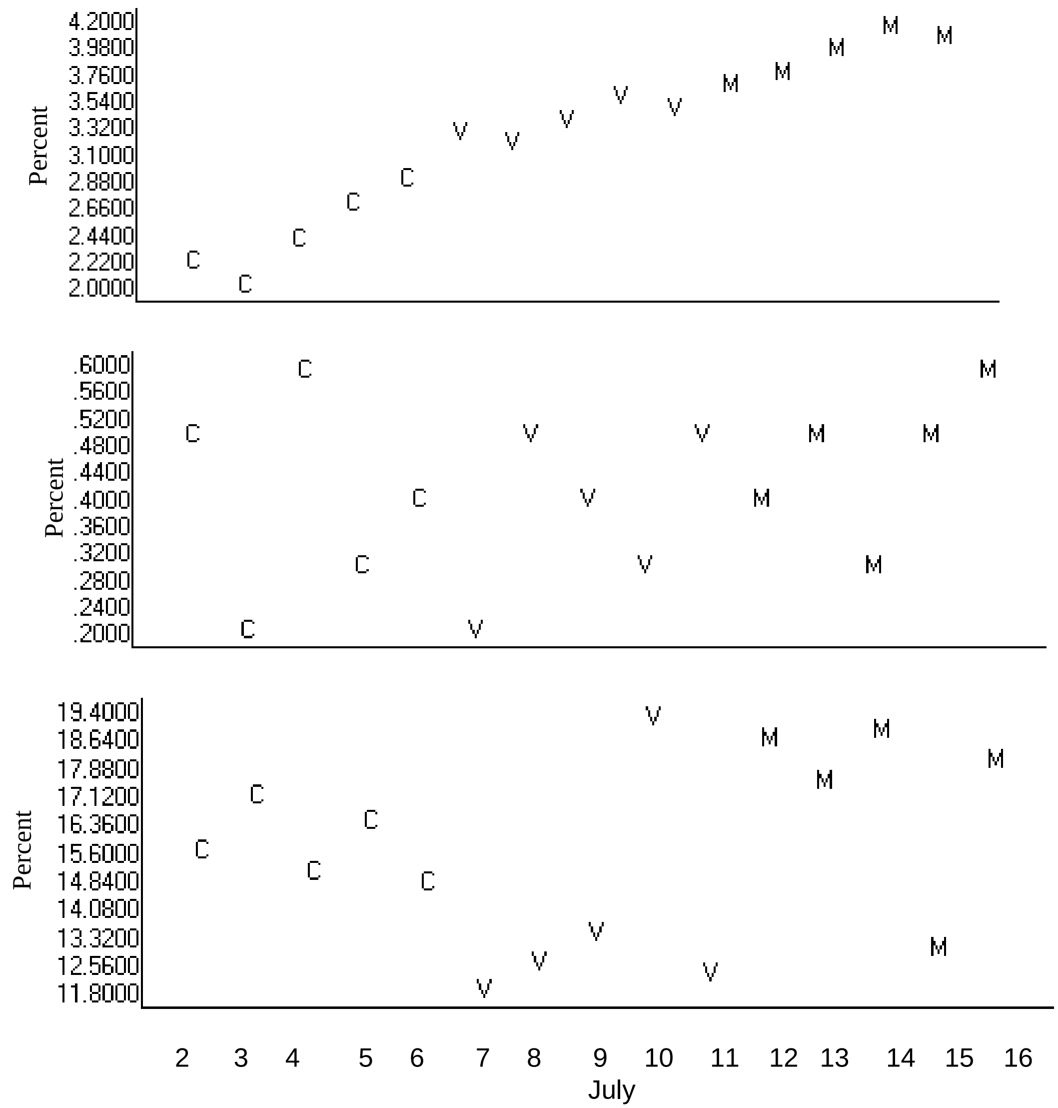
Control Method

Levels:

Current Method

Valve

Meter



Response Variables

Water

Target = ≤ 3.0 %

Sulfate

Target = ≤ 1.0 %

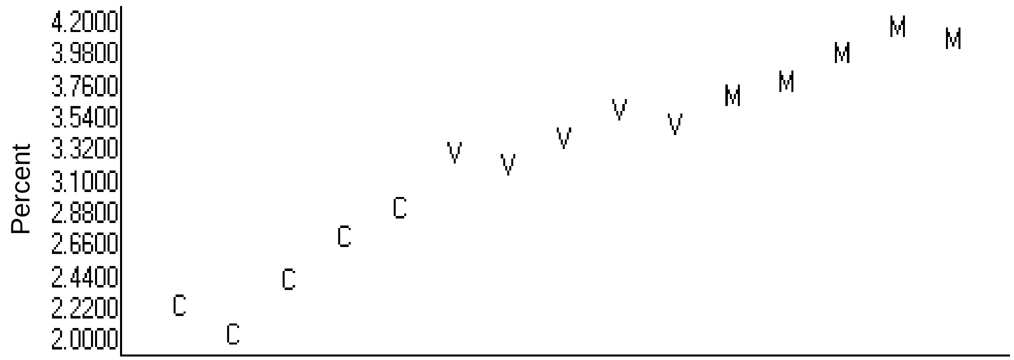
Ingredient X

Target = 15 +/- 3 %

Summary of Important Effects: *Water*

Factor	Small
Nuisance variables:	
Common Causes	Small
Special Causes	Important

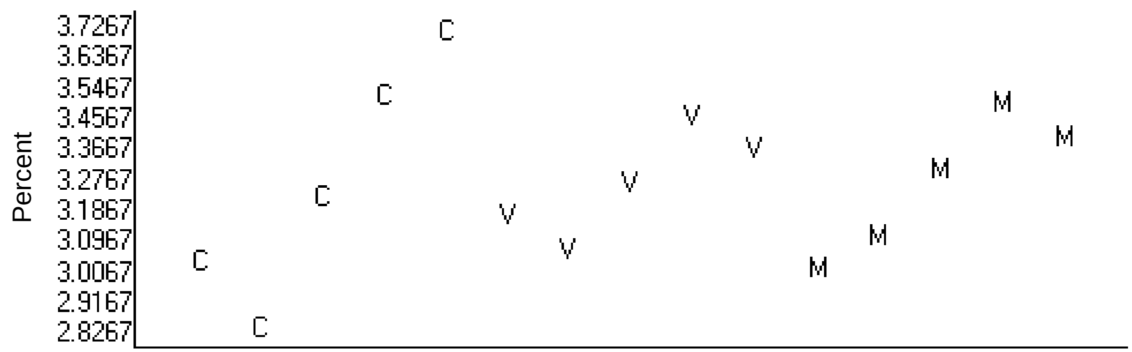
Run Order Data



Water

Target = ≤ 3.0 %

Adjusted Data



Adjusted Water

Target = ≤ 3.0 %

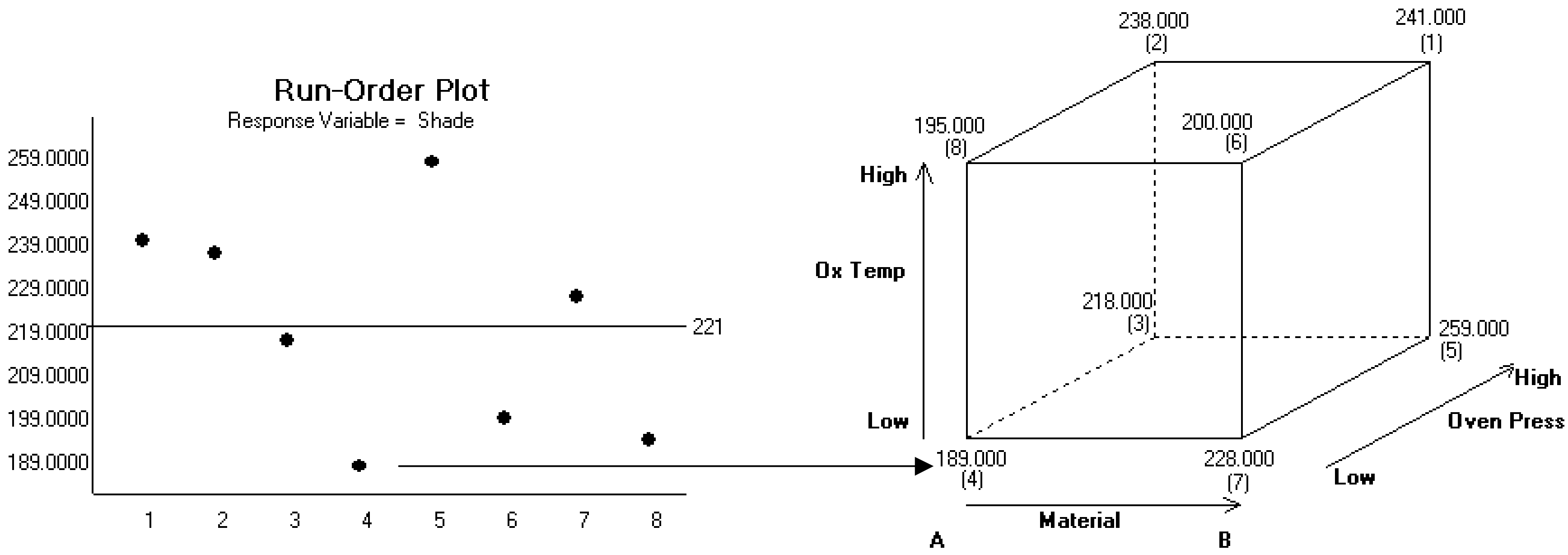
Summary of Important Effects

	Response variable		
Source of variation	**Percent water**	**Percent sulfate**	**Percent ingredient X**
Factor	**Small**	**Small**	**Important**
Nuisance variables:			
Common Causes	**Small**	**Important**	**Small**
Special Causes	**Important**	**None**	**Important**

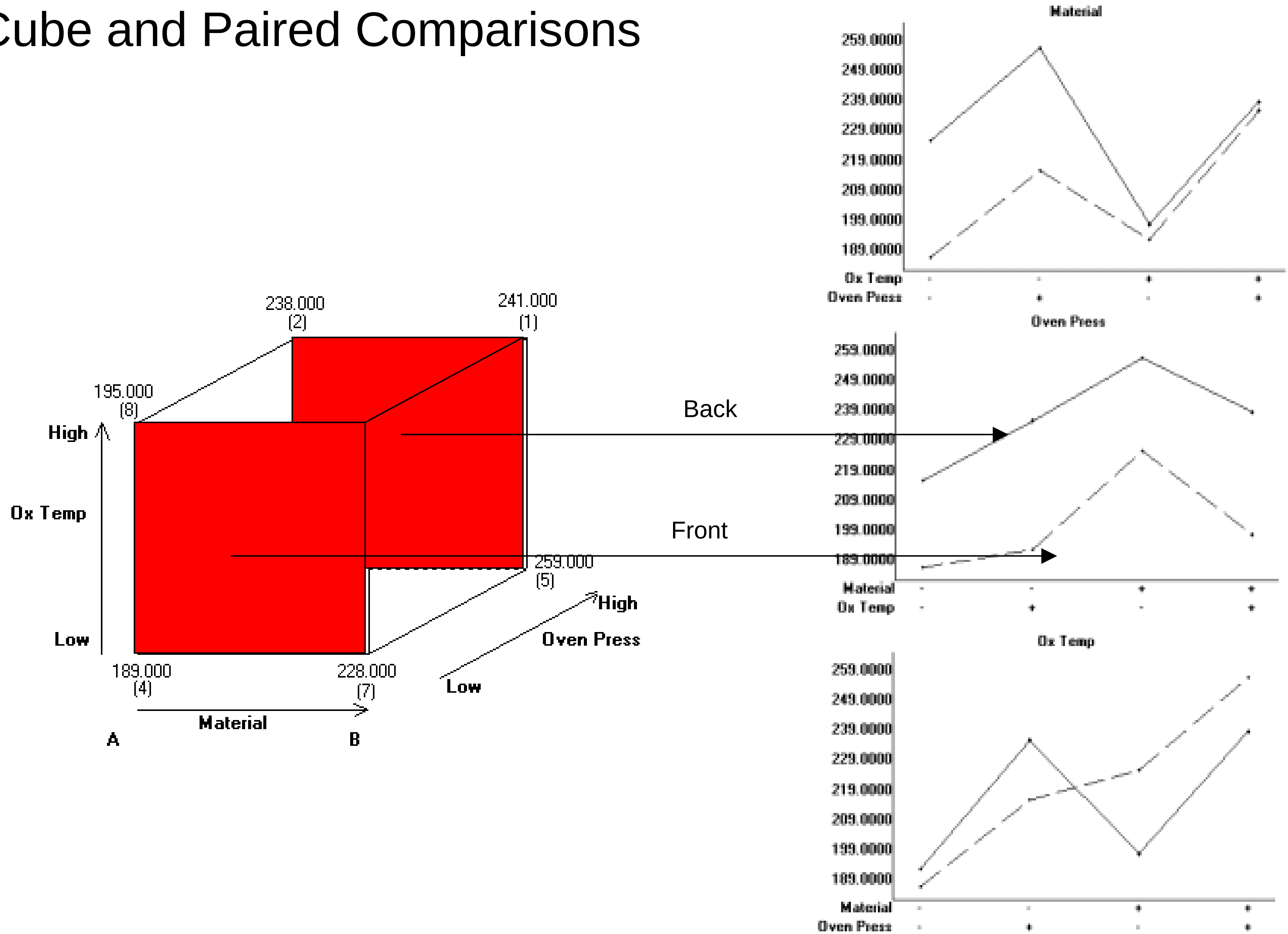
2^3 Design for a Dye Process

	Material Quality			
	A		B	
	Oxidation temperature		Oxidation temperature	
Oven Pressure	Low	High	Low	High
Low	189 (4)	195 (8)	228 (7)	200 (6)
High	218 (3)	238 (2)	259 (5)	241 (1)

2^3 Dye Process Experiment

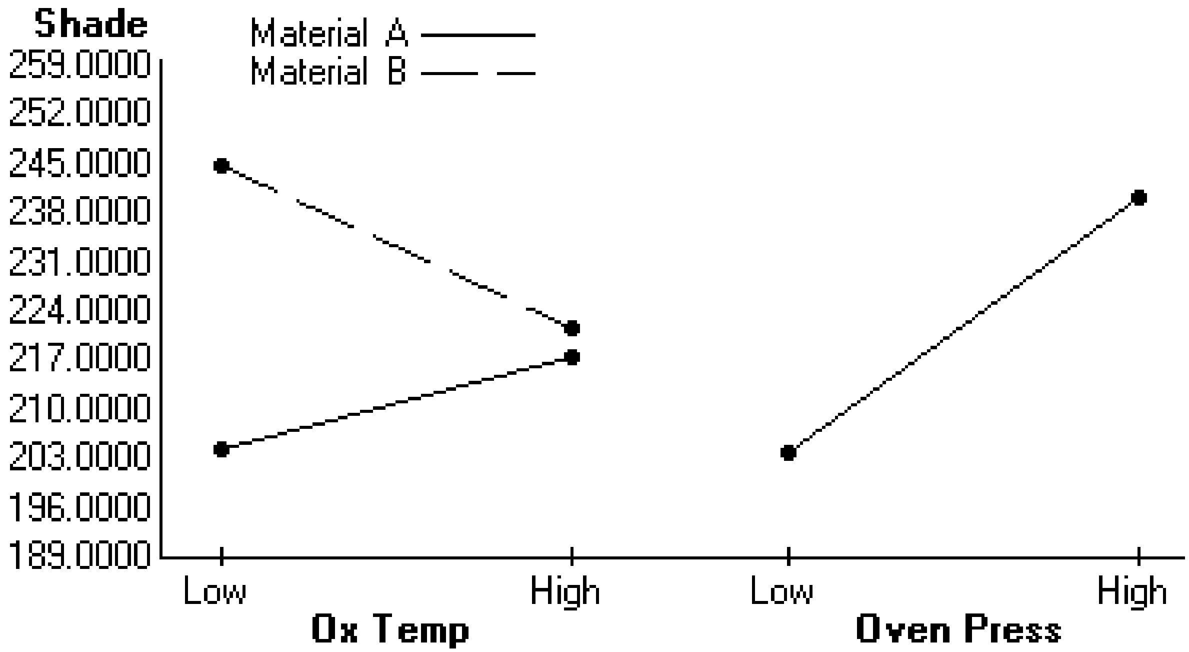


Cube and Paired Comparisons



Response Plots for Important Effects

(Dye Process)



Material	Ox Temp Low	Ox Temp High
A	203.50	216.50
B	243.50	220.50

Oven Press Low	Oven Press High
203.00	239.00

2001 QPR Conference Theme:
Industrial Statistics -A Competitive Necessity

Deming**:** *Prediction is the problem, whether we are talking about applied science, research and development, engineering, or management in industry, education, or government .*

Herculitis – *It is impossible to step in the same river twice*

The principles and methods of experimental design have an important role to play in ***analytic studies*** *where the aim is to improve product, process, or system.*

References

- *Some Theory of Sampling*, W. Edwards Deming (1950), Dover Publications, NY.
- *Design of Experiments*, 8th edition, Sir Ronald Fisher (1966), Hafner Publishing Company, NY.
- "On Probability as a Basis for Action", *The American Statistician*, Vol 29, No. 4, (1975), pp 146-152.
- *Out of the Crisis*, W. Edwards Deming (1982), MIT CAES, Cambridge.
- "Assumptions for Statistical Inference", *The American Statistician*, Vol 47, No. 1, Gerald Hahn, William Meeker (1993), pp 1-11.
- A Primer for Enumerative Vs. Analytic Studies: Using Caution in Statistical Inferences, *ASQ Statistics Division Newsletter*, Vol 16, No. 3 Eileen Beachell, Marilyn Monda (1996), pp 6-10.
- *Quality Improvement through Planned Experimentation*, 2nd edition Ron, Moen, Thomas Nolan, Lloyd Provost (1999), McGraw-Hill, NY.

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Use of Experimental Design in Analytical Studies

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Abstract:

Deming introduced the concept of analytic studies in the 1950's but he did not provide specific guidelines for incorporating the principles of experimental design in an analytic study. The aim of an analytic study is prediction that one of several alternatives will perform better than the other alternatives in the future.

Methods used to design analytic studies must be suited to a dynamic environment. Because of the effect of changing conditions, the primary source of uncertainty in an analytic study lies in identifying which variables will have the most influence on future outcomes of the product or process. Statistical theory does not provide quantification of the magnitude of this uncertainty.

This presentation will discuss extending R. A. Fisher's principles of experimental design to the environment of an analytic study. The appropriate use of experimental patterns, blocking (or planned grouping), randomization, and replication will be illustrated with examples of analytic studies. The analysis of data from analytic studies will also be presented.