ME 794

Statistical Design of Experiments

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Robust Design Methodology

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The Quality Revolution

- In 1980, US lost their dominant position in manufacturing and electronics
  - 90% of semiconductors were being produced in Asia despite their advent in US
  - Large segment of US population were driving automobiles that were not produced in US
- What happened? Quality Revolution!
- What was quality revolution about?
  - Was it about the technological breakthroughs? ✖
  - Or development of new methods and approaches towards design and manufacturing? ✖
  - **It was a fundamental shift in the philosophical approach to quality** ✔
  - **Shifting away from '*product control mentality*' to '*process control mentality*'** ✔
  - **Shifting away from inspection as means to filter bad quality product to a system embracing robust design and process monitoring** ✔

The Quality Revolution: Change in Philosophy

- Moving away from a mentality which **tolerated and remained oblivious to the ills of scrap, defects, and waste** to one which embraces the never-ending pursuit of quality and productivity improvement.
- It was a departure from the paradigm which viewed quality as the **responsibility of one person or department** to one which views quality as the responsibility of everyone.
- It was essentially an embrace of “an ounce of prevention is worth a pound of cure”
- The revolution has sparked a new relationship between design and manufacturing.

Redefining Quality

- Traditional view of quality control that drove the field for more than half a century

  "Quality Control was the final filter between manufacturing and shipping established to ensure that the product met stated specifications before it went out to the customer" → **"Conformance to Specifications"**

- Today this narrow view of quality has been
  - **Pushed Upward:** Management's role and responsibility to Quality
  - **Pushed Backwards:** Upstream into engineering design
  - **Spread Laterally:** No longer just a manufacturing issue
- "Continuous improvement in all aspects of the company"

What prevents continual improvement?

- Definition of quality as conformance to specifications promotes ‘product control’ and hence, significant inhibitor to principle of never-ending improvement through ‘process control’ approach.
- Some think it is important to calculate ‘cost of quality’ in some misdirected efforts towards ‘optimizing’ the system.
- Quality as an add-on function with associated cost:
    - Cost of inspection
    - Cost of implementing statistical process control (SPC) program
    - Cost of warranty and return
- We should NOT ask ‘What is the cost of quality?’
- We should ask ‘What is the cost of NOT having quality?’, i.e, what are the costs to the system for not continually striving for stable and predictable processes with low variability.

New Definition of Quality

“Loss imparted to society during product use as a result of functional variation”

Functional variation refers to the deviation of product performance from that intended by design, i.e., deviation of performance from the design target (nominal)

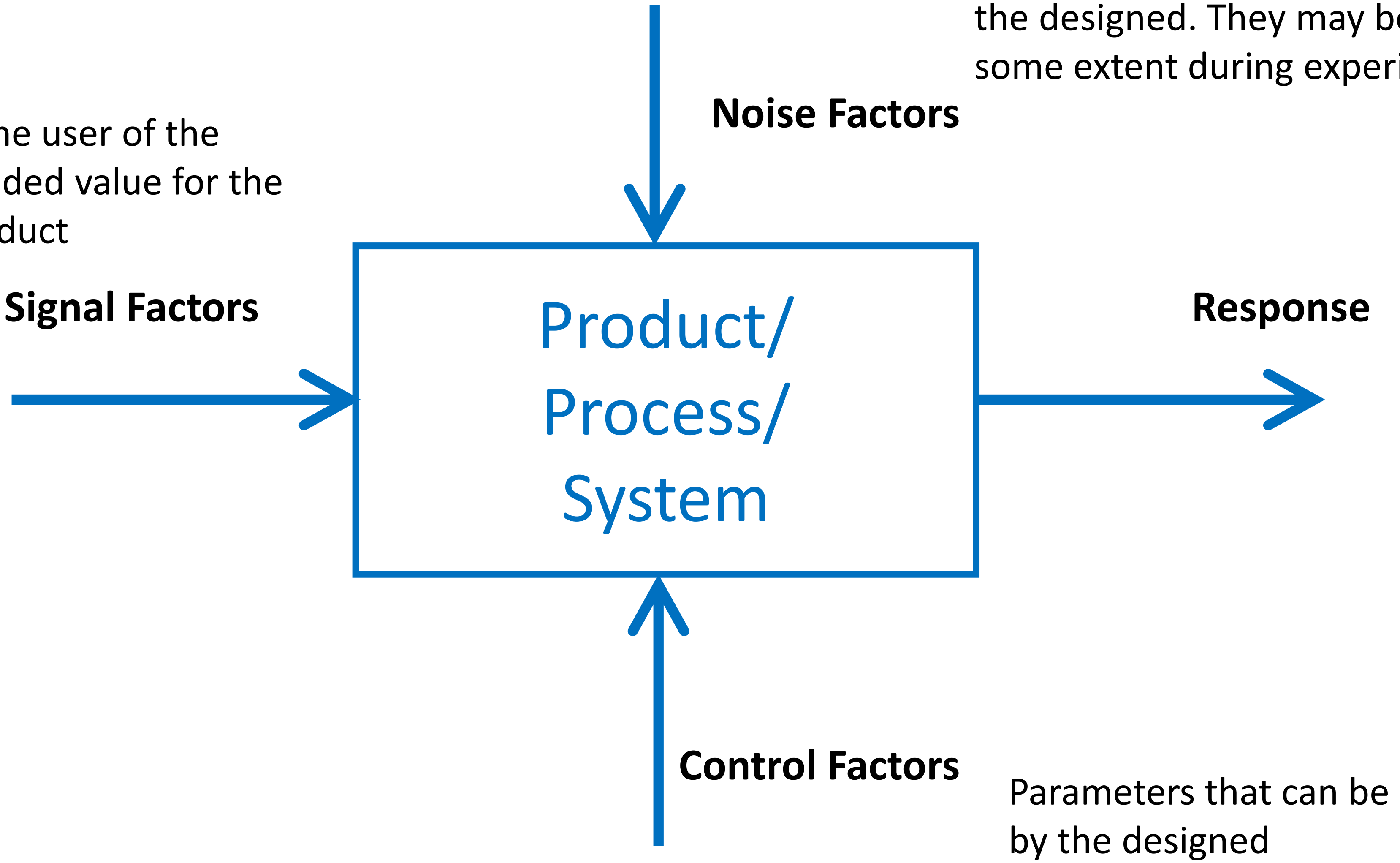
What is Variability?

- ALL manufacturing and measurement processes exhibit variation.
- For example, when we take sample data on the output of a process, such as critical dimensions, oxide thickness, or resistivity, we observe that all the values are NOT the same.
- This results in a collection of observed values distributed about some location value. This is what we call spread or variability.
- We represent variability numerically with the variance calculation and graphically with a histogram.

P Diagram

Parameters that cannot be controlled by the designed. They may be controllable to some extent during experiment

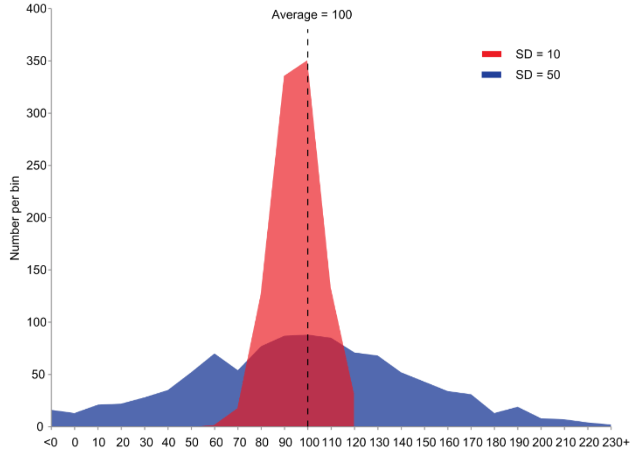
Parameters set by the user of the product to get intended value for the response of the product



Parameters that can be specified freely by the designed

Sources of Functional Variation

Taguchi suggests that variation in product and process function arises from three basic sources:



- **Outer Noise:** Sources of noise which influence performance as measured during field use under actual *operating conditions*, e.g., temp, humidity, supply voltage, vibration
- **Inner Noise:** Internal change in product characteristics such as drift from the nominal over time due to *deterioration*, e.g., mechanical wear, aging
- **Variational Noise:** Variation in the product parameters from one unit to another as a result of the manufacturing process, e.g., *manufacturing imperfection*

Example 1: Temperature Controlled Refrigerator

- **Outer Noise** [Operating Conditions]
  - The number of times the door is opened and closed
  - The amount of food kept and the initial temperature of the food
  - Variation in the ambient temperature
  - Supply voltage variation

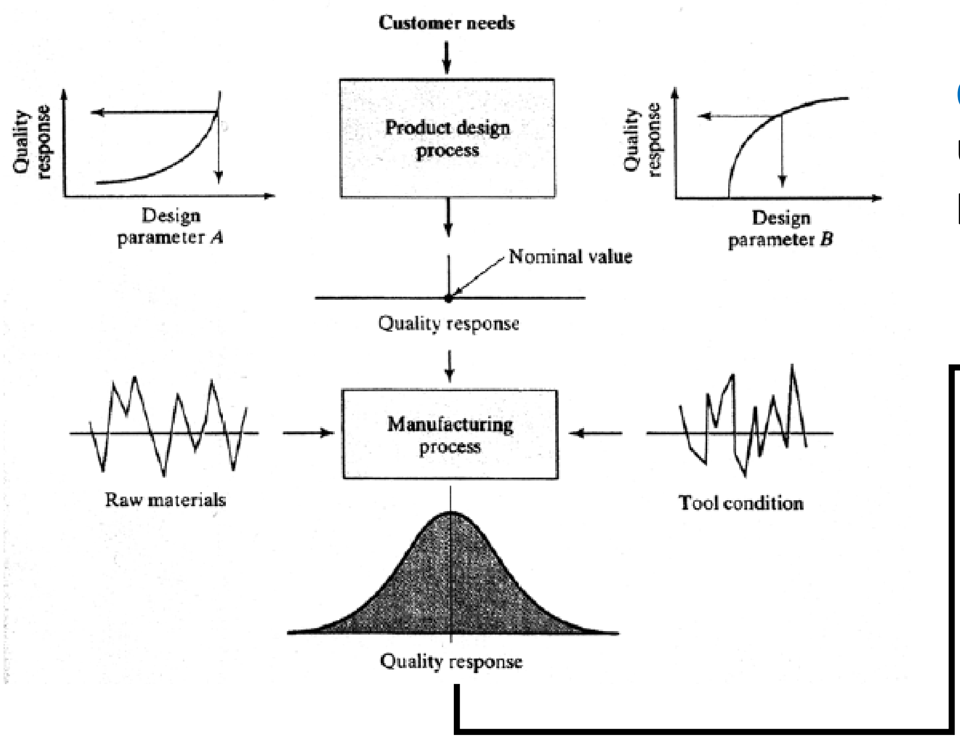
- **Inner Noise** [Deterioration]
  - The leakage of Refrigerant
  - Mechanical Wear of Compressor parts

- **Variational Noise** [Mfg/Use Imperfection]
  - The tightness of door closure
  - The amount of refrigerant used

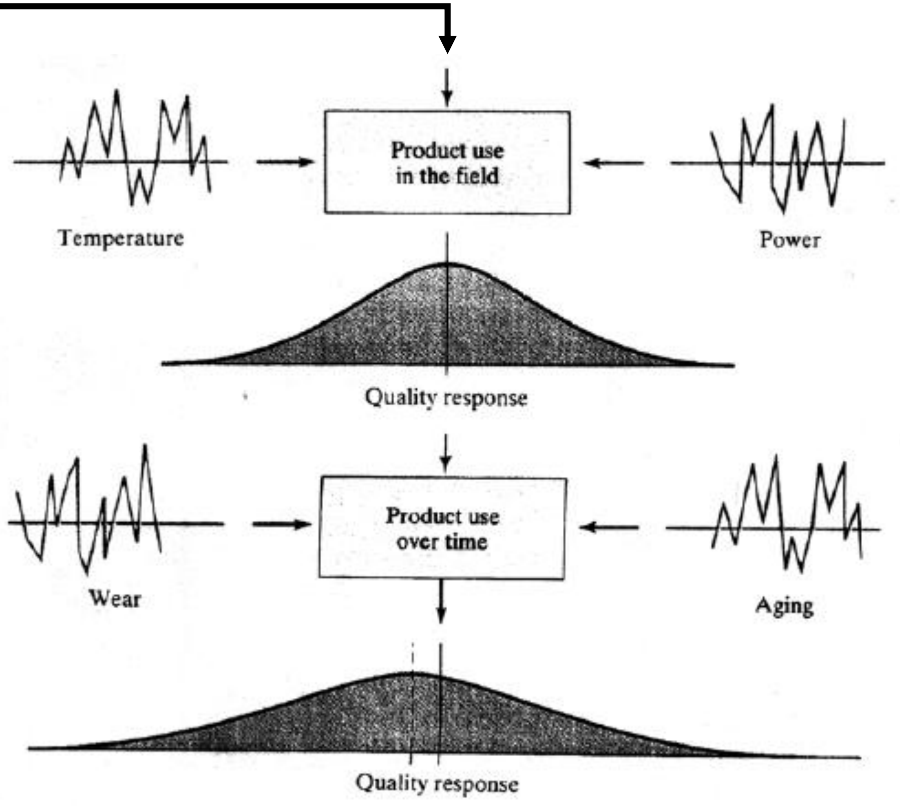
Example 2: Braking Distance of a Car

- Outer Noise [Operating Conditions]
  - Wet or dry road
  - Concrete or Asphalt pavement
  - Number of passengers in the car
- Inner Noise [Deterioration]
  - The leakage of brake fluid
  - Wear of brake drums and brake pads
- Variational Noise [Mfg/Use Imperfection]
  - Variation in friction coefficient of pads and drums
  - The amount of brake fluid

How do these sources affect Quality?



Outer Noise and Inner Noise can be dealt with upstream effectively only by the design process



Variational noise is a matter of manufacturing imperfection and can be dealt with *Statistical Process Control (SPC).*

Robust Parameter Design

- **Robust parameter design (RPD)** is an approach to product realization activities that focuses on choosing the levels of controllable factors (or parameters) in a process or a product to achieve two objectives:
  1. to ensure that the mean of the output response is at a desired level or target
  2. to ensure that the variability around this target value is as small as possible
- When an RPD study is conducted on a process, it is usually called a **process robustness study.**
- The general RPD problem was developed by a Japanese engineer, Genichi Taguchi, and introduced in the United States in the 1980s
- Taguchi proposed an approach to solving the RPD problem based on designed experiments and some novel methods for analysis of the resulting data.

Robust Parameter Design

In a robust design problem, the focus is usually on one or more of the following:

1. Designing systems that are insensitive to environmental factors that can affect performance once the system is deployed in the field. Example: Development of an exterior paint that should exhibit long life when exposed to a variety of weather conditions.

2. Designing products so that they are insensitive to variability transmitted by the components of the system. An example is designing an electronic amplifier so that the output voltage is as close as possible to the desired target regardless of the variability in the electrical parameters of the transistors, resistors, and power supplies that are the components of the system.

3. Designing processes so that the manufactured product will be as close as possible to the desired target specifications, even though some process variables (such as temperature) or raw material properties are impossible to control precisely.

4. Determining the operating conditions for a process so that the critical process characteristics are as close as possible to the desired target values and the variability around this target is minimized. Examples of this type of problem occur frequently. For example, in semiconductor manufacturing we want the oxide thickness on a wafer to be as close as possible to the target mean thickness, and we want the variability in thickness across the wafer (a measure of uniformity) to be as small as possible

Crossed Array Design

- The original Taguchi methodology for the RPD problem revolved around the use of a statistical design for the controllable variables and another statistical design for the noise variables.
- Then these two designs were "crossed"; that is, every treatment combination in the design for the controllable variables was run in combination with every treatment combination in the noise variable design. This type of experimental design was called a crossed array design.

Example: Leaf Spring Experiment

In this experiment, **five factors** were studied to determine their effect on the free height of a leaf spring used in an automotive application.

Out of five,

four are control variables, (a) furnace Temperature, (b) heating time, (c) transfer time, (d) hold don time

and one is noise variable (e) quench oil temperature

Example: Leaf Spring Experiment

The design for the controllable factors is a 2^{4-1} fractional factorial design with generator D = ABC. This is called the inner array design.

The design for the single noise factor is a 2^1 design, and it is called the outer array design.

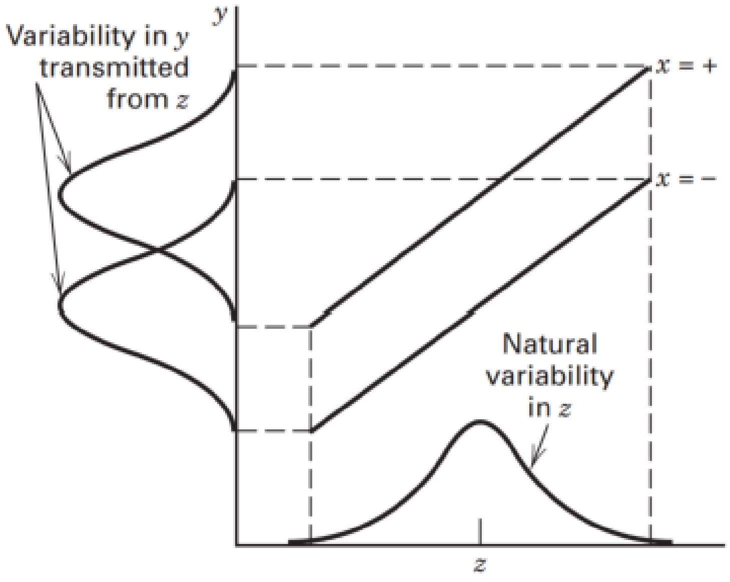
Notice how each run in the outer array is performed for all eight treatment combinations in the inner array, producing the crossed array structure. In the leaf spring experiment, each of the 16 distinct design points was replicated three times, resulting in 48 observations on free height.

The Leaf Spring Experiment

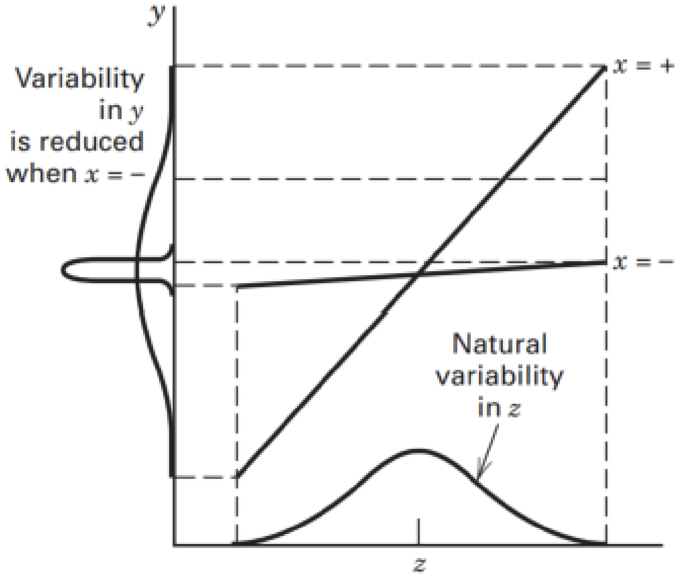
A	B	C	D	$E = -$	$E = +$	$\bar{y}$	s^2
−	−	−	−	7.78, 7.78, 7.81	7.50, 7.25, 7.12	7.54	0.090
+	−	−	+	8.15, 8.18, 7.88	7.88, 7.88, 7.44	7.90	0.071
−	+	−	+	7.50, 7.56, 7.50	7.50, 7.56, 7.50	7.52	0.001
+	+	−	−	7.59, 7.56, 7.75	7.63, 7.75, 7.56	7.64	0.008
−	−	+	+	7.54, 8.00, 7.88	7.32, 7.44, 7.44	7.60	0.074
+	−	+	−	7.69, 8.09, 8.06	7.56, 7.69, 7.62	7.79	0.053
−	+	+	−	7.56, 7.52, 7.44	7.18, 7.18, 7.25	7.36	0.030
+	+	+	+	7.56, 7.81, 7.69	7.81, 7.50, 7.59	7.66	0.017

Crossed Array Design

- An important point about the crossed array design is that it provides information about interactions between controllable factors and noise factors. These interactions are crucial to the solution of an RPD problem.
- For example, consider the two-factor interaction graph, where x is the controllable factor and z is the noise factor.
- In Figure A, there is no interaction between x and z; therefore, there is no setting for the controllable variable x that will affect the variability transmitted to the response by the variability in the noise factor z.
- However, in Figure B, there is a strong interaction between x and z. Note that when x is set to its low level, there is much less variability in the response variable than when x is at the high level.



(*a*) No control × noise interaction



(*b*) Significant control × noise interaction

Robust Design Strategy

- **Stage 1: Parameter Design**
  - Step 1: Reduce sensitivity to noise (reduce variability)
    - Find mean ($\bar{x}$) and std. dev (s)
    - Define signa-to-noise ratio, $\eta = 10\log_{10}\left(\frac{\bar{x}^2}{s^2}\right)$
    - Minimize η
  - Step 2: Set the mean ($\bar{x}$) on target using parameters that affect the variability the least

- **Stage 2: Tolerance Design**
  - Select Tolerances based on Cost vs. Performance (not covered in this class)
  - This step may become unnecessary if design parameters reduce variance sufficiently
  - Systematically balance cost and performance improvement

Example

Anti Satellite Attack Missile

Response variable is distance to shoot

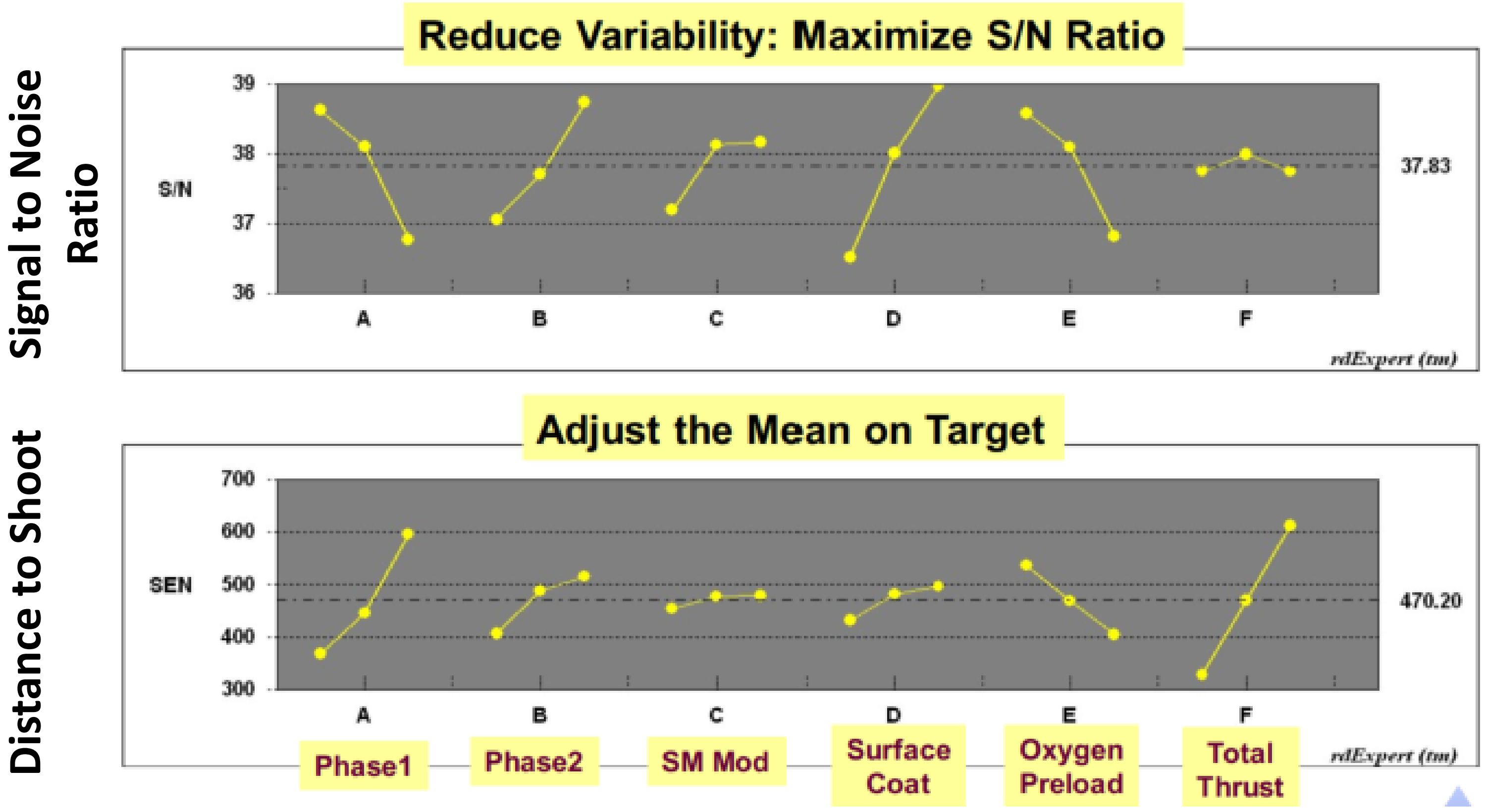


Image from Dr. Phadke's workshop