Engineering Project Management & Finance

(UESTC 3031 & UESTCHN 3012)

Design For Manufacturing (Part 3)

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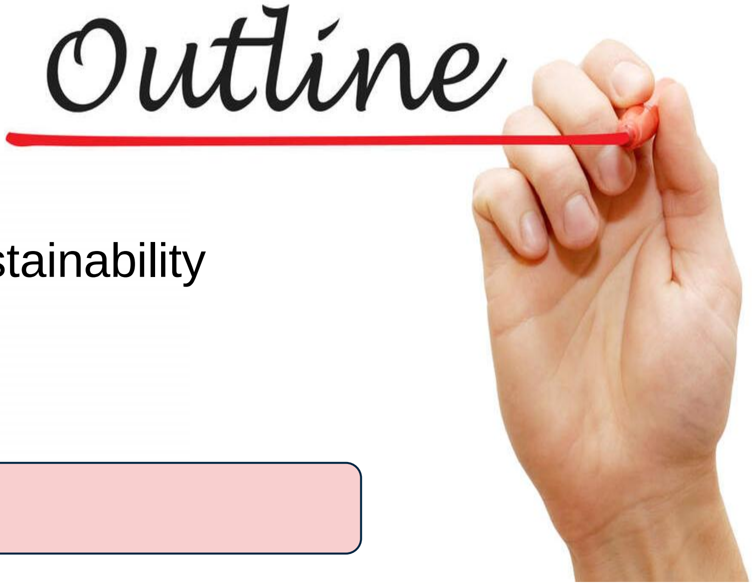
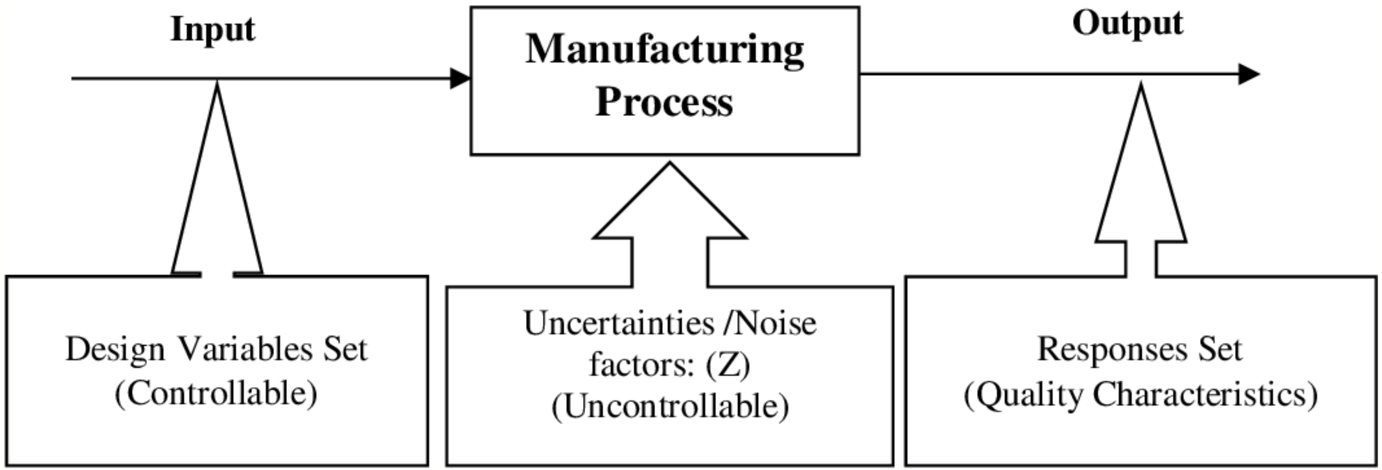
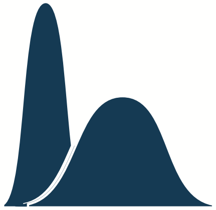


- **Part 1:** Introduction to DFM & Design for Sustainability
- **Part 2:** Quality Control & Cost of Quality
- **Part 3:** Robust Manufacturing Design
- **Part 4:** 6-Sigma & Process Capability

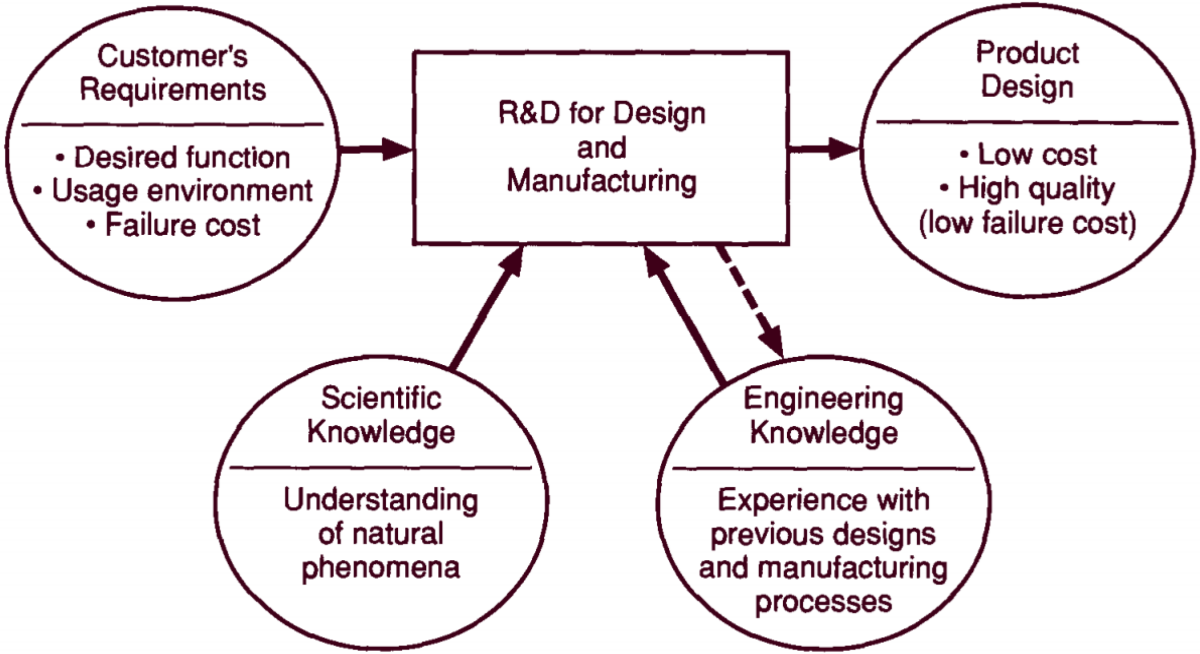
Robust Manufacturing Design





Robust Design (1/2)

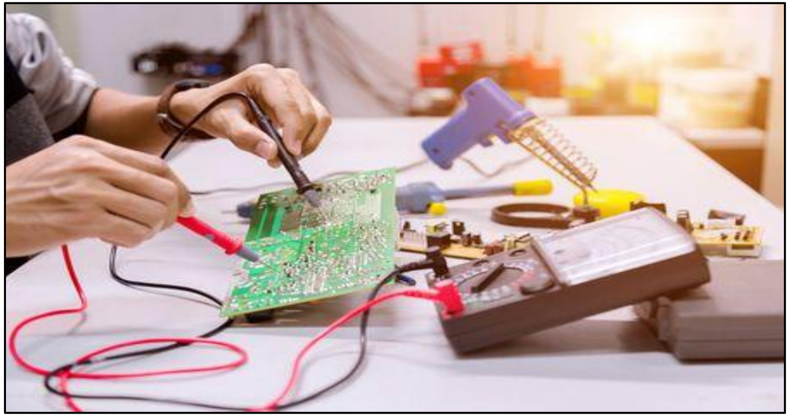
A major part of research and development (R&D), is to manufacture products that meet customer requirements.

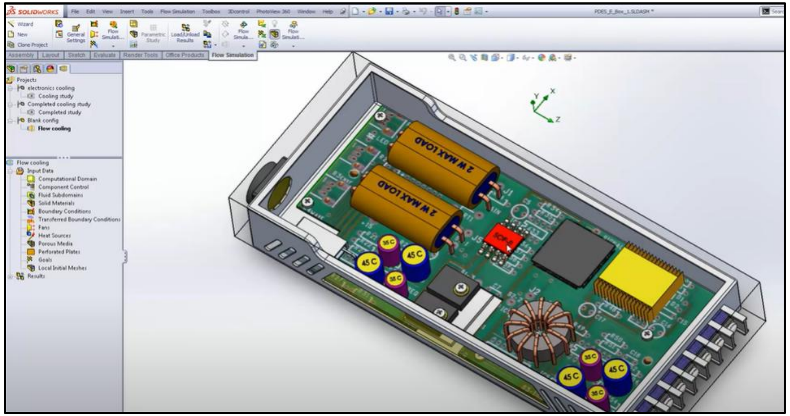


Block diagram of R&D activity.

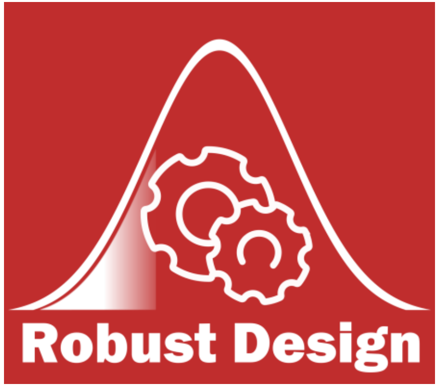
Robust Design (2/2)

- ✓ A large amount of engineering effort is consumed in conducting experiments (either with hardware or by simulation) to generate such information needed.
- ✓ Efficiency in generating such information is the key to meeting market windows, keeping development and manufacturing costs low, and having high-quality products.





Brief History

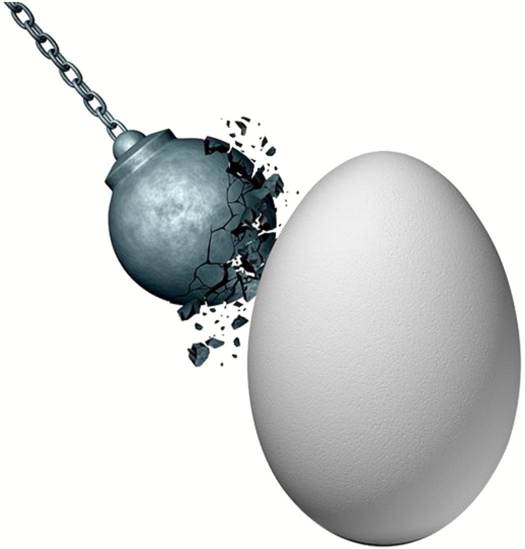


- ✓ The science of statistical experimental design originated with the work of Sir Ronald Fisher in England in the 1920s. Fisher founded the basic principles of experimental design and the associated data-analysis technique called analysis of variance (ANOVA).
- ✓ After World War II, the challenge was to produce high-quality products and continue to improve the quality under circumstances like shortage of good-quality raw material, manufacturing equipment and skilled engineers.
- ✓ Through the 1950s and the early 1960s, Dr. Genichi Taguchi developed the foundations of Robust Design and validated its basic philosophies by applying them in the development of many products.

Definition

Robust Design is an engineering methodology for improving productivity during research and development (R&D) so that high-quality products can be produced quickly and at low cost.

Robust Design draws on many ideas from statistical experimental design to plan experiments for obtaining dependable information about variables involved in making engineering decisions.



The idea behind the robust design is to increase the quality of a process/product by decreasing the effects of variation without eliminating the causes since they are too difficult or too expensive to control.

The Basic Idea Behind Robust Design

Reduce Variability

ROBUSTNESS ≡ QUALITY

Increase Quality

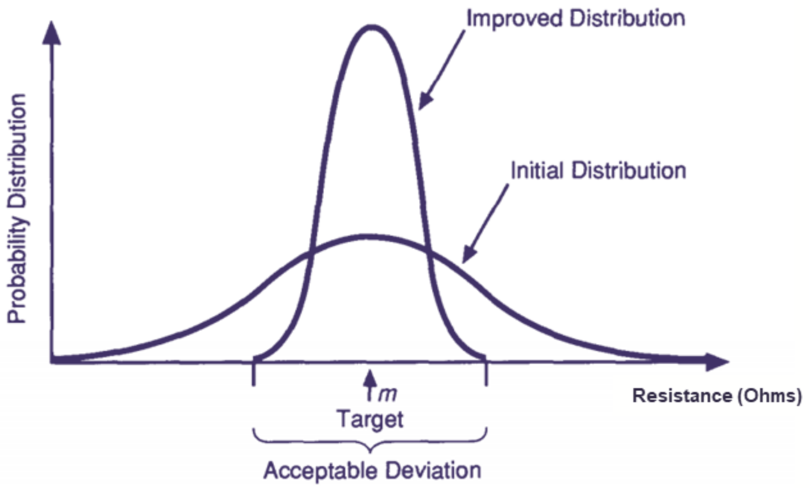
Reduce Cost

The Basic Idea Behind Robust Design

Example:

Resistor Manufacturing and Taguchi Method

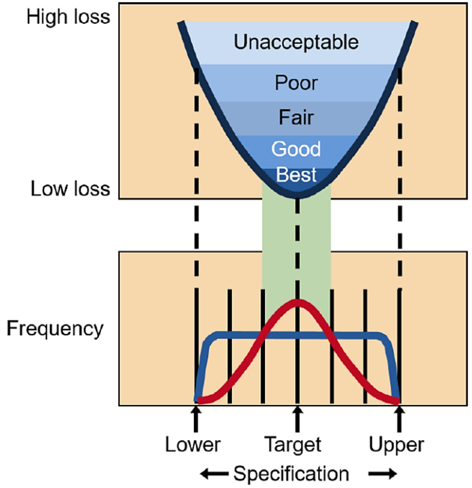
Imagine a factory produces 100-ohm resistors, but due to variations in materials and processes, the actual resistances range from 95 ohms to 105 ohms. This variation can affect circuit performance.



Using the Taguchi Robust Design, engineers identify and control key factors (like temperature, material quality, or machine settings) to minimize this variation. After applying Taguchi optimization, the resistors now range from 98 ohms to 102 ohms, meaning the variation has been reduced while still centering around 100 ohms.

What is Quality?

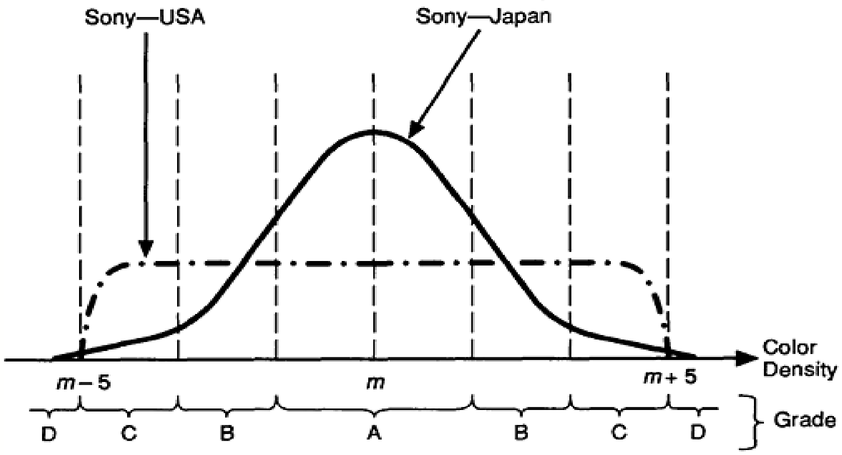
- ✓ Ideal quality: Customers can expect every product delivers the target performance each time the product is used (may be impossible).
- ✓ Following robust design (Taguchi) viewpoint, we measure the quality of a product in terms of the total loss to society (producer and customer) due to functional variation and harmful side effects.
- ✓ Under the ideal quality, the loss would be zero; the greater the loss, the lower the quality.



What is Quality?

Example 1:

In the 1970s, American consumers preferred Sony televisions made in Japan over those made in the USA, even though both used the same designs and tolerances. The reason wasn't the number of defective products but the color density. Sony-Japan's TVs had a normal distribution of color density centered around the target, with a small variation. Sony-USA's TVs had a more uniform distribution, but with wider variations. Despite Sony-USA having fewer defective units, the difference in quality was perceived due to the variation in color, not defects.

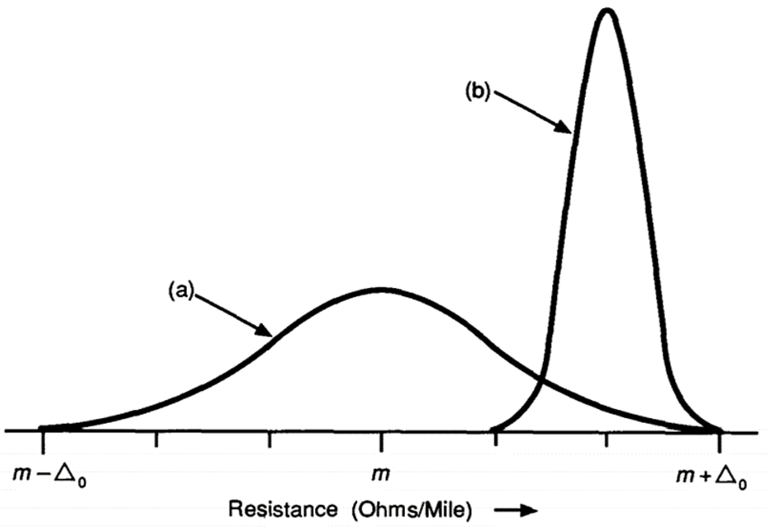


Distribution of color density in television sets. (Source: *The Asahi*, April 17, 1979).

What is Quality?

Example 2:

A manufacturer used the fraction of defective units as a quality measure for telephone cables, with a target resistance of "m" ohms per mile. They improved the process by reducing variance and shifting the mean resistance closer to the upper limit, reducing copper usage. However, this increase in resistance led to higher electrical losses in the network, causing complaints from users. This example demonstrates that both variance and deviation from the target point should be considered simultaneously for effective process improvement.



Distribution of telephone cable resistance. (a) Initial distribution. (b) After process improvement and shifting the mean.

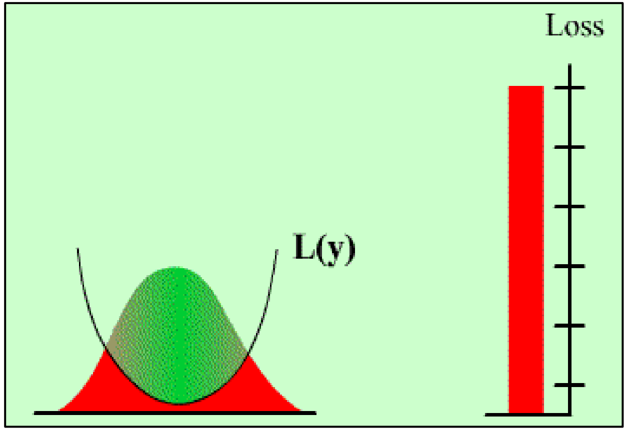
Quality at what cost?

- ✓ There are three main categories of cost:
  1. Operating Cost (e.g., cost of energy needed to operate the product, environmental control, maintenance, scrap, rework, inventory of spare parts and units, etc.)
  2. Manufacturing Cost (e.g., equipment, machinery, raw materials, labor, etc.)
  3. R&D Cost
- ✓ The manufacturing cost and R&D cost are incurred by the producer and then passed on to the customer through the purchase price of the product.
- ✓ Higher quality means lower operating cost and vice versa.
- ✓ Robust Design is a systematic method for keeping the operating cost low while delivering a high-quality product (customer's satisfaction).

Major Tools Used In Robust Design

The two major tools used in Robust Design are:

1. Quality Loss Function: measurement of quality during design/ development.
2. Orthogonal Arrays: efficient experimentation to find dependable information about the design parameters.

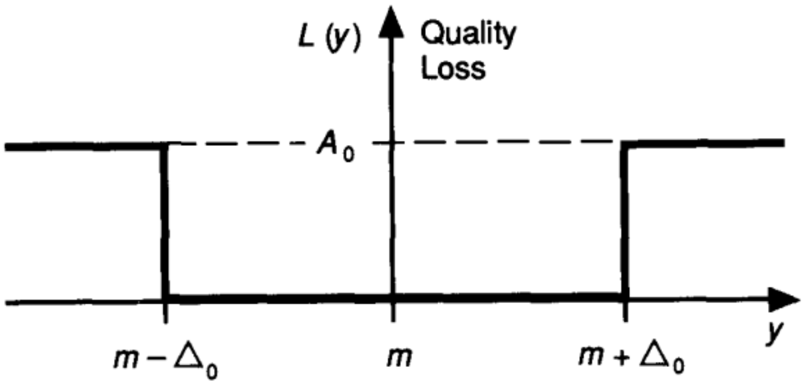


Experiment Number	Column 1	2	3
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

Traditional viewpoint

The quality loss quantify as below:

$$L(y) = \begin{cases} 0, & if \quad |y - m| < \Delta_0 \\ A_0, & otherwise \end{cases}$$



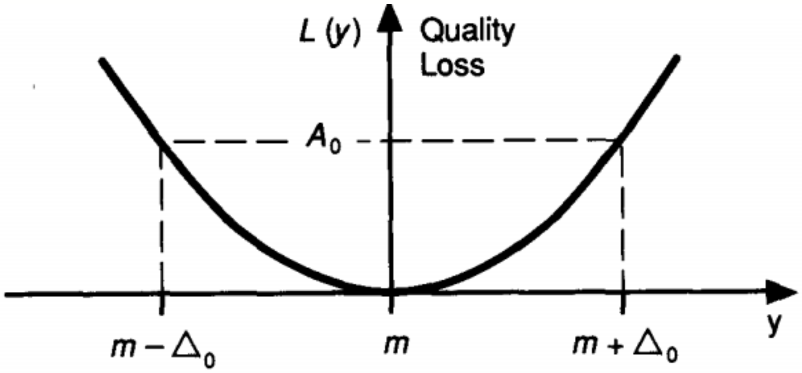
Here, A_0 is the cost of replacement or repair. Any value in the range $(m - \Delta_0)$ to $(m + \Delta_0)$ is equally good for the customer and that as soon as the range is exceeded the product is bad.

Taguchi Viewpoint (Quadratic Loss Function)

The quality loss quantify as below:

$$L(y) = k(y - m)^2$$

where k is a constant called *quality loss coefficient*: $k = \frac{A_0}{\Delta_0^2}$



Notice that at $y = m$ the loss is zero. This is quite appropriate because m is the best value for y. The loss $L(y)$ increases slowly (less slope) when we are near m; but as we go farther from m the loss increases more rapidly.

Example - Television Set Color Density:

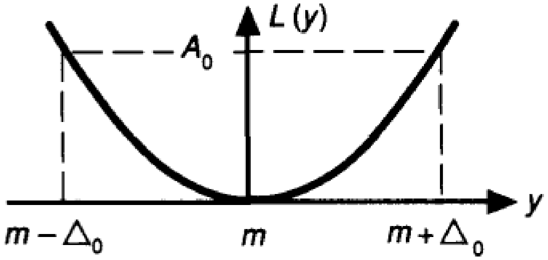
Suppose the functional limits for the color density are $m \pm 7$. Let the repair of a television set in the field cost on average $A_0 = \$98$. The quadratic loss function can be written as:

$$L(y) = \frac{98}{7^2}(y-m)^2 = 2(y-m)^2$$

Thus, the average quality loss incurred by the customers receiving sets with color density $m+4$ is $L(m+4) = \$32$, while customers receiving sets with color density $m+2$ incur an average quality loss of only $L(m+2) = \$8$.

Example - Power Supply Circuit:

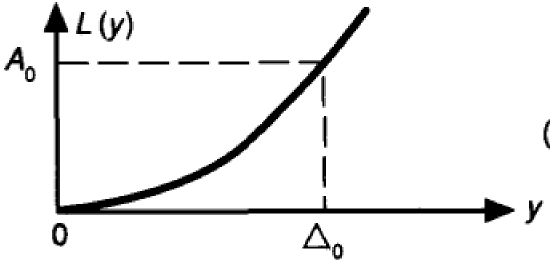
Consider a power supply circuit used in a stereo system for which the target output voltage is 110 volts. If the output voltage falls outside 110 ± 20 volts, then the stereo fails in half the situations and must be repaired. Suppose it costs $\$100$ to repair the stereo. Calculate the average loss associated with a particular value y of output voltage.



(a) Nominal-the-best

E.g., Operating Temperature, Duty Cycle, Bandwidth, Voltage Regulation, etc.

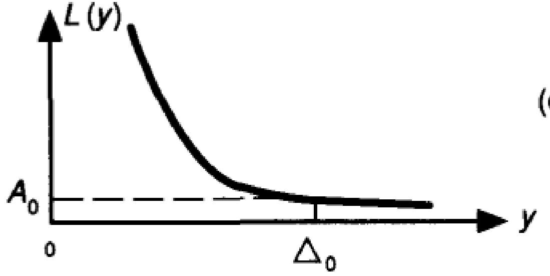
$$L(y) = k(y-m)^2, \qquad k = \frac{A_0}{\Delta_0^2}$$



(b) Smaller-the-better

E.g., Response time of a computer, leakage current in electronic circuits, and pollution from an automobile, etc.

$$L(y) = ky^2, \qquad k = \frac{A_0}{\Delta_0^2}$$



(c) Larger-the-better

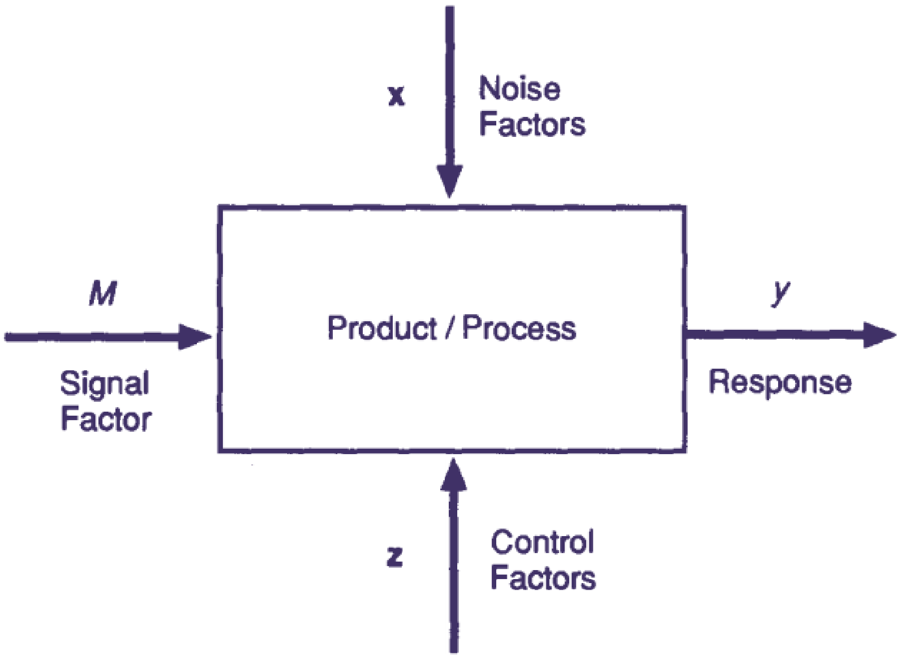
E.g., Efficiency, accuracy, Power amplification, etc.

$$L(y) = k\frac{1}{y^2}, \qquad k = A_0\Delta_0^2$$

Classification of Parameters: P Diagram

- ✓ A number of parameters can influence the quality characteristic or response of the product.
- ✓ These parameters can be classified into the following three classes (note that the word "parameter" is equivalent to the word "factor" in most of Robust Design literature):

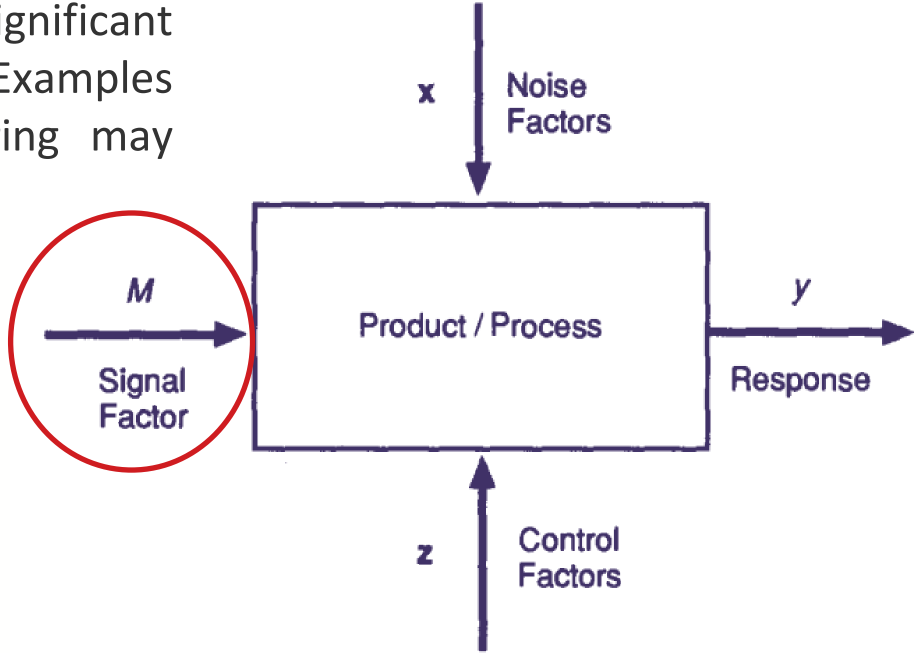
1. Signal factors
2. Noise factors
3. Control factors



Signal Factor(s)

Signal factors are the signals used to get the desired response. These factors have a direct and significant impact on the performance of the product. Examples of signal factors in electronic manufacturing may include:

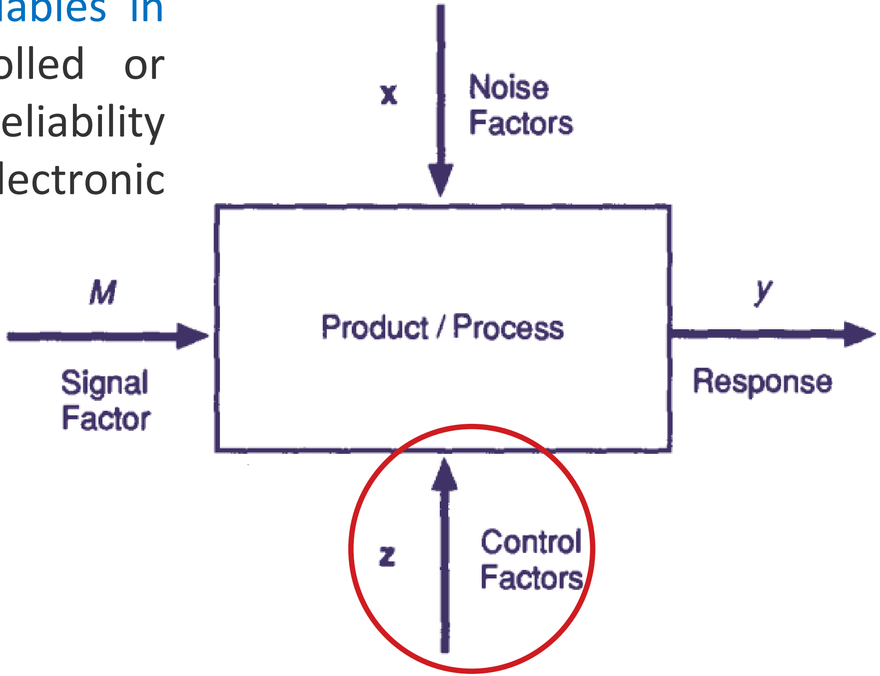
- ✓ Voltage level
- ✓ Current level
- ✓ Frequency of operation
- ✓ Resistance
- ✓ Capacitance
- ✓ Etc.



Control Factor(s)

These parameters can be specified optimally by a designer. These are equivalent to design variables in optimization. These factors can be controlled or manipulated to improve the performance and reliability of the product. Examples of control factors in electronic manufacturing may include:

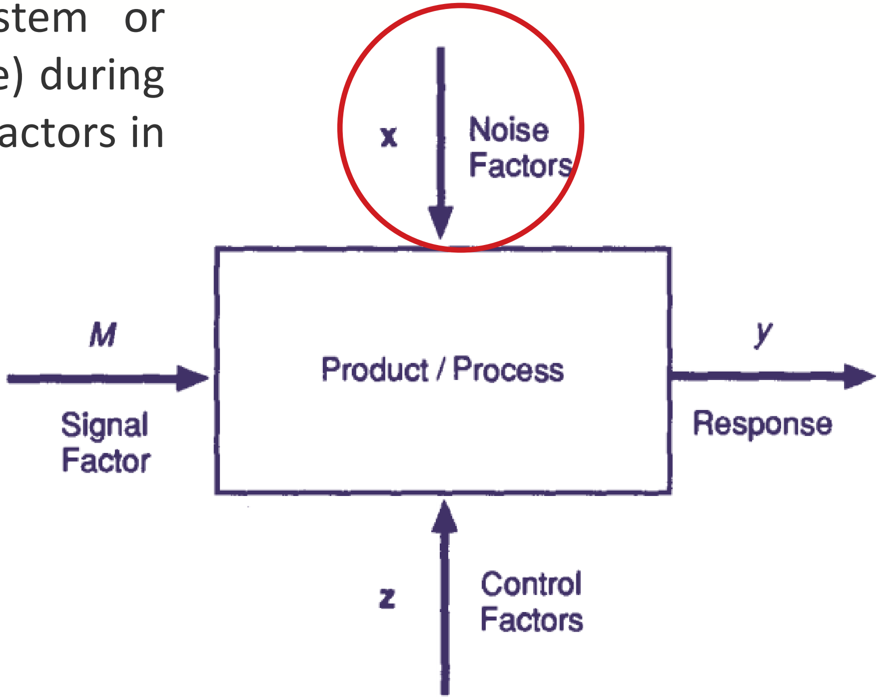
- ✓ Manufacturing process parameters
- ✓ Material properties
- ✓ Component selection
- ✓ Assembly techniques
- ✓ Testing procedures
- ✓ Etc.



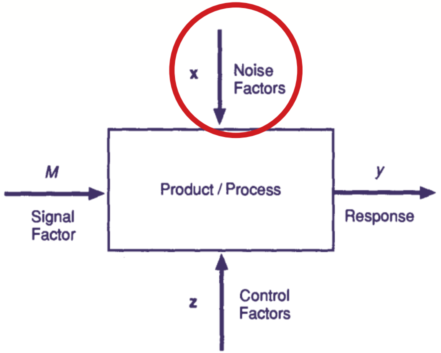
Noise Factor(s)

Noise factors are factors that cause variability (uncertainty) in the performance of a system or product but cannot be controlled (or expensive) during production or product use. Examples of noise factors in electronic manufacturing may include:

- ✓ Temperature fluctuations
- ✓ Humidity levels
- ✓ Electrical interference
- ✓ Component tolerances
- ✓ Process variations
- ✓ Human error
- ✓ Etc.



Noise Factor(s)



Noise factors can be generally classified as follows:

1. External. The environment in which a product works is the main external source of variation of a product's function. Some examples of environmental noise factors are temperature, humidity, dust, supply voltage, electromagnetic interference, vibrations, and human error in operating the product.

2. Unit-to-unit variation. The variation that is unavoidable in a manufacturing process leads to variation in the product parameters from unit to unit. For example, the value of a resistor may be specified to be 100 kilo-ohms, but the resistance value turns out to be 101 kilo-ohms in one particular unit and 98 kilo-ohms in another.

3. Deterioration. When a product is sold, all its functional characteristics may be on target. As time passes, however, the values of individual components may change leading to deterioration in product performance.

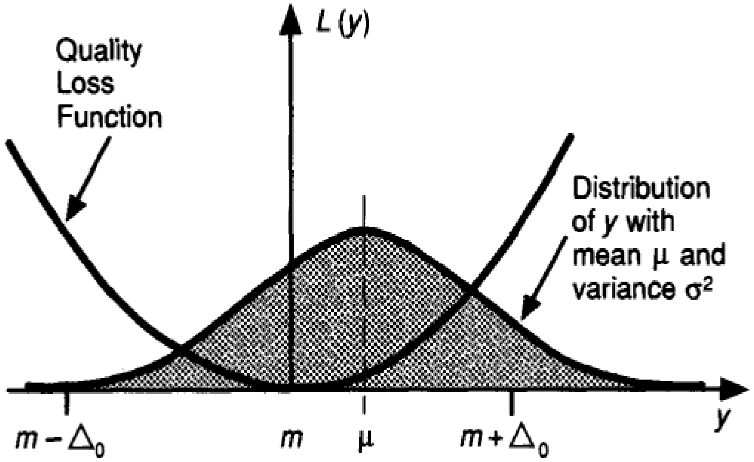
Average Quality Loss

Because of the noise factors, the quality characteristic y of a product varies from unit to unit, and from time to time during the usage of the product.

Let y_1, y_2, ..., y_n be n representative measurements of the quality characteristic y taken on a few representative units throughout the design life of the product.

Let y be a nominal-the-best type quality characteristic and m be its target value. Then, the average quality loss, Q, resulting from this product is given by:

$$Q = \frac{1}{n}[L(y_1) + L(y_2) + \cdots + L(y_n)]$$



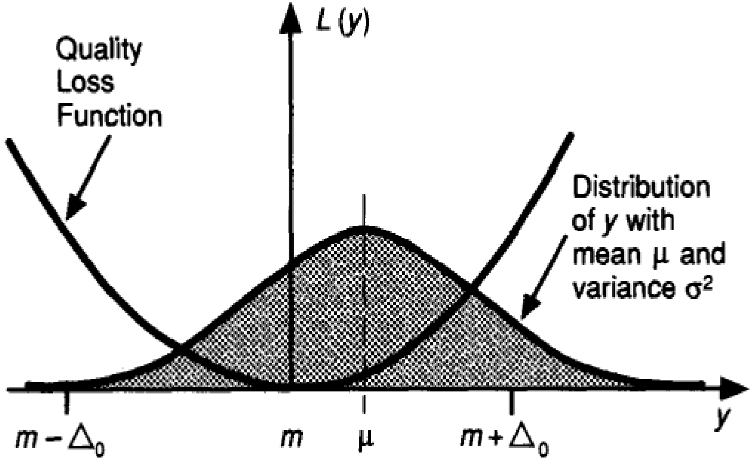
Average Quality Loss

$$Q = \frac{1}{n}[L(y_1) + L(y_2) + \cdots + L(y_n)] = \frac{k}{n}[(y_1 - m)^2 + (y_2 - m) + \cdots + (y_n - m)]$$

$$= k\left[(\mu - m)^2 + \frac{n-1}{n}\sigma^2\right]$$

where μ and σ^2 are the mean and the variance of y, respectively, as computed by

$$\mu = \frac{1}{n}\sum_{i=1}^{n} y_i \qquad \sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(y_i - \mu)^2$$



When n is large, then $\boldsymbol{Q = k\left[(\mu - m)^2 + \sigma^2\right]}$

Average Quality Loss

Example

Let's say that we are manufacturing a device that amplifies an input signal, and the desired output signal strength is 10 volts. However, due to various sources of variation in the manufacturing process, the output signal strength may deviate from the target value. We manufacture 10 devices, and we measure the output signal strength of each device. Here are the results:

Calculate the average quality loss function, if assume the cost of repairing of devices if fault out of 10 ± 0.5 would be $2.

Device 1: 9.5 volts
Device 2: 9.8 volts
Device 3: 10.1 volts
Device 4: 9.9 volts
Device 5: 9.7 volts
Device 6: 10.2 volts
Device 7: 9.6 volts
Device 8: 10.3 volts
Device 9: 10.0 volts
Device 10: 9.4 volts

Average Quality Loss

Answer

Device 1: 9.5 volts
Device 2: 9.8 volts
Device 3: 10.1 volts
Device 4: 9.9 volts
Device 5: 9.7 volts
Device 6: 10.2 volts
Device 7: 9.6 volts
Device 8: 10.3 volts
Device 9: 10.0 volts
Device 10: 9.4 volts

Engineering Design Problem

Consider the strategy of minimizing the manufacturing cost while delivering a specified quality level. The following strategy consists of three steps can be attended:

1. Concept Design: Concept design is a process of selecting a product or process based on competing technologies, customers, price, or any other important considerations. Moreover, the biggest advantage of this method is that organizations can produce high-quality products with low production costs.

2. Parameter Design: Parameter design refers to the identification of control factors for the process and also to determine the optimal (target) level of each control factor. The goal of this method is to find a robust (insensitive against the noise) optimal design of process/product.

3. Tolerance Design: In tolerance design, a trade-off is made between reduction in the quality loss due to performance variation and increase in manufacturing cost (sensitivity analysis).

Taguchi Parameter Design

1. Brainstorming
2. Identify Design Parameters and Noise Factors
3. Construct Design of Experiments (DOE)
4. Perform Experiments
5. Analyze Results

Design Parameters (Control Factors): Variables under your control

Noise Factors: Variables you cannot control or that are too expensive to control

Ideally, you would like to investigate all possible combinations of design parameters and noise factors and then pick the best design parameters. Unfortunately, cost and schedule constraints frequently prevent us from performing this many test cases – this is where DOE come in!

Design of Experiment (DOE)

- ✓ **Design of Experiments (DOE)**: An information gathering exercise. DOE is a structured method for determining the relationship between process inputs and process outputs.

- ✓ Full factorial always needs more experiments

Full factorial design → Number of Experiments = $(\#\ levels)^{\#\ factors}$

Example: The total number of experiments required for 2 levels can be calculated by:

Conditions	Number of Experiments (Full factorial)
2 level 3 factors	$2^3 = 8$
2 level 4 factors	$2^4 = 16$
2 level 6 factors	$2^6 = 64$
2 level 15 factors	$2^{15} = 32{,}768$

Design of Experiment (DOE)

- ✓ Our objective is to intelligently choose the information we gather so that we can determine the relationship between the inputs and outputs with the least amount of effort (a smaller number of experiments).

- ✓ One of the common method for designing of experiments (DOE) is Taguchi Orthogonal Array (OA). It is based on a design matrix proposed by Dr. Genichi Taguchi and allows you to consider a selected subset of combinations of multiple factors at multiple levels.

- ✓ Orthogonal arrays have the property that every factor setting occurs the same number of times in every test set of all the other factors. This allows for making a balanced comparison among factor levels under various conditions.

Design of Experiment (DOE)
Orthogonal Array (OA)

Example: $L_4\ (2^3)$ and $L_9(3^4)$ orthogonal array

Number of Variable Levels

Number of Variables

$L_4(2^3)$

Number of Experiments

$L_4(2^3)$ Orthogonal Array

Exp. Num	Variables		
	X_1	X_2	X_3
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

$L_9(3^4)$ Orthogonal Array

Exp. Num	Variables			
	X_1	X_2	X_3	X_4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

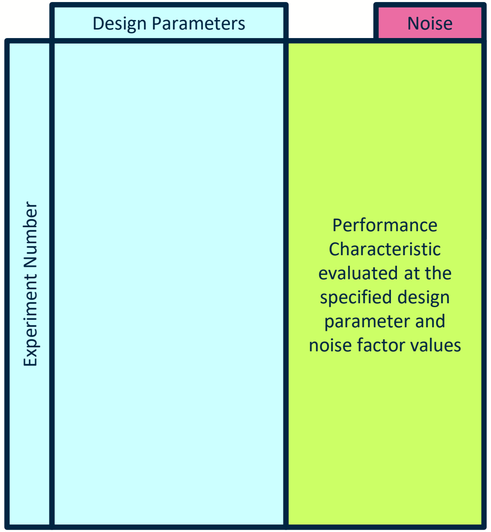
Design of Experiment (DOE)- Orthogonal Array (OA)

Standard OAs

Orthogonal Array	Number of Rows	Maximum Number of Factors	Maximum Number of Columns at These Levels			
			2	3	4	5
L_4	4	3	3	-	-	-
L_8	8	7	7	-	-	-
L_9	9	4	-	4	-	-
L_{12}	12	11	11	-	-	-
L_{16}	16	15	15	-	-	-
L'_{16}	16	5	-	-	5	-
L_{18}	18	8	1	7	-	-
L_{25}	25	6	-	-	-	6
L_{27}	27	13	-	13	-	-
L_{32}	32	31	31	-	-	-
L'_{32}	32	10	1	-	9	-
L_{36}	36	23	11	12	-	-
L'_{36}	36	16	3	13	-	-
L_{50}	50	12	1	-	-	11
L_{54}	54	26	1	25	-	-
L_{64}	64	63	63	-	-	-
L'_{64}	64	21	-	-	21	-
L_{81}	81	40	-	40	-	-

Design of Experiment (DOE)- Orthogonal Array (OA)

Inner & Outer Arrays (Crossed Arrays)



				N_3	1	2	2	1
				N_2	1	2	1	2
				N_1	1	1	2	2
	X_1	X_2	X_3	X_4	1	2	3	4
1	1	1	1	1				
2	1	2	2	2				
3	1	3	3	3				
4	2	1	2	3				
5	2	2	3	1				
6	2	3	1	2				
7	3	1	3	2				
8	3	2	1	3				
9	3	3	2	1				

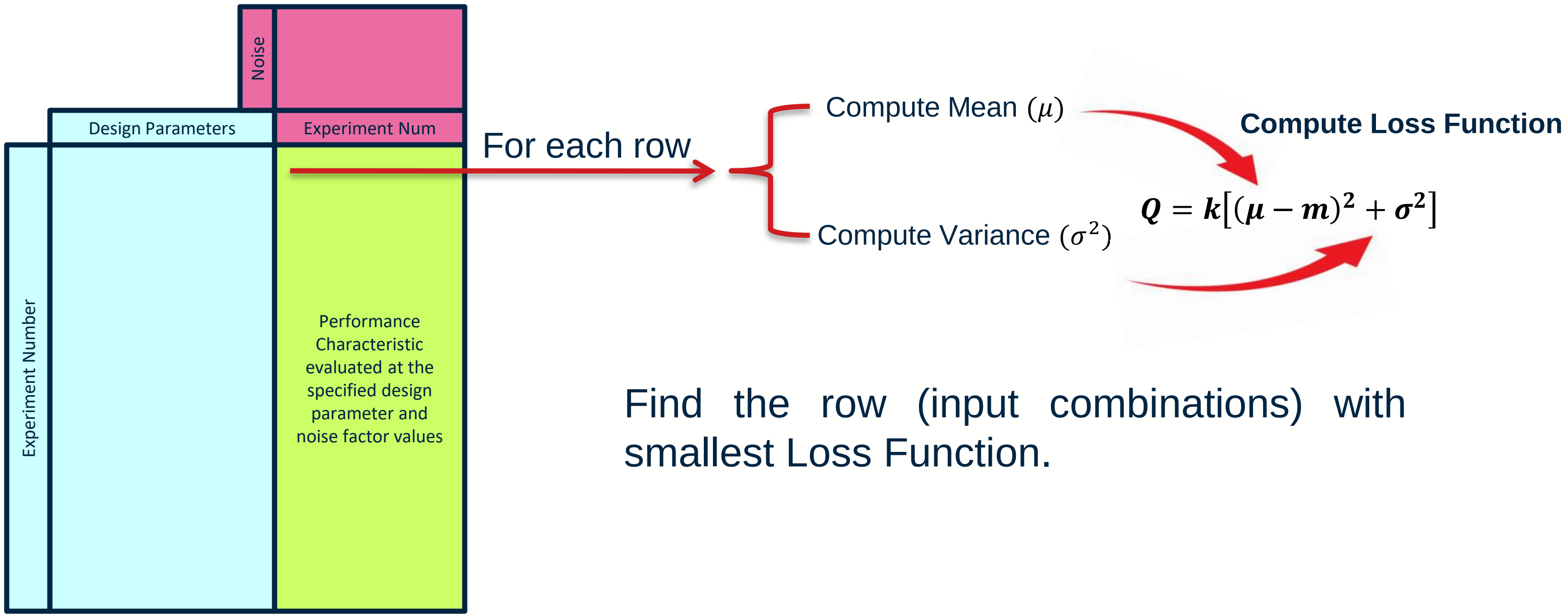
$$y_{11} = f\,\{X_1(1), X_2(1), X_3(1), X_4(1), N_1(1), N_2(1), N_3(1)\}$$

$$y_{52} = f\,\{X_1(2), X_2(2), X_3(3), X_4(1), N_1(1), N_2(2), N_3(2)\}$$

Inner Array – design parameter matrix

Outer Array – noise factor matrix

Design of Experiment (DOE)- Orthogonal Array (OA)



Inner Array – design parameter matrix

Outer Array – noise factor matrix

Find the row (input combinations) with smallest Loss Function.

Example

✓ There are four controllable factors (A, B, C, D) each at three levels and three noise or uncontrollable factors (E, F, G) each at two levels.

					(*b*) Outer Array							
					E	−	−	−	−	+	+	+	+
					F	−	−	+	+	−	−	+	+
					G	−	+	−	+	−	−	−	+
(*a*) Inner Array												
Run	*A*	*B*	*C*	*D*								
1	−1	−1	−1	−1		15.6	9.5	16.9	19.9	19.6	19.6	20.0	19.1
2	−1	0	0	0		15.0	16.2	19.4	19.2	19.7	19.8	24.2	21.9
3	−1	+1	+1	+1		16.3	16.7	19.1	15.6	22.6	18.2	23.3	20.4
4	0	−1	0	+1		18.3	17.4	18.9	18.6	21.0	18.9	23.2	24.7
5	0	0	+1	−1		19.7	18.6	19.4	25.1	25.6	21.4	27.5	25.3
6	0	+1	−1	0		16.2	16.3	20.0	19.8	14.7	19.6	22.5	24.7
7	+1	−1	+1	0		16.4	19.1	18.4	23.6	16.8	18.6	24.3	21.6
8	+1	0	−1	+1		14.2	15.6	15.1	16.8	17.8	19.6	23.2	24.2
9	+1	+1	0	−1		16.1	19.9	19.3	17.3	23.1	22.7	22.6	28.6

Example (Response)

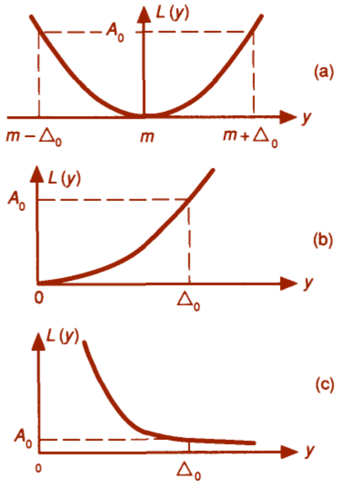
- ✓ Using the experimental results in this crossed arrays design, find the relevant robust optimal product design (assume the target point for the product in 20, and K=1 in quality loss function).

Summary

- ✓ The most processes are affected by external uncontrollable factors in real condition, which cause that quality characteristics are far from ideal points and have variation.
- ✓ In process robustness studies, it is desirable to minimize the influence of noise factors and uncertainty on the process and simultaneously determine the levels of input (control factors) which optimizing the overall responses, or in another sense, optimizing product and process which are minimally sensitive to the various causes of variance.
- ✓ More sophisticated DOE and analysis methods may be used to deal with many of these issues. E.g., Regression and Response Surface Methodology (RSM), Statistical Design of Experiments and Analysis of Variance (ANOVA).


Q
A

The four different versions of the quadratic loss function are plotted in Figure below based on the Taguchi overview. List the name of any two of these loss functions.



Accept any of the below:

- (a): nominal the best
- (b): smaller the better
- (c): Larger the better

In robust design terminology, the performance of a product as measured by the quality characteristic varies in the field due to a variety of causes. We call all such causes noise factors, and they can be generally classified into three types. Explain any two types of noise factors.

Accept any 2 of the below:

- External. The environment in which a product works and the load to which it is subjected are the two main external sources of variation of a product's function. Some examples of environmental noise factors are temperature, humidity, dust, supply voltage, electromagnetic interference, vibrations, and human error in operating the product. The number of tasks to which a product is subjected simultaneously and the period of time a product is exercised continuously are two examples of load-related noise factors.

- Unit-to-unit variation. The variation that is inevitable in a manufacturing process leads to variation in the product parameters from unit to unit. For example, the value of a resistor may be specified to be 100 kilo-ohms, but the resistance value tums out to be 101 kilo-ohms in one particular unit and 98 kilo-ohms in another.

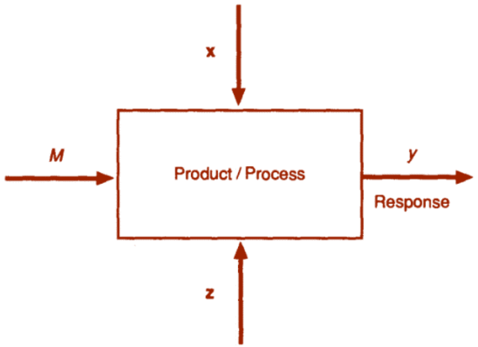
- Deterioration. When a product is sold, all its functional characteristics may be on target. As time passes, however, the values of individual components may change leading to deterioration in product performance.

From the viewpoint of robust design, an engineering design problem can be optimized through three main steps. List any two of these steps.

Accept any two of the below:

- Concept design
- Parameter design
- Tolerance design

The response of the product is denoted by y. The response can be the output of the product or some other suitable quality characteristic. Three classes of parameters (as shown in Figure below by Z, M, and X) can influence the response or quality characteristic of the product. List any two of them.



Accept any two of the below:

- Signal factors.
- Noise factors.
- Control factors.

Assume the product engineer collect 10 observation (test results) from one product's quality characteristic (nominal the best). If the target point for this quality characteristic is 8.5, compute the Taguchi loss function for this set of data (assume constant k=1 is the associated loss function formulation).

Observation No. 1 = 8.100
Observation No. 2 = 8.900
Observation No. 3 = 8.450
Observation No. 4 = 9.250
Observation No. 5 = 8.860
Observation No. 6 = 8.350
Observation No. 7 = 8.250
Observation No. 8 = 8.680
Observation No. 9 = 8.900
Observation No. 10 = 9.050

The Taguchi loss function for nominal the best responses can be computed by: $L = k[(\mu - m)^2 + \sigma^2]$, where m is the target point and here is 8.5, k is constant and here is equal to 1, μ is the mean (average of data), and σ is the standard deviation of data.

- μ is the average o test results and computed to 8.679,
- σ is the standard deviation of test results and computed to 0.3762

so $L = 1[(8.679 - 8.5)^2 + 0.3762^2] = 0.1736$

In the Next Lesson:

Part 4: 6-Sigma & Process Capability

Appendix: Taguchi OA samples

- L4: Three two-level factors
- L8: Seven two-level factors
- L9 : Four three-level factors
- L12: Eleven two-level factors
- L16: Fifteen two-level factors
- L16b: Five four-level factors
- L18: One two-level and seven three-level factors
- L25: Six five-level factors
- L27: Thirteen three-level factors
- L32: Thirty-two two-level factors
- L32b: One two-level factor and nine four-level factors
- L36: Eleven two-level factors and twelve three-level factors
- L50: One two-level factors at 2 levels and eleven five-level factors
- L54: One two-level factor and twenty-five three-level factors
- L64: Thirty-one two-level factors
- L64b: Twenty-one four-level factors
- L81: Forty three-level factors


thank you