Introduction to Robust Design and its applications

Out line

- Introduction.
- Quality Control
- Quality Engineering
- Taxonomy of Quality
- Evaluation of Quality loss
- Tools used in Robust Design
- Process Capability
- Conclusions.

Introduction

Dr. G. Taguchi:

Dr. Taguchi, is born in 1924. He started his career from Naval institute of Japan between 1942 – 45 and then with ministry of public health and welfare. Later he joined ministry of education subsequently moved to Nippen telephone at japan.

Dr. Taguchi is the inventor of the famous orthogonal array OA techniques for the design of experimentation. He published his first book on OA in 1951 Taguchi also visited Indian statistical institute between 1954 – 55. He wrote a book on design of experiments.

Dr. Taguchi philosophy is Robust Engineering Design. He blended statistics with engineering applications and pioneered work in Industrial Experimentation. He is also the innovator of the quality loss function concept and promoted robust design related to this he propagated signal to noise ratio phenomenon in SPC. He developed a three stage off Line QC methods viz., system design, parameter design and Tolerance design.

Genichi Taguchi, a Japanese statistician, is in the forefront of the pioneers of the Quality Control. His major contribution is the concept of Robust Design, which is acclaimed as the most significant one throughout the world. His concepts have revolutionized the very idea of quality control and hence these techniques are widely applied by the manufacturing and service industries successfully in the advanced countries like Japan, US, UK, etc. In the early 1970's, Taguchi developed the concept of the Quality Loss Function.

Quality

- Quality is defined as “fitness for use”.
- As per G. Taguchi, the quality of a product is the (minimum) loss imparted by the product to the society from the time the product is shipped.
- Quality plays a vital role in all walks of life, starting from the household to big engineering and service industries.

Quality Control

- It is an activity of ensuring the manufacturing of good quality products which satisfy the customers’ needs.
- Quality control techniques are broadly classified into On-line and Off-line.
- The On-line quality control techniques are applied to monitor a manufacturing process to verify the levels of quality of goods already produced.
- The Off-line quality control techniques are applied to improve the quality of a product/process in the design stage itself i.e., before the products are manufactured and made available to customers.

For any company to compete in the world class market scenario, its leaders must understand, digest, disseminate and guide the implementation of simple and powerful tools that go well beyond the traditional quality control techniques. They are

- Design of Experiments (DOE)
- Multiple Environment Over Stress Test (MEOST)
- Quality Function Deployment (QFD)
- Total Productive Maintenance (TPM)
- Benchmarking
- Poka-Yoke
- Next Operation As a Customer (NOAC)
- Supply Chain Management (SCM)
- Failure Mode and Effect Analysis (FMEA) and
- Cycle Time Reduction

The Design of Experiments (DOE) is one of the most powerful techniques that helps to achieve the world-class quality.

Quality Engineering

It consists of the activities directed at reducing the variability and thereby reducing the loss. The fundamental principle of robust design is to improve the quality of product/process by minimizing the effect of the causes of variation without eliminating the causes. This is achieved by optimizing the product/process design to make the performance minimum sensitive to the cause of variation. The robust design process encompasses three stages namely

System Design – It is the process of applying scientific and engineering knowledge to produce a basic functional prototype design.

- Development of a system to function under an initial set of nominal conditions.
- Requires technical knowledge from science and engineering.
- Originality / Invention / Marketing strategy.

Parameter Design - It is the process of investigation towards identifying the settings of design parameters that optimizes the performance characteristics and reduces the sensitivity of engineering design to the source of variation (noise factors).

- Determination of control factor levels so that the system is least sensitive to noise.
- Involves use of orthogonal arrays and signal – to Noise Ratio.
- Improves quality at minimal cost.

Tolerance Design – It is the process of determining the tolerances around the nominal settings identified in the parameter design process.

- Specification of allowable ranges for deviations in parameter values.
- Involves cause detection and removal of causes.
- Typically increases product cost. However, cost may be minimized by experimenting to find tolerances that can be relaxed without adversely affecting quality.

Taxonomy Of Quality

There are three fundamental issues regarding quality:

· To evaluate the quality

· To improve quality cost-effectively and

· To monitor and maintain quality cost-effectively. Quality characteristics are classified into two:

· Variable characteristic and

· Attribute characteristic

Variable characteristics can be classified into three types:

· Nominal**-The-Best :** A characteristic with a specific target value.
Examples: Dimension, Clearance, Viscosity etc.

· **Smaller-The-Better :** Here the ideal target value is zero.
Examples: Wear, Shrinkage, Deterioration etc.

· **Larger-The-Better :** The ideal target value is infinity
Examples: Strength, Life, Fuel efficiency etc.

· **Attribute Characteristics :** Based on visual inspection
Examples : Appearance, Taste, Good/bad, etc.

Evaluation Of Quality Loss

- Traditional interpretation of quality loss
- Taguchi's interpretation of quality loss.

Traditional interpretation of quality loss Step Function

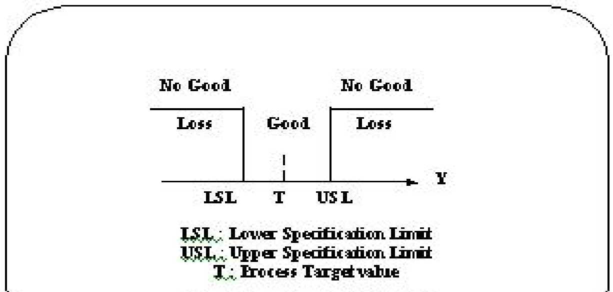


Figure 1.1 STEP FUNCTION

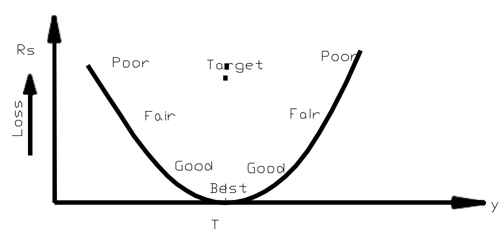
Taguchi emphasizes that the loss incurred by a product which falls close to LSL and which falls just below LSL is almost same. The problem with most of the traditional measures of quality (rework rate, scrap rate, Cp, Cpk, etc.) is that by the time we get these figures, the product is already either in production or in the hands of customer.

Taguchi's interpretation of Quality Loss Function (TQLF)

- The objective of TQLF is the quantitative evaluation of loss resulting from the functional variation of the output quality characteristic from the target value.

- The two important points to be considered to establish Taguchi's QLF are

* Consumer tolerance
* the customer loss



Taguchi's Quadratic Representation of the QLF

There are three cases of TQLF namely :

- TQLF for Nominal-The-Best
- TQLF for Smaller-The-Better and
- TQLF for Larger-The-Better.

To establish the characteristics of Taguchi's QLF, the two important aspects to be considered are consumer tolerance and consumer loss.

Tqlf For Nominal-The-Best (NTB):

Taguchi's QLF for the case of NTB is given by
$L(y) = K * (y-T)^2$

Where L(y) = loss is rupees per unit of product for the output characteristic of 'y'

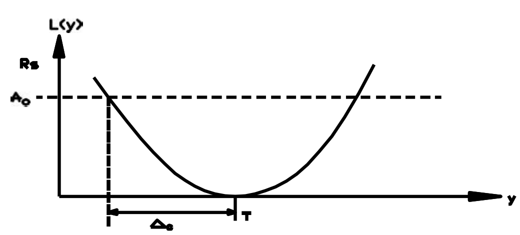
T = Target value of 'y'
K = Constant of proportionality that depends upon financial importance of the output characteristic

Taguchi recognized the loss as a continuous function and it does not occur suddenly. The quadratic representation of QLF i.e., $L(y) = K * (y-T)^2$.

Where Loss L(y) is minimum at y =T and L(y) increases as 'y' deviates from the target value T.

$$\therefore K = \frac{L(y)}{(y-T)^2} = \frac{A_o}{\Delta_0^2}$$

where 'Δ_0' is the consumer tolerance and 'A_o' is the consumer loss which are shown in Figure below.



TQLF for Nominal-The-Best

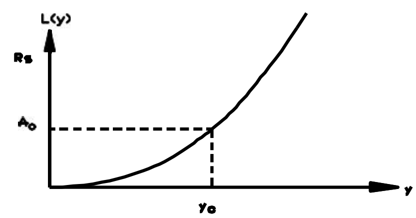
TQLF For Smaller-The-Better (STB)

When the out-put characteristic is to be a minimum value, the loss function is characterized as "Smaller-The-Better". The examples for STB are shrinkage, pollution, radiation leakage etc.

The ideal value for this is zero. The Loss function is slightly different but the procedure is same as the Nominal–The–Best.

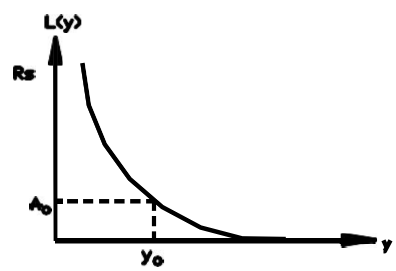
For STB, the loss function is given by

L(y) = K * y 2   and K = A0 / y0 2

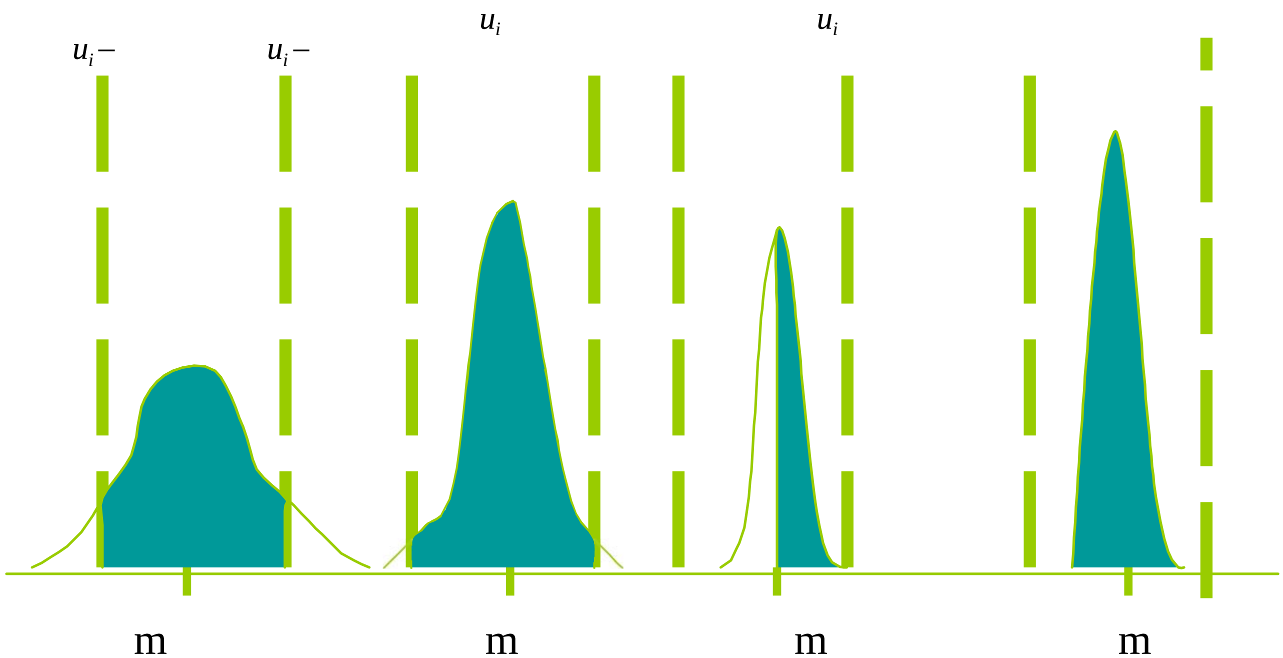


TQLF For Larger-The-Better (LTB)

The loss function for LTB is the reciprocal of the Smaller-The-Better case and is given by L (y) = K * (1 / y2) and K = Ao * yo2 .   This is shown in figure below. Some examples of LTB are strength of a permanent adhesive, strength of a welded joint, fuel efficiency, corrosion resistance etc. The ideal value for LTB is infinity.



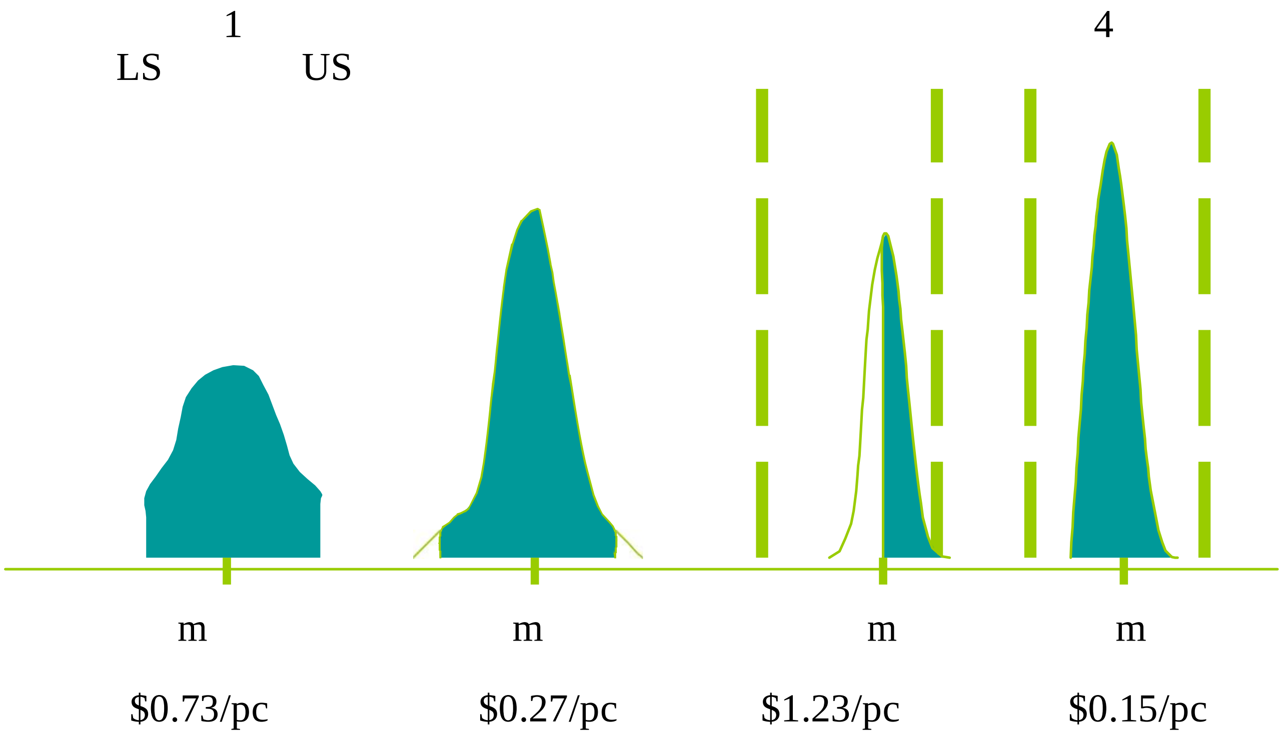
TQLF : Larger-The-Better



y = Output Characteristic (nominal-the-Best)
m = target Value

- Same product, same specifications
- All are 100% inspected
- Cost to you is the same from all four sources.

Which factory would you choose to be your vendor? Why?



It is, therefore, very much essential to analyze and quantify the losses to the society using TQLF. This will help in identifying the level of one's own quality in comparison with the competitors' quality to take remedial actions for improvements, if necessary, to compete in the present day global competition. The TQLF can be used to determine the optimum tolerances for the levels of optimized parameters determined by the parameter design technique.

Tools Used in Robust Design

- Signal- To - Noise Ratio (S/N) - which measures quality
- Orthogonal Arrays - which are used to study many design parameters simultaneously

$$S/N = \frac{\text{Energy (or power) that is transformed into intended output}}{\text{Energy (or power) that is transformed into unintended outputs}}$$

$$S/N = \frac{\text{Useful output energy}}{\text{Harmful output energy}}$$

The higher the ratio, the higher the quality

S/N ratios for Static Problems
S/N ratio for Smaller-The-Better

When the output characteristic can be classified as Smaller-The-Better, the standard S/N ratio is
With n observations, y1, y2, y3 ……. Yn

L(y) = K(y2)
K(MSD)

where

K= A0 / Yo2

MSD = $\frac{y12 + y22 + y32 + \ldots\ldots Yn2}{n}$

S/N (dB) = -10 log10 (MSD)

S/N Ratio for Nominal-The-Best

When the output characteristic is classified as Nominal-The-Best the standard S/N ratio is:
With n observations, y1, y2, y3 ……. yn

$$\overline{Y} = \frac{u}{n}\sum_{i=1} Y_i \quad and \quad O^2 = \frac{1}{n-1}\sum_{i=1} (Y_i - \overline{Y})^2$$

The Signal to Noise ratio is

$$n = 10 \log_{10} \frac{Y_L}{\sigma^2}$$

S/N ratio for Larger-The-Better

When the output characteristic can be classified as
Larger-The-Better , the standard S/N is:

L(y) = K(1 / y2)
K(MSD)

K = Aoyo2

$$MSD = 1/n \sum_{i=1}^{n} yi2$$

Signal to Noise Ratio is
S/N (dB) = -10 log10 (MSD)

S/N ratio for Fraction Défective

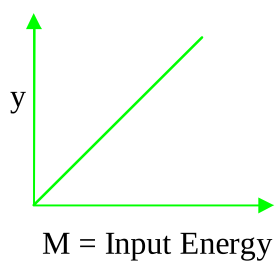
The Quality Characteristic is denoted by p, a fraction assuming values between 0 and 1. When the fraction defective is p, on an average we have to manufacture 1 / (1-p) to produce one good piece.For every good piece produced there is a waste and hence a loss, equivalent to the cost of the processing {1/(1-p) - 1} pieces.

Thus, the Quality Loss Q is given by
Q = K (p / 1-p)

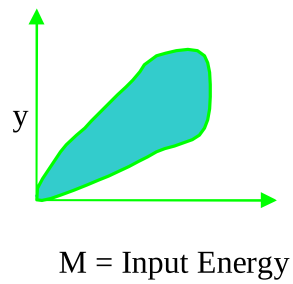
Where K is the cost of processing one piece Ignoring K, we obtain the objective function to be maximized in the decibel scale as

$$n = -10\log_{10}\left(\frac{p}{1-p}\right)$$

Ideal Function
y = Output Response

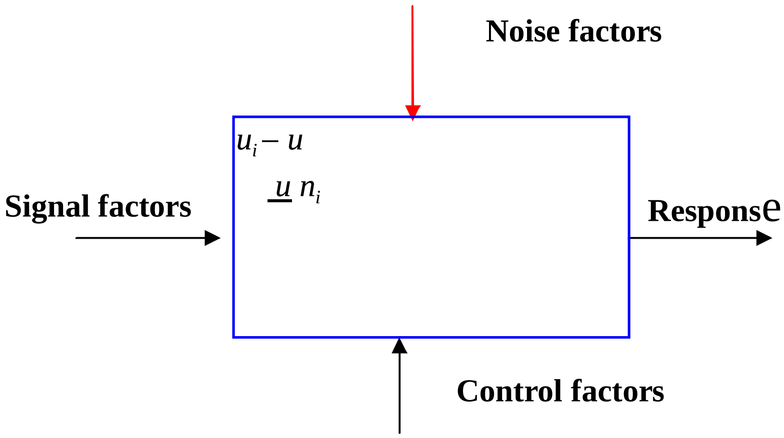


Reality
y = Output ``



The most common way of expressing a design's Ideal Function is :
y = þM
Where y = Output response
m = Input signal

Classification of Parameters



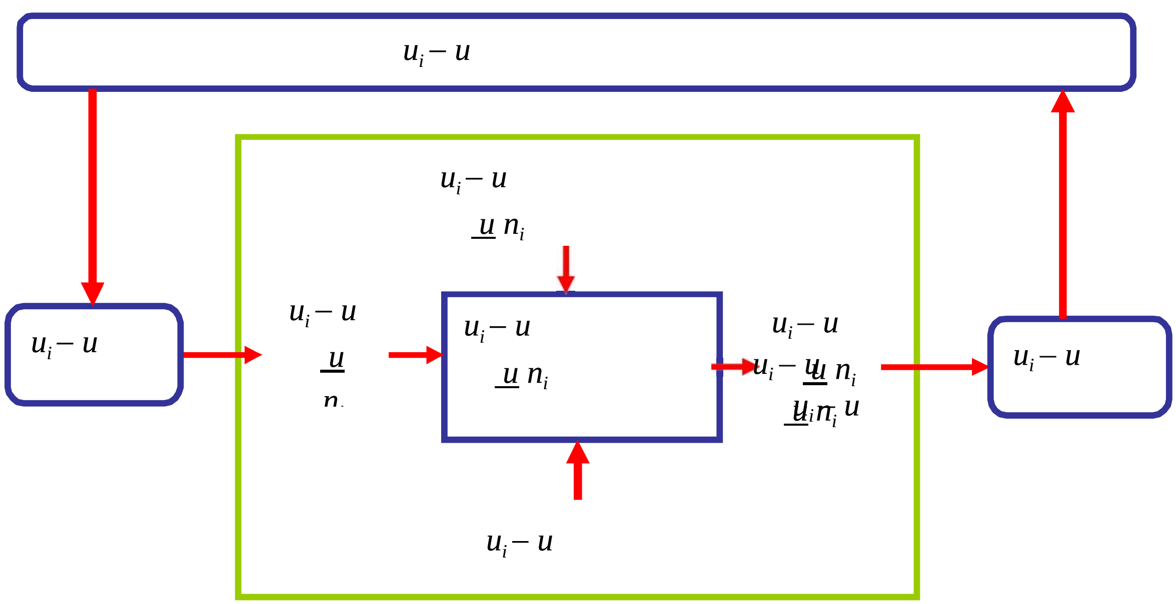
Block Diagram of a Product/Process

Signal factors – these are the parameters set by the user of the product to express the intended value for the response of the product. The signal factors are selected by the design engineer based on the engineering knowledge of the product being developed.

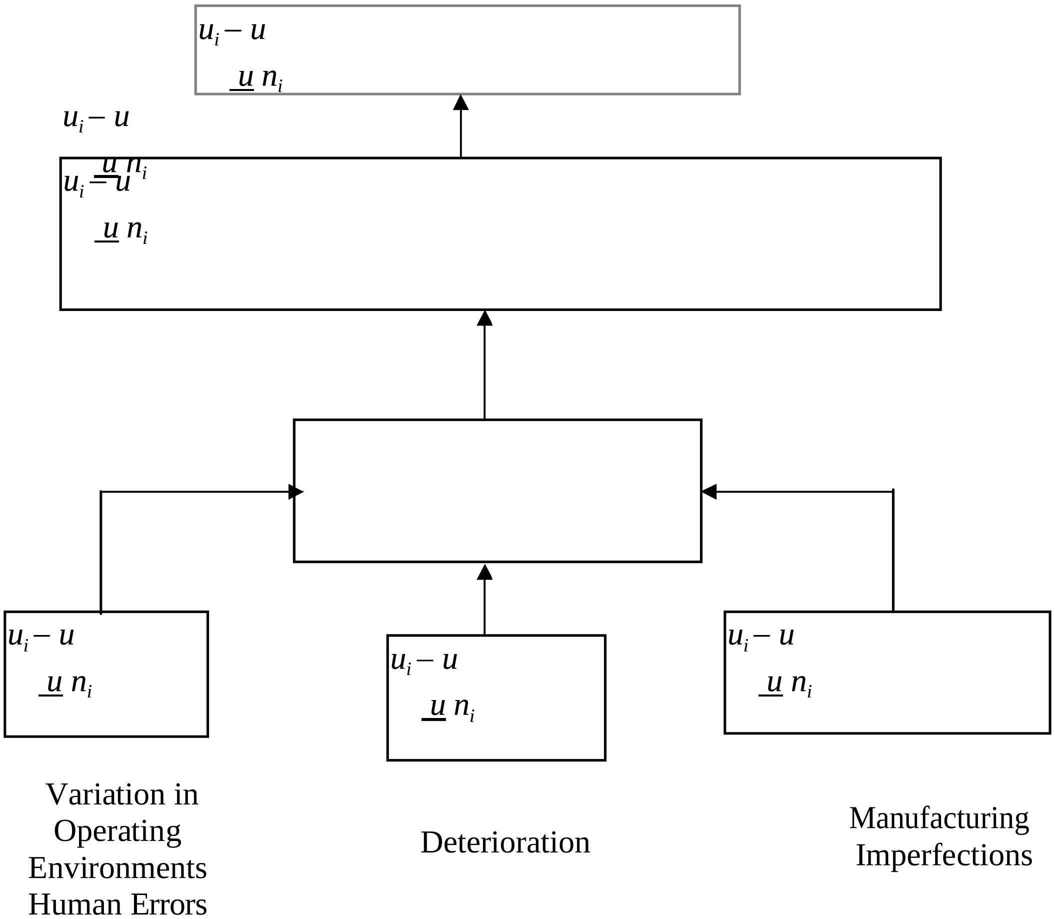
Control factors – these are any design parameters of a system that engineers can specify by nominal values and maintain cost effectively.

Noise factors – these are the variables that affect the system function and are either uncontrollable or too expensive to control.

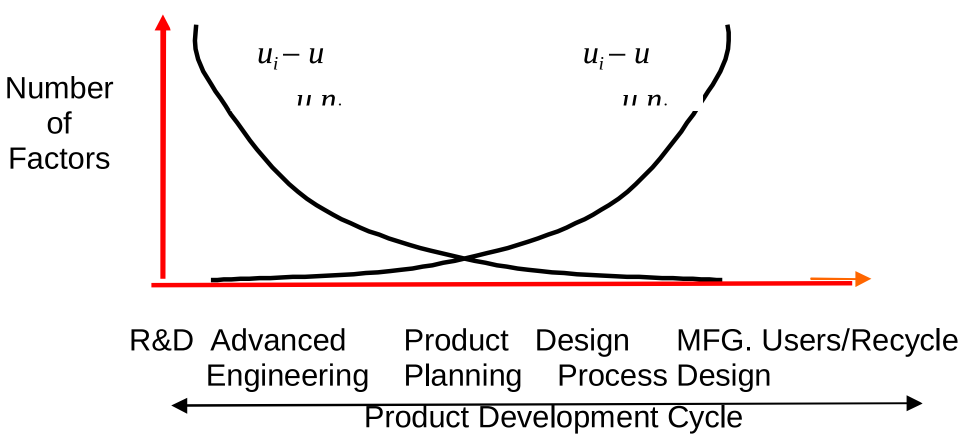
The Engineered System consists of four (4) components:

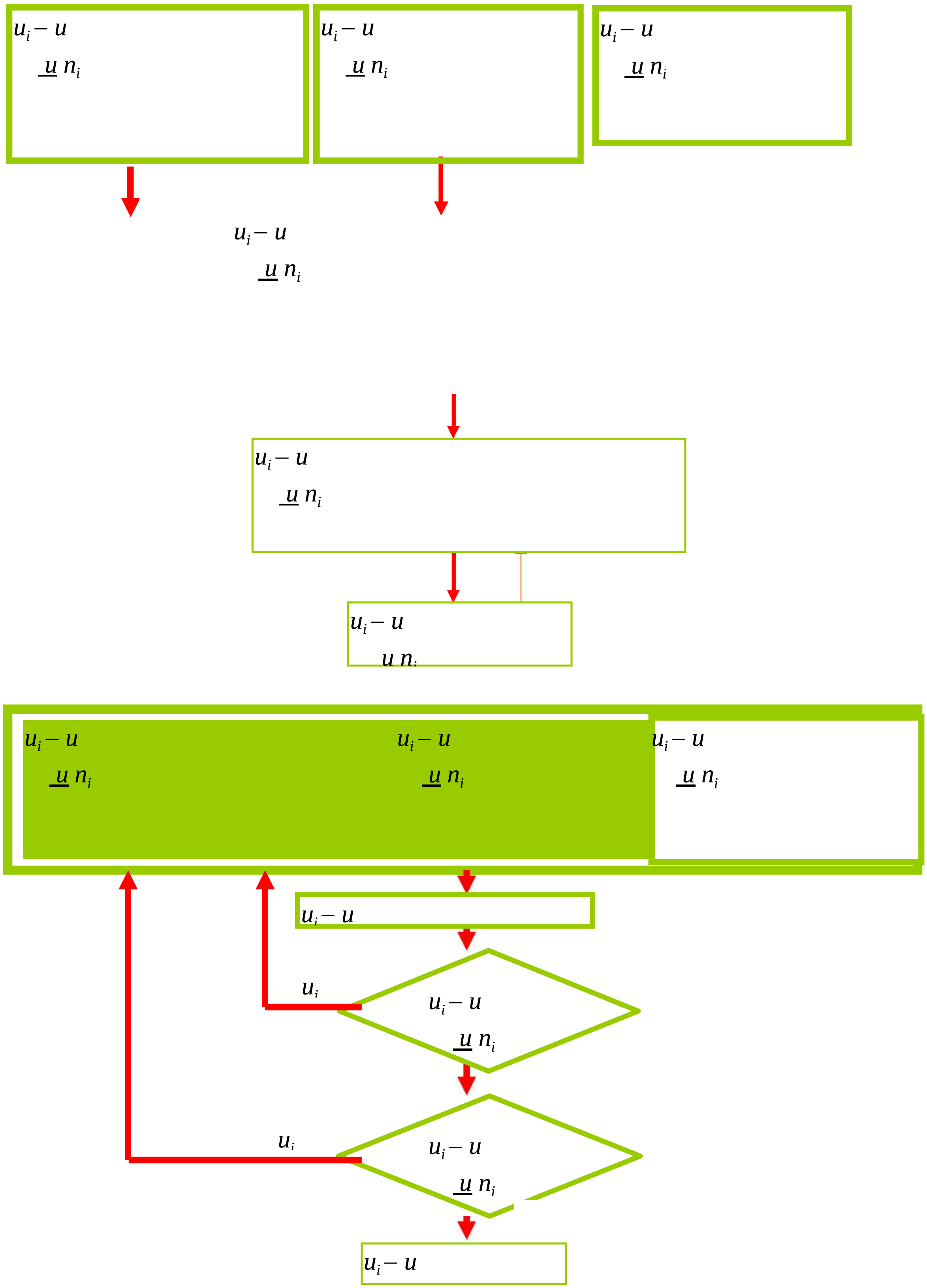


The Relationship Between Loss and Noise Factors



Relationship between Control Factors Vs Noise Factors is represented graphically below.





$u_i - u$
$u\ n_i$
$u_i - u$
$u\ n_i$
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$u\ n_i$
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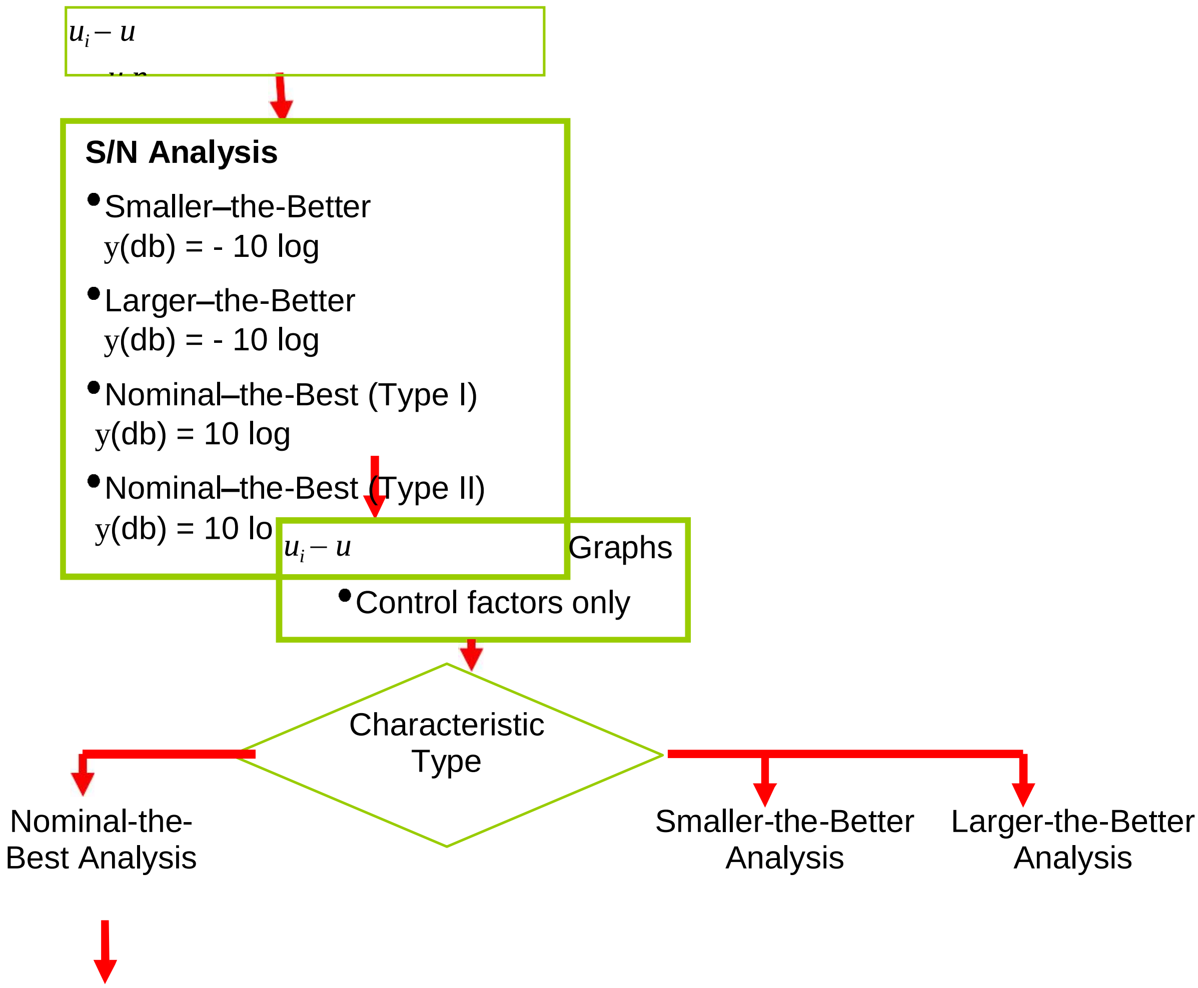


Six Sigma

Process Capability

It is a measure of the inherent uniformity of the process. Before examining the sources and causes of variation and their reduction we must measure the variation.

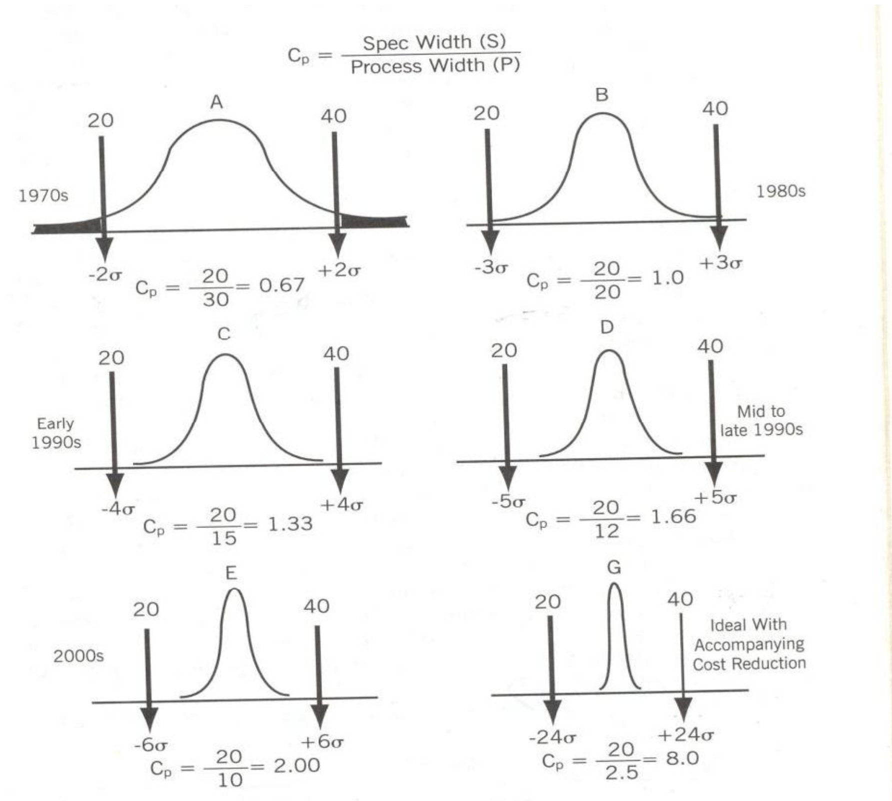
Yard-Sticks Of Process Control:

Cp - measuring capability of a process
Cpk - Capability of process, but corrected for non-centering

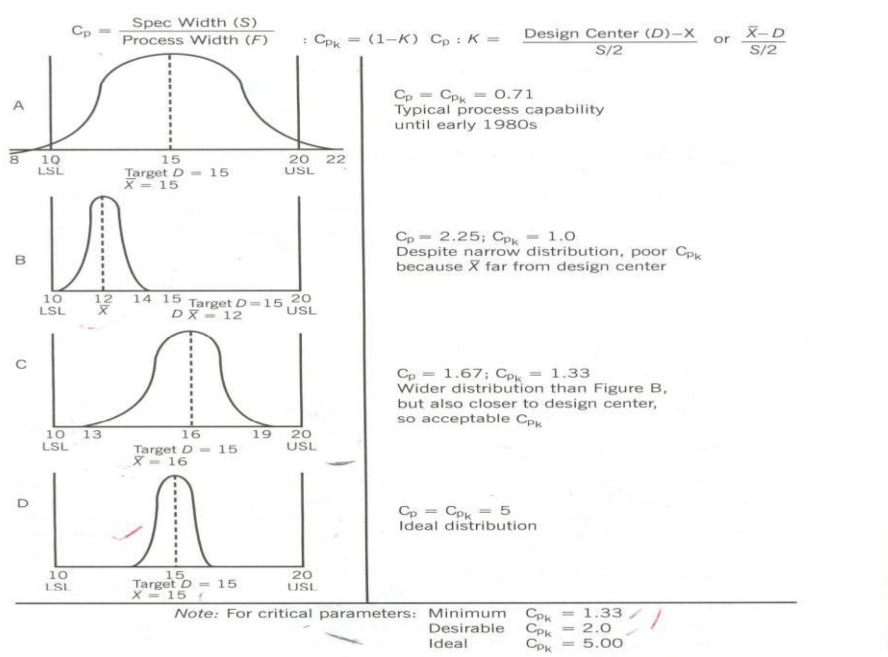
Process Capability Indices:

Cp is a measure of spread.
Cp = Specification (S) / Process width (P)
Cpk is a measure of centering the process and its spread.
Cpk is minimum of Cpu= (USL - μ) / 3σ and Cpl = (μ - LSL) / 3σ
The relationship between Cp and Cpk is Cpk = (1 – k) Cp

where :
k : Correction factor and is the minimum of
(T -μ) / S / 2 or (μ - T) / S / 2

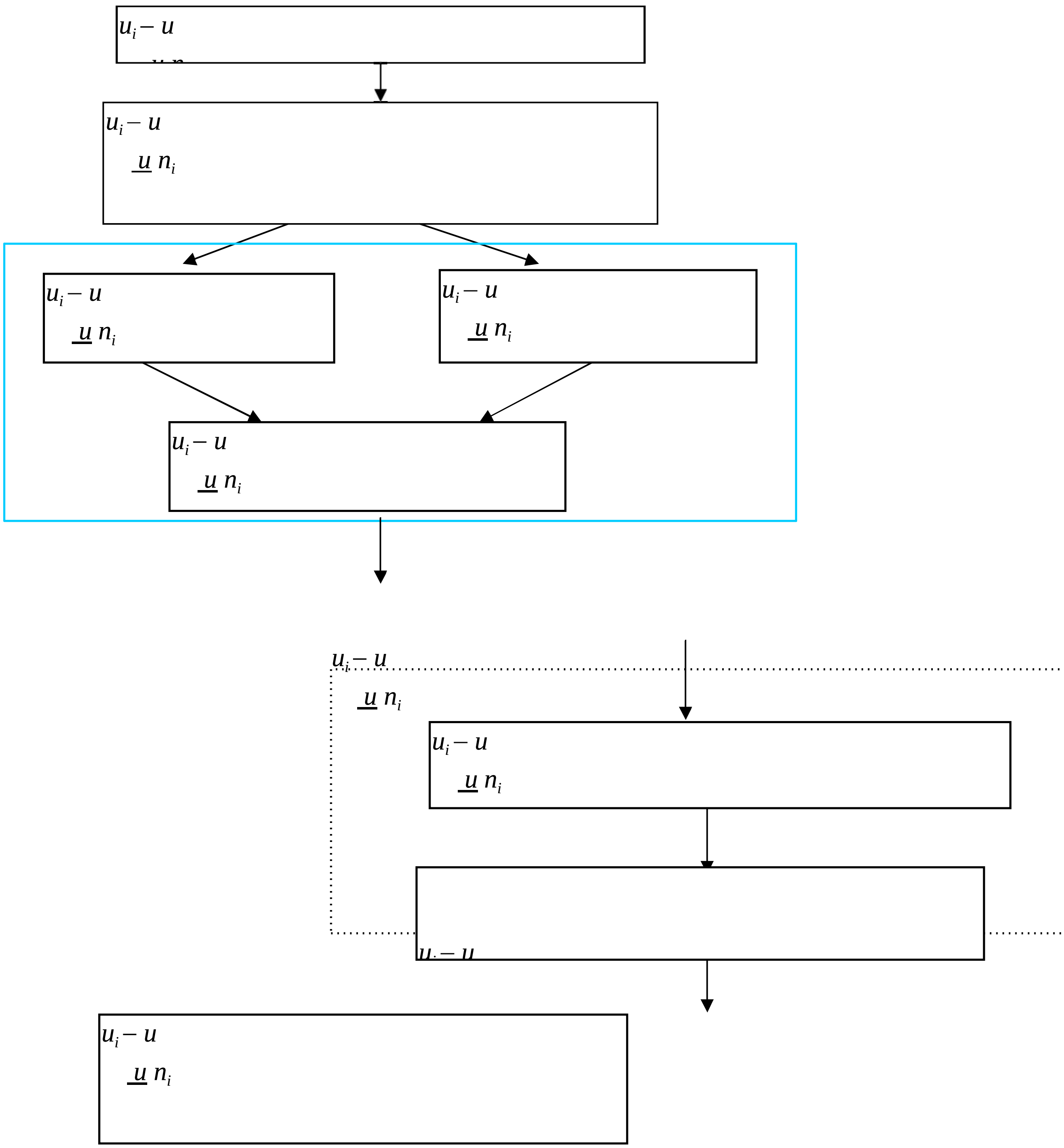


Cp - Measure of variation



Process Capability

Flow Chart Showing Stages Of Quality Engineering.



The Basic Steps In Parameter Design

1. Define project scope / objectives
   - Define project objectives
   - Identify the system or subsystems
   - Select team leader and members
   - Establish overall strategies

2. Identify Ideal Function / Response to be Measured
   - Establish intent, desired results
   - Define input signal and output response
   - Define ideal function.
   - Determine measurement feasibility

3. Develop Signal and Noise Factor Strategies
   - Define Signal levels and ranges.
   - Identify all noise factors
   - Select critical noise factors and set levels
   - Determine Noise Strategies.
4. Establish control factors and levels
   - Identify all control factors
   - Select critical control factors and set levels
   - Select orthogonal array
   - Assign control factors to orthogonal array

5. Control experiments
   - Plan / prepare for experiment
   - Conduct experiment
   - Collect data
6. Conduct data analysis
   - Calculate S/N ratios and þ’s
   - Complete /interpret response tables / graphs
   - Perform two step optimization
   - Make predictions.

7. Conduct confirmation run

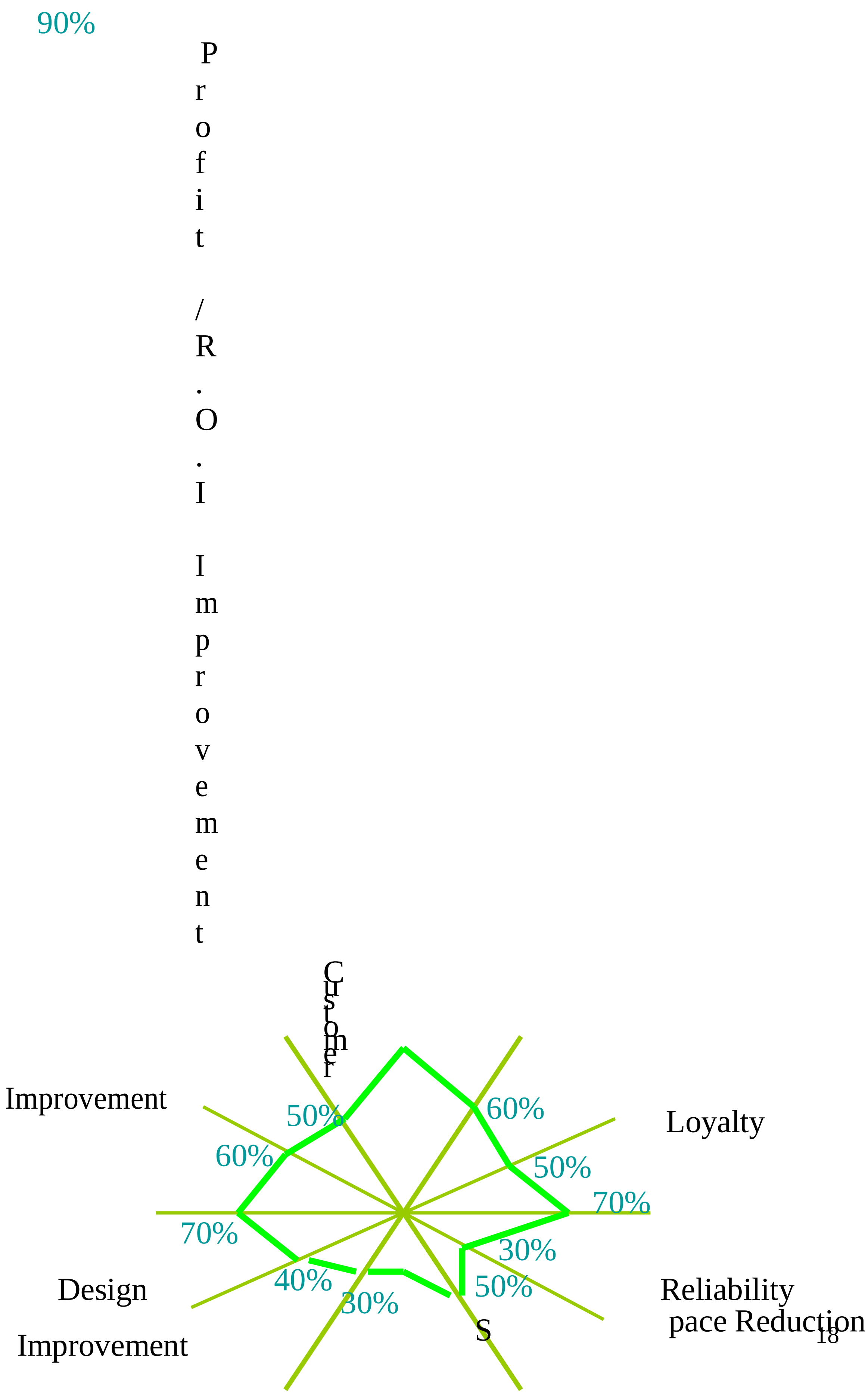
8. Implement and document results

Contributions of DOE to Business Excellence: A Spider Chart

Chronic
Problem Solving

Supp
lier

Employee
Morale


90%
Profit / R.O.I Improvement
Customer
Improvement
Loyalty
Design
Improvement
Reliability
S
pace Reduction
50%
60%
70%
40%
30%
50%
30%
70%
50%
60%

30%

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Applications of Computer based Robust Engineering

- Reduction of R&D cycle time using Simulation based Robust Engineering.
- Software testing and Algorithm Optimization.
- Design of Information Systems for Pattern Analysis.

Statistical Theory of Tolerances

Purpose of Specification .

A specification is a definition of a design. The design remains a concept in the mind of the designer until he define it through verbal description, sample, drawing, writing etc. It defines in advance what the manufacturer expects to make. It defines what the consumer can expect to get. The specification serves as an agreement between manufacturer and consumer on the nature of characteristics of the product.

It is helpful to recognize the distinction between a design specification and an inspection specification. The design specification deals with what is desired in a manufactured article, i.e. it deals with the specification function. In contrast, the inspection specification deals with means of judging whether what is desired is actually attained, in other words it deals with inspection function (quality of conformance).

Specifying the tolerance. It is practically impossible to manufacture one article exactly like another or one batch like another. Variability is one of the fundamental concepts of modern quality control. Therefore, the range of permissible difference in dimension have been standardized under the name limits. The limit of size for dimension or a part are two extreme permissible sizes for that dimension (high limit and low limit).

Design engineer have a tendency to specify tight tolerance for the following reason.

1. Lack of time. Tolerance are to be set up on many dimension, therefore, the designers may not have sufficient time to give much attention to tolerances on all dimension. Therefore, to be on the safer side the designers are tempted to specify much closer tolerance

2. The concept of factor of safety. Designers have been taught to allow for the unexpected or the unusual i.e. overloading of the machine, use of unintended purpose, change in the condition of use . The designers may assume more factor of safety to anticipate failure of conformance by the shop.

3. Setting tolerances assuming ideal conditions. Design engineering seems to specify tolerance with reference to some what idea l conditions, assuming good machine, well trained operators, skilled supervision and good working condition. Or they use reference tables which may tacitly assume such factor. In actual practice, nearly ideal condition may be obtained during some part of the process, but almost never for say, extended period of time.

4. Lack of knowledge of the production process. The designers may not have sufficient knowledge about the production process. Therefore, they may design the product with little or no critical consideration of the various production problems involved to meet the tolerance.

5. Lack of information about the process capability. In some case the designers do not have information regarding the production facilities available in the plant, their condition and process capability.

6. Lack of awareness of the quantitative effect of tolerance decision on factory economy

7. Tendency of shop personnel to loose up the tolerances. The design may be conscious of the difference between the blue print tolerance and those which are actually enforced. Therefore, in order to get what they think they need, they tend to specify loser tolerance then they believe necessary.

Definition:

It is not possible to manufacture each & every item identically. It is a customary to allow a certain variability in the measured quality characteristic called the tolerance. Generally in any industry design section specifies what is to be produced &sets the dimension & tolerance of the characteristic. The responsibility of the manufacturing dept, is to manufacture the items according to the specification laid down by the design department. The inspection dept. checks whether the product is meeting the specification given by the design dept, unless there is a proper co-ordination it is difficult to manufacture the item exactly.

while establishing the specification limits the fall pts must be considered

1. Functional utility of the product.
2. Capability of the product and process.
3. Inspection procedures.

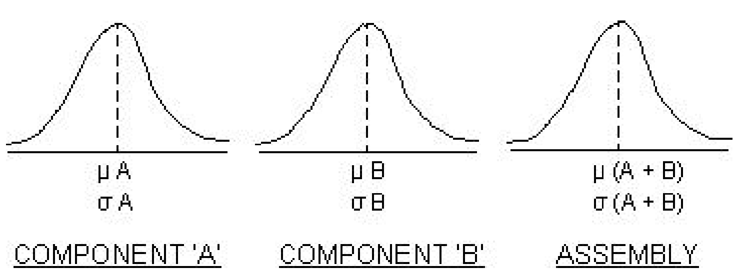
Tolerance spread: T = (U-L)

It is set by the engg. design section to design the mini & max values available for the product to work properly.

Theorems in statistical Tolerance

- **Addition theorem**

When the components are added together linearly



mean of the assembly = μ assembly = μ A + μ B

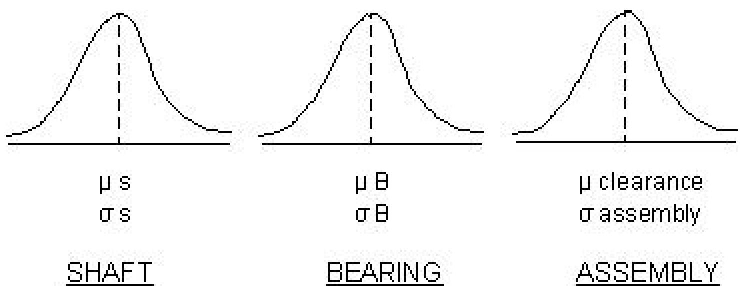
std deviation assembly = o assembly = $\sqrt{u_i - u}$

If n components are assembled together linearly, then the mean of the whole assembly = μ assembly = μ A + μ B + - - -μ n

std. deviation of assembly = o assembly = $\sqrt{u_i - u}$

1. <u>Difference theorem</u>

When the components are mating together, eg: shaft and the bearing.



μ clearance = $\mu_B - \mu_S$

σ combined assembly = $\sqrt{\sigma_B^{\,2} + \sigma_S^{\,2}}$

The combined tolerance of the assembly is T_C

$$T_C = \sqrt{T_A^{\,2} + T_B^{\,2} + - - -}$$

Assumption to be made for the above formula in statistical tolerance

1. The component dimension are independent of each other & are assembled randomly.
2. The component dimension must follow a normal distribution
3. A control chart has to be maintained for each of the component dimension / characteristic.
4. The actual average of each component is equal to the nominal value stated in the specification.

Conventional tolerance	Statistical tolerance
1. 100% of the interchangeability of the components is possible for assembly 2. The tolerance of the interacting dimension are smaller than the necessary.	1 . A small % of the assembly will fall outside the tolerance limit but this can be corrected with a selective assembly 2. This method permits a larger tolerance On the interacting dimension
3. No assumption are necessary 4. No special process control procedures are required	3. The interacting dimension must be independent of each other & each characteristic must follow a normal distribution 4. The process average of each components must be maintained at a nominal dimension value (target value)

Statistical Theory of Tolerances

Statistical Tolerance

Use of statistical method of tolerance can lead to economic production, when we are dealing with interacting dimensions. Interacting dimensions are those which mate or merge with other dimensions to create a final result.

A dimension of an assembled product may be the sum of the dimensions of several parts. Or an electrical resistance may be the sum of several electrical resistances of parts. Or a weight may be the sum of number of weights of parts. In such situations it is necessary to determine the relationship of the tolerances of the sum.

The statistical theory of tolerance results in larger component tolerances with no change in manufacturing process and no change in the assembly tolerance. Larger tolerances, increase the production

Output, minimize waste of material and productive effort and are generally responsible for reduction in manufacturing costs. This is the effect of statistical approach.

If an overall tolerance is fixed but not being met, then the problem is which component tolerances should be reduced to meet overall tolerance. The statistical theorem can help to determine which of the component tolerances have the greatest effect on the overall tolerances. This information, when coupled with economic considerations on achieving a smaller tolerance, can form basis for a decision.

A risk involved in the use of statistical theorem is that : it is possible that an assembly will result which falls outside of the assembly tolerance. However, the chance can be calculated and a judgment made on whether or not to accept risk. The probability that assembly length will fall outside the tolerance limits can be found out by analyzing the area under the normal curve for assembly lengths.

1. The component dimensions are independent and the components are assembled randomly.
2. Each component dimension should be normally distributed. Some departure from this assumption is permissible.
3. The actual average for each component is equal to the nominal value stated in the specification.

Problem 1.

Manufacturer A produces a metal piece the dimension of which is normally distributed with $\overline{X}'_A = 8.5cm$ & $\overline{R}_A = 0.004cm$ based on a subgroup size of 4. The manufacturer B produces a 2nd metal pieces which is also normally distributed with $\overline{X}'_B = 6.5cm$ & $\overline{R}_B = 0.005cm$ based on a subgroup size 9 of a company C purchases these 2 parts & assembles them together to obtain a combined dimension of 15 cm. What % of the combined assembly.
Would you expect to have the dimension is excess of 15.006 cm.

Solution :

$$\overline{X}'_A = 8.5cm \ \& \ \overline{R}_A = 0.004cm \qquad n_A = 4$$

$$\overline{X}'_B = 6.5cm \ \& \ \overline{R}_B = 0.005cm \qquad n_B = 9$$

from the table, for a subgroup size of 4, d2=2.059
from the table, for a subgroup size of 9, d2=2.97

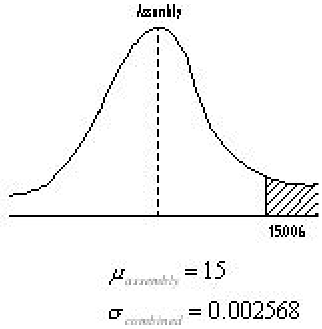
$$\sigma^1 = \frac{\overline{R}}{d_2} = \frac{0.004}{2.059} = 0.00194$$

$$\sigma^1 = \frac{\overline{R}}{d_2} = \frac{0.005}{2.97} = 0.001683$$

$$\sigma^1_{combined} = \sqrt{{\sigma^1_A}^2 + {\sigma^1_B}^2} = \sqrt{(0.00194)^2 + (0.001683)^2}$$

$$\sigma^1_{combined} = 0.002568$$

$$\mu_{assembly} = \mu_A + \mu_B$$
$$= \overline{X}^1{}_A + \overline{X}^1{}_B$$
$$= 8.5 + 6.5$$
$$\mu_{assembly} = 15\,cm$$



The % of assembled items which have dimensions in excess of 15.006 is

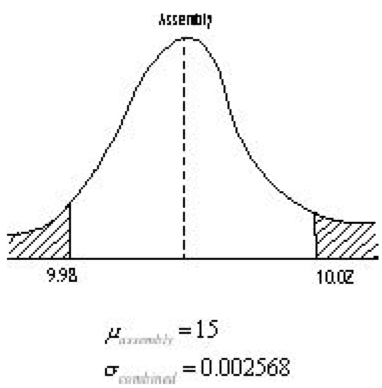
$$Z = \frac{x-\mu}{o} \rightarrow Z = \frac{x-\mu_c}{\sigma_C}$$

$$Z = \frac{15.006 - 15}{0.002568} = 2.33$$

The tables, for Z=2.33, the prob. Is 0.9901 *i.e.. 99.01%*

i.e. 100 -99.01 = 0.99%

There fore 0.99% assembled items will have dimensions more than 15.006.



Problem-2

Two Parts A&B are received in an assembly operation, where each part is permanently attached to the other . When the combined width of the parts dose not meet the specification of 10 ±0.02 the assembled product must be scrapped. If the width of the part **B** is normally distributed with $\overline{X}^1 = 6.5$ & $\sigma^1 = 0.012$ and the width of the part A is also normally distributed with $\overline{X}^1_A = 3.5$ & $\sigma^1_A = 0.008$

The assembly is at random. Determine the %of the assembled product that has to be scrapped

solution :

Specification = 10±0.02

USL = 10.02

LCL = 9.98

$$\overline{X}^1_A = 3.5 \ \& \ \sigma^1_A = 0.008$$

$$\overline{X}^1_B = 6.5 \ \& \ \sigma^1_B = 0.012$$

$$\sigma \ Combined = \sqrt{\sigma_A^{12} + \sigma_B^{12}} = \sqrt{(0.008)^2 + (0.012)^2}$$

$$= 0.01442$$

$$\mu \ combined = \overline{X}^1_A + \overline{X}_B$$

$$= 3.5 + 6.5$$

$$= 10$$

The % of assembled items below 9.98or scrap is

$$Z = \frac{x - \mu_C}{\sigma_C} = \frac{9.98 - 10}{0.01442} = -1.39$$

For Z= -1.39, the prob. From the tables is

0.0823

I e = 8.23%

Since it is symmetric, the % of items of that are scrapped (The scrap & rework) is

2x0.0823 = 0.1646

I.e. = 16.46%