UTM
UNIVERSITI TEKNOLOGI MALAYSIA
UTM Razak School of Engineering and Advanced Technology
RESEARCH UNIVERSITY

Robust Engineering Using Taguchi Method

6-7 April 2017

Prof Dr Sha'ri Mohd Yusof
Razak School of Engineering and Advanced Technology
shari@.utm.my

Off line Quality Control

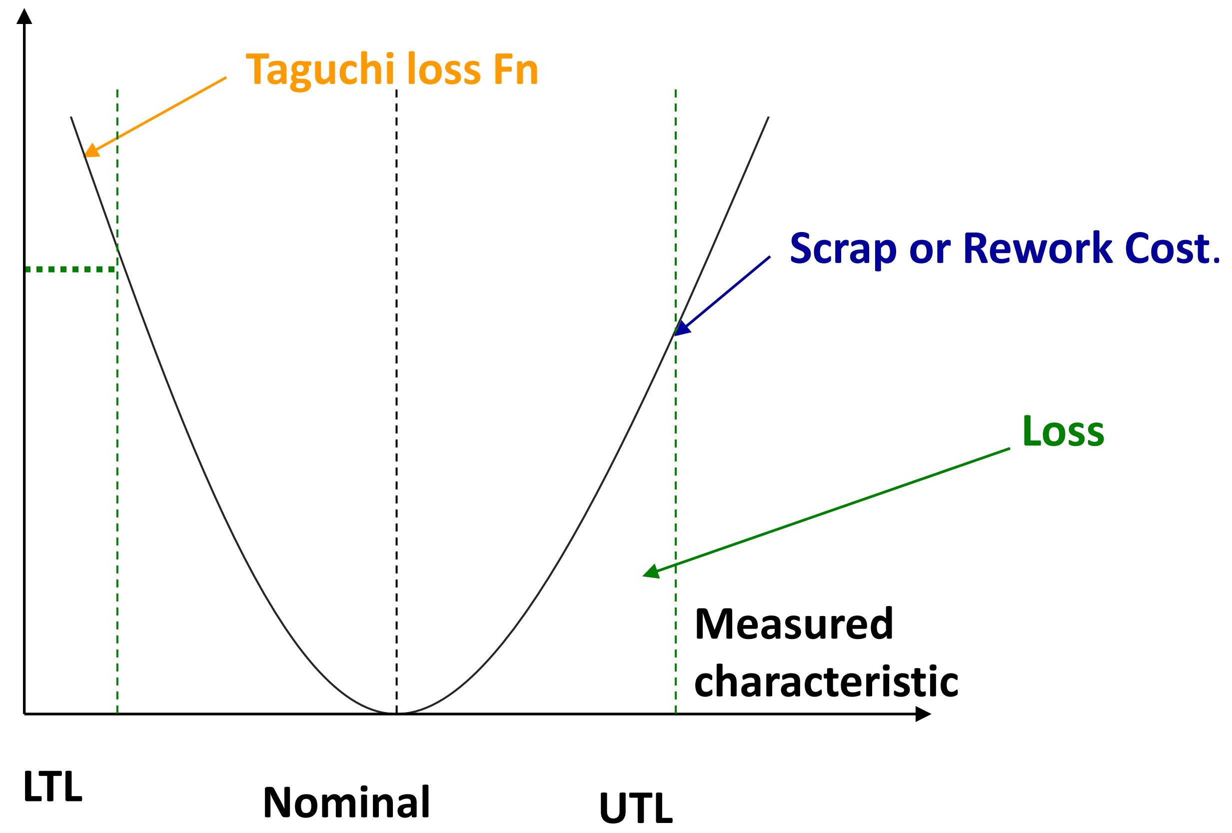
- Off line QE – essence of Taguchi approach for product and process improvement
- Off line – activities at the design stage versus on line – activities during manufacture e.g. SPC
- Need to design quality into product – Taguchi approach provide this

Principles in Taguchi Method

7 principles

- Quality of manufactured product can be quantified by the loss it imparts to society
- In competitive economy, quality improvement and cost reduction are necessary to stay in business
- A continuous quality improvement program should be based on incessant efforts to reduce the variation of product and process characteristics
- The loss due to variation is often proportional roughly to square of the deviation from the target
- The final quality and cost are determined largely by design of product and processes used in its manufacture
- The performance variations can often be reduced by exploiting the non-linear effects of parameters on performance
- Statistically planned experiments can be used to find parameter values that minimize variation of important characteristics

Taguchi’s U-shaped loss Function Curve



Taguchi’s method: Loss function..

Loss = $L(y) = L(m + (y-m))$

$$= L(m) + (y-m)\,L'(m)/1! + (y-m)^2\,L''(m)/2! + \dots$$

Ideally:

(a) $L(m) = 0$ [if actual size = target size, Loss = 0], and

(b) When $y = m$, the loss is at its minimum, therefore $L'(m) = 0$

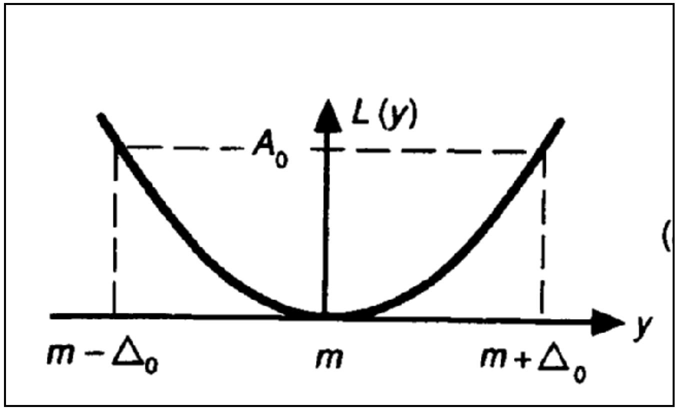
Taguchi’s Approximation: $L(y) \approx k(y-m)^2$

Variation of the Quadratic Loss Function

1) *Nominal the best type*:

Whenever the quality characteristic y has a finite target value, usually nonzero, and the quality loss is symmetric on the either side of the target, such quality characteristic called *nominal-the-best type*. This is given by equation

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



Nominal-the-best

Example: Color density of a television set and the out put voltage of a power supply circuit.

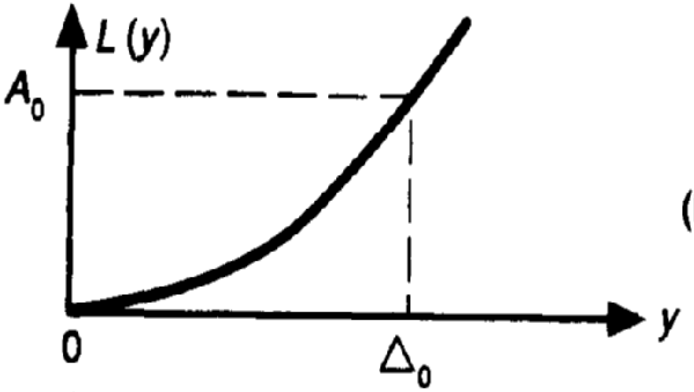
***2)Smaller-the-better type*:** Some characteristic, such as radiation leakage from a microwave oven, can never take negative values. Also, their ideal value is equal to zero, and as their value increases, the performance becomes progressively worse. Such characteristic are called smaller-the-better type quality characteristics.

Examples: The response time of a computer, leakage current in electronic circuits, and pollution from an automobile.

In this case **m** = 0

$L(y) = ky^2$

This is one side loss function because y cannot take negative values.



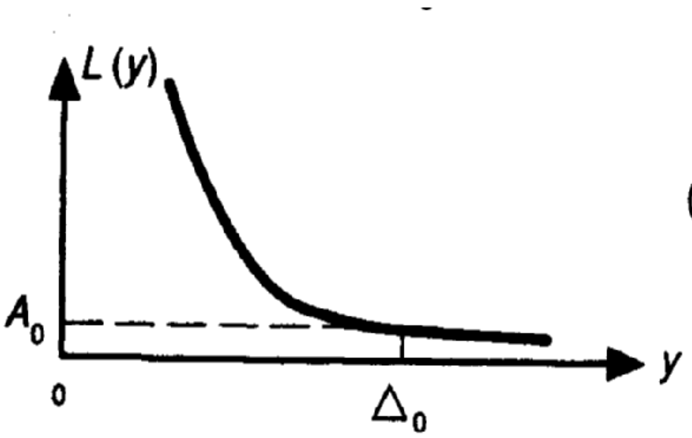
(b) Smaller-the-better

3)Larger-the-better type: Some characteristics do not take negative values. But, zero is there worst value, and as their value becomes larger, the performance becomes progressively better-that is, the quality loss becomes progressively smaller. ,, also Their ideal value is infinity and at that point the loss is zero. Such characteristics are called larger-the-better type characteristics.

Example: Such as the bond strength of adhesives.

Thus we approximate the loss function for a larger-the-better type characteristic by substituting 1/y for y in

$$L(y) = k [1/y^2]$$



(c) Larger-the-better

Aspects of Design

- System design – consists of applying scientific and engineering knowledge to produce basic functional design, initial choice of design parameters to give required product characteristics in terms of performance, manufacturability , etc

Parameter Design

- Parameter design – the process of finding the values of the design parameters that reduce the sensitivity of the product or process to fluctuations of factors outside control of user
- Uncontrollable factors = noise
- Internal noise – aspects internal to and inherent in product or process
- External noise – factors due to uncontrollable aspects of environment, materials, operators

Parameter Design

- Involves determining the specification for product and process parameters in terms of nominal values so that final product will be less sensitive to sources of variation caused by environmental factors, product deterioration, and manufacturing variation

Parameter Design

- Environmental factors – conditions in the environment in which product will be used by customer, including human variation in operating the product,
- Product deterioration – changes in product parameters over time from wear and tear on product during its life cycle
- Manufacturing variations – conditions that cause production of product that deviates from its nominal value

- Tolerance design – optimal allocation of manufacturing tolerances to minimize societal loss due to product or process

Experimentation for Design Improvement - Terminologies

- **Factor** – Some property of product or process suspected having some influence on its response
  - can be measurable (pressure, temperature, etc)
  - Indicator (different material suppliers, presence or absence of some attribute in design)
  - Control factors = can be adjusted by experimenter
  - Noise factors = cannot control, vary routinely during use of product or in manufacture of product (processes)
  - Environment (ambient temp, humidity), aging, etc.

Experimentation for Design Improvement - Terminologies

- **Level** – the value taken by a factor. Choice of experimental levels up to experimenter. Simplest 2 levels for each factor
- Presence or absent of indicators = no choice but 2 levels
- Conventionally, level 1 assigned for numerically lower value and level 2 for next highest
- For indicator = level 1 is absent and level 2 = presence

Experimentation for Design Improvement - Terminologies

- **Response** = outcome of the particular combination of levels of factor
- **Effect** = the change in expected response due to unit change in value of a factor from its mean value

One factor at a time (OFAT) versus 'All together experiment'

- OFAT – change one variable others constant = inefficient
- A simple example of 3 factors each at 2 levels
- A casting process

Factor	Level 1	Level 2
A – Mould Temp	A1 = 500 ^{0}C	A2 = 600 ^{0}C
B – Melt temp	B1 = 1350 ^{0}C	B2 = 1450 ^{0}C
C - Additive	C1 = No additive	C2 = Additive Present

- Response of resulting casting is scale 0 (good) – 100 (bad)

OFAT

- Expt No 1 – A1 B1 C1 (base level)
- Expt No 2 – A2 B1 C1 (change A to get effect of this factor)
- Expt No 3 – A1 B2 C1 (chang get effect)
- Expt No 4 – A1 B1 C2 (ch to give C effect)

UNBALANCED or NOT ORTHOGONAL

	A1		**A2**	
	B1		**B1**	**B2**
C1	**Expt**	**pt 3**	**Expt 2**	
C2	**Ex**			

Full factorial Design

Factor	A	B	C
1	1	1	1
2	1	1	2
3	1	2	1
4	1	2	2
5	2	1	1
6	2	1	2
7	2	2	1
8	2	2	2

Each level of factor occur same number of time

Each factor has 4 trials at each level = same amount of info

DISADVANTAGE 2x number of expts compared with OFAT - overcome use Fractional

Balanced design or Orthogonal

	A1		A2	
	B1	**B2**	**B1**	**B2**
C1	[1]	[3]	[5]	[7]
C2	[2]	[4]	[6]	[8]

Design Grid for Full factorial

Fractional factorial Design

- Fractional factorial – less experiments (4) and maintain orthogonality of experimental design

	A	B	C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

	A1		**A2**	
	B1	**B2**	**B1**	**B2**
C1	**[1]**			**[4]**
C2		**[2]**	**[3]**	

Example

- Consider Full factorial for the casting experiment with porosity score at each combination of factors shown below
- 3 factors at 2 levels (2^3)
- Response of resulting casting is scale 0 (good) – 100 (bad)

Factor	Level 1	Level 2
A – Mould Temp	A1 = 500 ^{0}C	A2 = 600 ^{0}C
B – Melt temp	B1 = 1350 ^{0}C	B2 = 1450 ^{0}C
C - Additive	C1 = No additive	C2 = Additive Present

	A1		**A2**	
	B1	**B2**	**B1**	**B2**
C1	61	75	67	79
C2	52	87	59	90

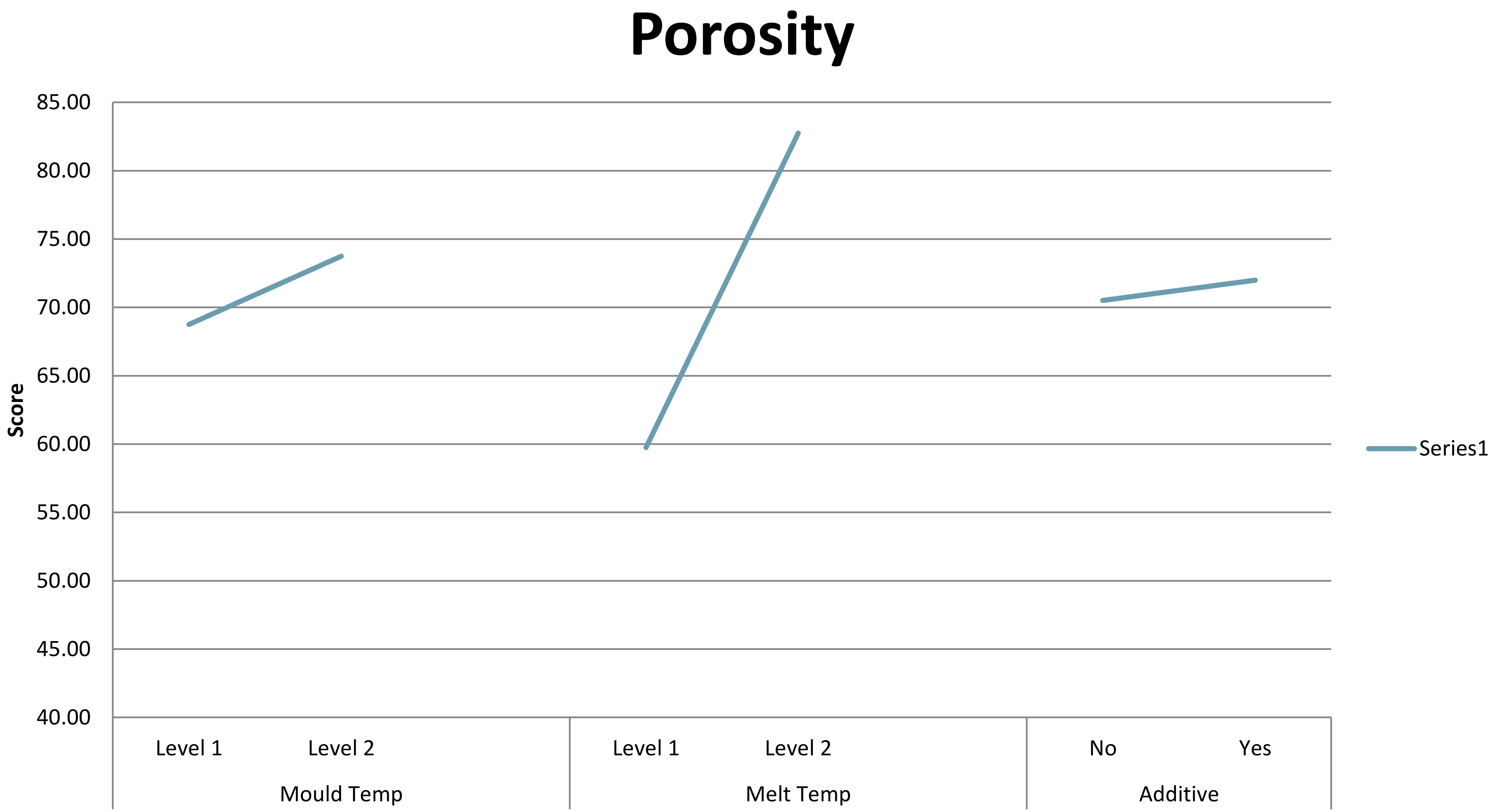
Analysis

Avg of results A at Level 1 = (61+52+75+87)/4 =68.75
Avg of results A at level 2 = (67+79+59+90)/4 = 73.75

Effect raising A from level 1 to level 2 = 73.75-68.75=5.0
Similarly for B – Effect is 82.75-59.75 = 23.0
and C- Effect is 72.0-70.50 = 1.5

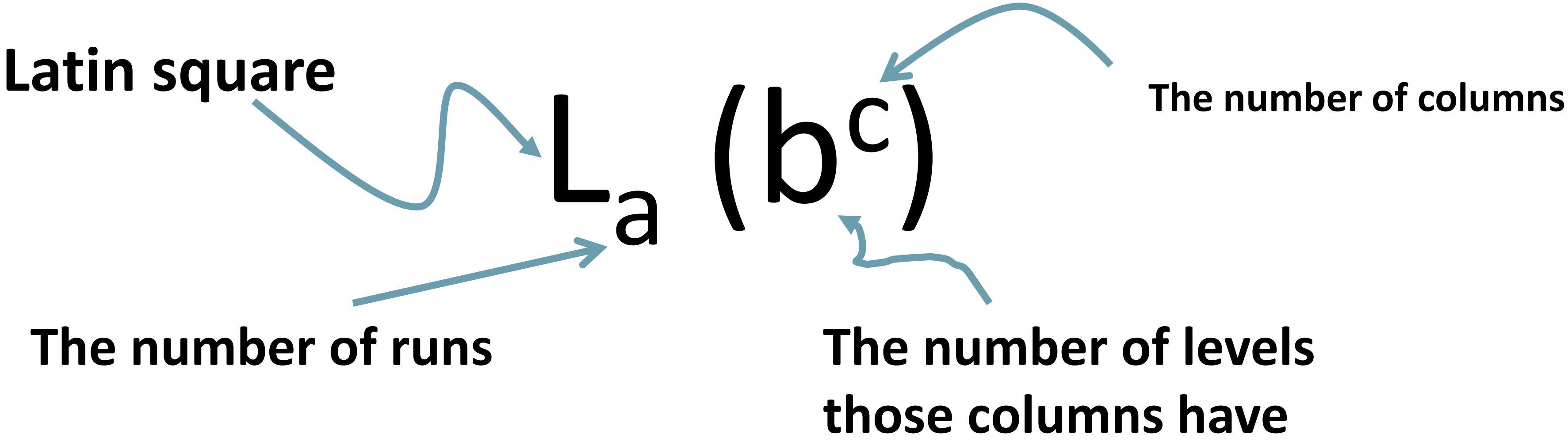
Evident that there is strong positive B effect, and comparatively minor A and C effect (could purely be from random error due to noise factors not included in the experiment). Use of Analysis of Variance not useful in small scale experiment such as this. Useful to show effects graphically – response diagram/graph.

Response Graphs



Orthogonal Arrays

- In Taguchi presentation of designs, rather than using Design Grid, he uses Orthogonal Array = another way of presenting exactly same info .
- Array denoted as Lk, where k = no of experimental combinations of factors



Latin square

$$L_a\ (b^c)$$

The number of columns

The number of runs

The number of levels those columns have

Selecting OA

Total #of Factors	**# of 2-level**	**# of 3-level**	**# of 6-level**	**Orthogonal Array**
Up to 8	1	7	--	**L_{18} $(2^1 \times 3^7)$**
Up to 7	---	6	1	**L_{18} $(6^1 \times 3^6)$**
Up to 23	11	12	--	**L_{36} $(2^{11} \times 3^{12})$**
Up to 26	1	25	--	**L_{54} $(2^1 \times 3^{25})$**
Up to 11	11	--	--	**L_{12} (2^{11})**

Example:
L_{18} $(2^1 \times 3^7)$ consists of one 2-level column and seven 3-level columns with 18 runs

Orthogonal Arrays

Recommended For Robust Design Optimization

- L_{12} (2^{11})
- L_{18} $(2^1 \times 3^7)$
- L_{18} $(6^1 \times 3^6)$
- L_{36} $(2^{11} \times 3^{12})$
- L_{54} $(2^1 \times 3^{25})$

Power of Two Series

- L_4 (2^3)
- L_8 (2^7)
- L_{16} (2^{15})
- L_{32} (2^{31})
- L_{64} (2^{63})

Power of Three Series

- L_9 (3^4)
- L_{27} (3^{13})
- L_{81} (3^{40})

2^n Series Orthogonal Array

L_4 (2^3) Orthogonal Array

No	**1**	**2**	**3**
1	1	1	1
2	1	1	2
3	1	2	2
4	1	2	1

L_8 (2^7) Orthogonal Array

No	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Orthogonal Array L8 Design

Column/ Factor	A	B	C	D	E	F	G
Expt							
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

2^n Series Orthogonal Array

L_4 (2^3) Orthogonal Array

No	1	2	3
1	1	1	1
2	1	1	2
3	1	2	2
4	1	2	1

L_8 (2^7) Orthogonal Array

No	1	2	3	4	5	6	7
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Exercise: Control Factor Assignment to an Orthogonal Array

Objective: To practice how factors can be assigned in OA

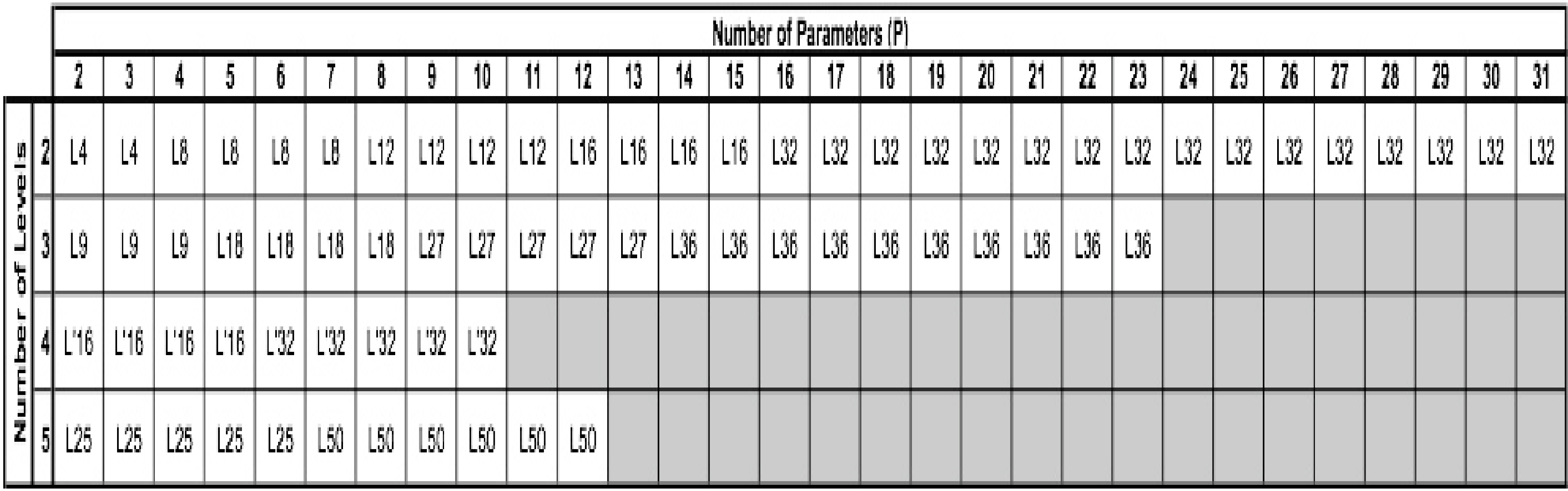
Task : Assign the following situations to an Orthogonal Array.
Specify an OA and explain how factors are assigned

1. 2 level factor: A, B, C, D, E, F, G, H, I ____________________
2. 2-level factor: A, B, C
   3-level factor: D,E
   4-level factor: F ______________________________________
3. 5-level factor: A
   3-level factor: B,C,D,E,F
   2-level factor: G, H ____________________________________
4. 3-level factor: A,B,C,D,E,F,G,H,I,J,K
   L,M,N,O,P,Q,R,S,T,U,V ____________________

Determining Orthogonal Array

- Determining what levels of a variable requires in-depth understanding of the process, including the minimum, maximum, and current value of the factor/parameter.
- If difference between the min and max is large, values can be further apart or more values can be tested. If small, then less values can be tested or the values tested can be closer together.
- Example, if the temperature of a reactor jacket can vary between 20 and 80 degrees C and it is known that the current operating jacket temperature is 50 degrees C, three levels might be chosen at 20, 50, and 80 degrees C.
- Once factors and levels determined, the proper orthogonal array can be selected. Using the array selector table shown below, appropriate array can be found by looking at the column and row corresponding to the factors and number of levels
- Arrays created using algorithm Taguchi developed, and allows for each variable and setting to be tested equally. For example, if we have three factors (voltage, temperature, pressure) and two levels (high, low), it can be seen the proper array is L4.

Determining Orthogonal Array



		Number of Parameters (P)																													
		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Number of Levels	2	L4	L4	L8	L8	L8	L8	L12	L12	L12	L12	L16	L16	L16	L16	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32
	3	L9	L9	L9	L18	L18	L18	L18	L27	L27	L27	L27	L27	L36	L36	L36	L36	L36	L36	L36	L36	L36	L36								
	4	L'16	L'16	L'16	L'16	L'32	L'32	L'32	L'32	L'32																					
	5	L25	L25	L25	L25	L25	L50	L50	L50	L50	L50	L50																			

Optimization for Non-dynamic response

- Optimization for Non-dynamic response
  - Nominal-the-best Type 1
  - Nominal-the-best Type 2
  - Smaller-the-better
  - Larger-the-better
  - Classified attribute
  - Operating window

Non-dynamic Response

To gain knowledge on how to apply steps, tools, and analysis techniques for Robust Design Optimization in a project involving Non-dynamic Response Situation

Same Eight Steps:

1. Define Scope for Optimization
2. Identify Response
3. Develop Noise Strategy
4. Establish Control Factors and Levels
5. Execute and Collect Data
6. Conduct Data Analysis
7. Predict and Confirm
8. Document and go to Tolerance Design/Verify

Non-dynamic Response

- Nominal-the-best Type 1
- Nominal-the-best Type 2
- Smaller-the-better
- Larger-the-better
- Classified attribute
- Operating window

Nominal-the Best Type 1 vs. Type 2

	Nominal-the –Best Type-1	Nominal-the-Best Type-2
S/N	$S/N = 10\log\frac{\bar{y}^2}{\sigma_{n-1}^2}$	$S/N = 10\log\frac{1}{\sigma_{n-1}^2}$
Variability Assessment	±%	± Absolute Units
Example	Non-negative response Work done Energy transformed/produced Power generated Displacement Velocity Force RPM Δ Temperature Luminance Weight Money	Response that take minus variance Misalignment Clearance Tolerance Stack-up response Temperature in C Temperature in F Typically non-energy response

Energy thinking

Very symptomatic

Nominal-the-best Type 2 Responses

- Example: y= clearance between automobile door and its body
- It is recommended to avoid this type of response for Robust Optimization
- Approach to improve variability
  1. Reduce variability of components dimensions (most essential)
  2. Adjustment of subassemblies (up stream compensation)
  3. Selective or Matching Assembly (compensation at assembly)
  4. Adjustment/rework after assembly so called ‘Door fitting’ (Compensation after assembly)

$$S/N = 10\log\frac{\overline{y}^2}{\sigma_{noise}^2}$$

S/N for NTB Type-1Response

$$S/N = 10\log\frac{1}{\sigma_{noise}^2}$$

S/N for NTB Type-2 Response

Differences in the S/N Ratios

- S/N for Nominal-the-Best Type 1 measures variability in +/- % around the mean
- σ measures "variability' in +/- absolute units around the mean
- When evaluating "variability" of function that is nominal-the-best and always work (energy) related, it is better to use Type 1

Illustrative Examples of how Mean, Sigma and S/N Types 1 and 2 vary with variation in data

	Data			Mean	σ	%	S/N Type 1	S/N Type 2
A1	9	10	11	10.0	1.0	10.00%	20.0	0.0
A2	90	100	110	100.0	10.0	10.00%	20.0	-20.0
A3	99	100	101	100.0	1.0	1.0%	40.0	0.0
A4	900	1000	1100	1000.0	100.0	10.00%	20.0	-40.0
A5	990	1000	1010	1000.0	10.0	1.0%	40.0	-20.0
A6	999	1000	1001	1000.0	1.0	0.10%	60.0	0.0
A7	9.9	10.0	10.1	10.0	0.1	1.00%	40.0	20.0
A8	99.9	100.0	100.1	100.0	0.1	0.10%	60.0	20.0
A9	999.9	1000.0	1000.1	1000.0	0.1	0.01%	80.0	20.0

Smaller-the-better Responses

- Smaller-the-better- Responses are non-negative responses that have an ideal value of zero. Closer to zero means higher quality
- Examples
  - Wear
  - Seal leakage
  - % Defective
  - Failure Rate

S/N for STB Response

$$S/N = \eta = 10\log\frac{1}{\frac{1}{n}\sum_{i=1}^{n} y_i^2} = 10\log\frac{1}{\bar{y}^2 + \sigma^2}$$

Larger-the-better Responses

- Larger-the=better Responses have a goal of the largest possible value. Infinity would be ideal
- Examples :
  - Strength (Tensile, Pull, etc)
  - Reliability Measures (MTTF,MTBF, etc)
  - Pressure to leak

S/N for LTB Response

$$S / N = \eta = 10 \log \frac{1}{\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2}}$$

Classified Attribute Response

- Classified attribute response are used when product/process output can be measured on a continuous scale. Subjective judgment is used to classify performance
- Examples :
  - Go/No-go
  - Appearance (Good/Normal/Bad)
  - Visual standards (A/B/C/D)
  - Evaluation by Jury
  - OK/NG

Define a Scoring system →

$$y = \begin{cases} 1 \text{ if 'excellent'} \\ 2 \text{ if 'Good'} \\ 3 \text{ if 'Fair'} \\ 4 \text{ if 'Poor'} \\ 5 \text{ if 'Severely poor'} \end{cases}$$

Use Classified Attribute response ONLY when no appropriate measurement is available . Measurements are always more desirable and accurate

The Operating Window Concept

The operating window concept enlarges the ‘window’ of operation for the response being measured, to reduce the occurrence of excessive energy failure mode and insufficient energy failure mode.

This method enlarges the window of operation by treating one threshold as Smaller-the-better (X) and the other as Larger-the-Better (Z). The concept was developed by Dr Don Clausing, formerly of Xerox and MIT

Example: In a welding operation, two types of failure modes, **“no weld”** condition and **“burn through”** result from either too little current or too much current. Using the operating Window method, the experimenter treats X = the threshold needed to make the weld as a **Small-the-Better** response, and Z = the threshold to burn through as the **Larger-the-Better** response

S/N for OW Response

$$S/N = \eta_{db} = 10\log \frac{1}{\frac{1}{n^2}\left[\left(\sum x_i^2\right)\left(\sum \frac{1}{z_i^2}\right)\right]}$$

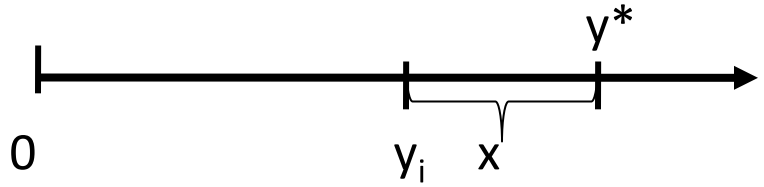
Note on Larger-the-Better Response

Signal-to-Noise Ratio for Larger-the-Better assumes response can become infinity. In many cases, this assumption is questionable because there exists a physical or theoretical limitation. Taguchi recommended to use following approaches.

a) Let y be the Nominal-the-Best Type 1 and while applying two step optimization, give more priority to maximize its mean

b) Let y^* be the physical/theoretical limitation. Let

$$X = y^* - y$$



Then treat x as a Smaller-the-Better response

Exercise: Response Types

	Responses	Type	Pros cons /effectiveness
a.	Failure rate for		
a1.	Misfeed		
a2.	Multifeed		
a3.	Paper Jam		
a4.	Delay feed		
a5.	Partial feed		
b	MTBF for above failure mode		
c.	Overall MTBF		
d.	Paper Skew		
e.	Degree of Paper Damage		
f.	Down Time		
g.	Up Time		
h.	Success Rate		
i.	Paper Velocity		
j.	Paper Arrival Time		
k.	Friction between Feed Roller and Top Sheet		
l.	Ratio of f1/f2; f1=friction between roller and top sheet, f2=friction between top sheet and 2nd sheet		
m.	Paper feed rate		

Calculate S/N Ratio

- Calculation for n data , y_1 , y_2,y_3...... y_n =

$$\overline{y} = \frac{y_1 + y_2 + y_3 + \ldots\ldots y_n}{n}$$

$$\sigma_{n-1}^2 = \frac{\sum_{i-1}^{n} (y_i - \overline{y})^2}{n-1} = \frac{(y_1 - \overline{y})^2 + (y_2 - \overline{y})^2 + \ldots.(y_n - \overline{y})^2}{n-1}$$

$$S/N = 10 \log \frac{\overline{y}^2}{\sigma_{noise}^2}$$

L18 Tile Manufacturing Case Study Analysis S/N Ratio

	A	B	C	D	E	F	G	H										
	1	2	3	4	5	6	7	8	P1	P2	P3	P4	P5	P6	P7	Sigma	Mean	S/N
1	1	1	1	1	1	1	1	1	10.18	10.18	10.12	10.06	10.02	9.98	10.20	0.087	10.11	41.31
2	1	1	2	2	2	2	2	2	10.03	10.01	9.98	9.96	9.91	9.89	10.12	0.078	9.99	42.19
3	1	1	3	3	3	3	3	3	9.81	9.78	9.74	9.74	9.71	9.68	9.87	0.064	9.76	43.65
4	1	2	1	1	2	2	3	3	10.09	10.08	10.07	9.99	9.92	9.88	10.14	0.096	10.02	40.34
5	1	2	2	2	3	3	1	1	10.06	10.05	10.05	9.89	9.85	9.78	10.12	0.129	9.97	37.74
6	1	2	3	3	1	1	2	2	10.20	10.19	10.18	10.17	10.14	10.13	10.22	0.032	10.18	50.03
7	1	3	1	2	1	3	2	3	9.91	9.88	9.88	9.84	9.82	9.80	9.93	0.048	9.87	46.34
8	1	3	2	3	2	1	3	1	10.32	10.28	10.25	10.20	10.18	10.18	10.36	0.071	10.25	43.21
9	1	3	3	1	3	2	1	2	10.04	10.02	10.01	9.98	9.95	9.89	10.11	0.070	10.00	43.13
10	2	1	1	3	3	2	2	1	10.00	9.98	9.93	9.80	9.77	9.70	10.15	0.156	9.90	36.04
11	2	1	2	1	1	3	3	2	9.97	9.97	9.91	9.88	9.87	9.85	10.05	0.071	9.93	42.88
12	2	1	3	2	2	1	1	3	10.06	9.94	9.90	9.88	9.80	9.72	10.12	0.139	9.92	37.05
13	2	2	1	2	3	1	3	2	10.15	10.08	10.04	9.98	9.91	9.90	10.22	0.120	10.04	38.46
14	2	2	2	3	1	2	1	3	9.91	9.87	9.86	9.87	9.85	9.80	10.02	0.069	9.88	43.15
15	2	2	3	1	2	3	2	1	10.02	10.00	9.95	9.92	9.78	9.71	10.06	0.129	9.92	37.69
16	**2**	**3**	**1**	**3**	**2**	**3**	**1**	**2**	10.08	10.00	9.99	9.95	9.92	9.85	10.14	0.097	9.99	40.23
17	**2**	**3**	**2**	**1**	**3**	**1**	**2**	**3**	10.07	10.02	9.89	9.89	9.85	9.76	10.19	0.147	9.95	36.60
18	**2**	**3**	**3**	**2**	**1**	**2**	**3**	**1**	10.10	10.08	10.05	9.99	9.97	9.95	10.12	0.067	10.04	43.48
																Avg	9.98	41.31

Helicopter Project

- You are a team of design engineers from Paper Helicopters Corporation, and it is your job to investigate the effects of relevant factors on the flight times of paper helicopters from ceiling to floor in a standard room.
- The diagram below shows the design of the standard helicopter and factors you might like to consider include paper type, wing length, body length, body width, fastening a paper clip to the body, etc.
- Design a suitable experiment, collect the data and report your findings.

Model of a Paper Helicopter Design