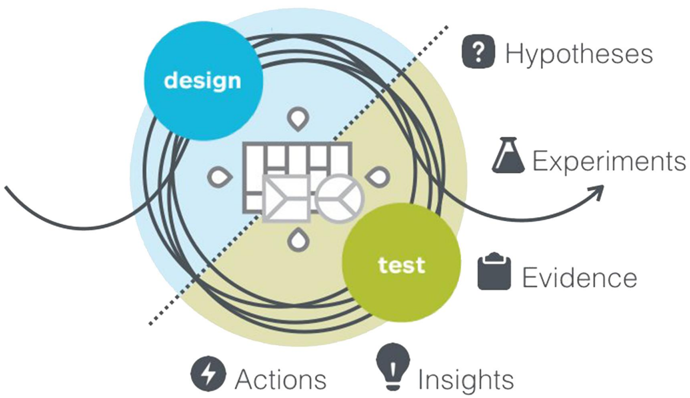



3 Days Online Workshop on

# Design of Experiments- An Engineering Perspective

**22, 23 & 24th April 2020**

**jaeronline.com/doeworkshop**

ORGANISED BY

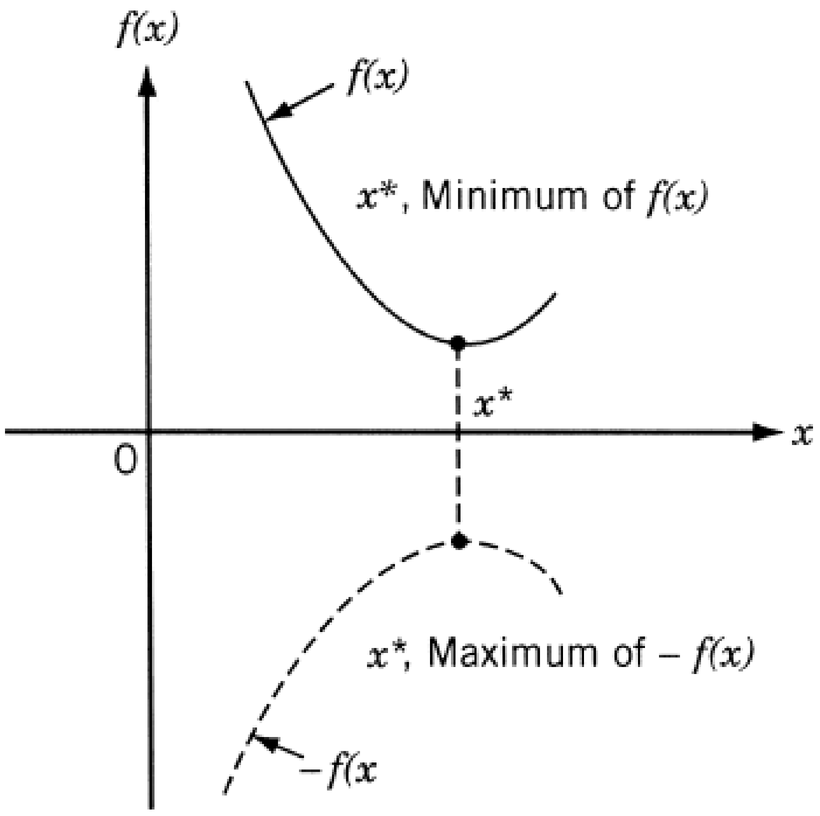
JAER

HEXACUBE

# TAGUCHI'S TECHNIQUE FOR OPTIMIZATION

# WHAT IS MEANT BY OPTIMIZATION

1. Optimization is the act of obtaining the best result under given circumstances.
2. Optimization can be defined as the process of finding the conditions that give the maximum or minimum value of a function.

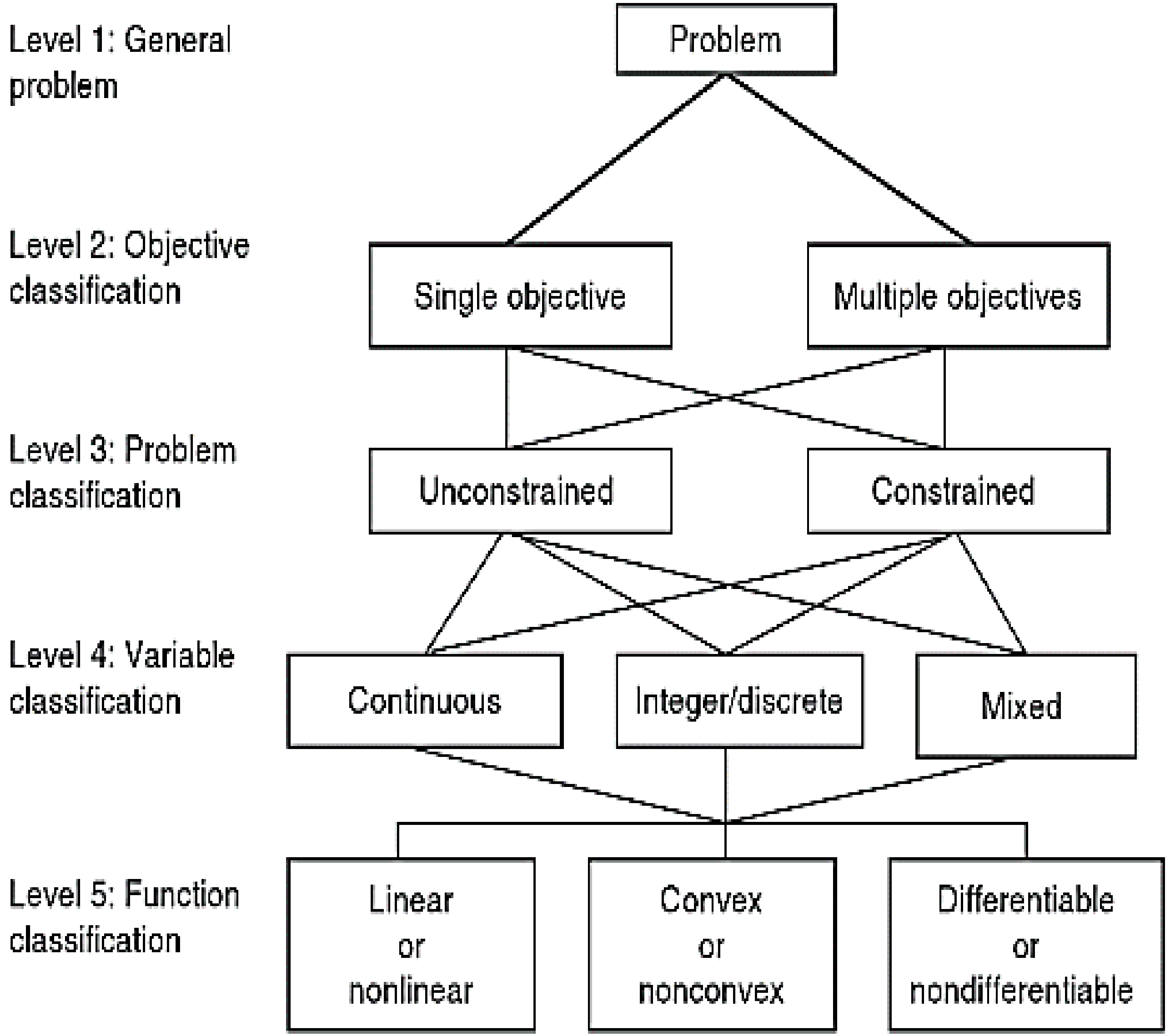


| Mathematical programming or optimization techniques | Stochastic process techniques | Statistical methods |
|---|---|---|
| Calculus methods | Statistical decision theory | Regression analysis |
| Calculus of variations | Markov processes | Cluster analysis, pattern recognition |
| Nonlinear programming | Queueing theory | |
| Geometric programming | Renewal theory | Design of experiments |
| Quadratic programming | Simulation methods | Discriminate analysis (factor analysis) |
| Linear programming | Reliability theory | |
| Dynamic programming | | |
| Integer programming | | |
| Stochastic programming | | |
| Separable programming | | |
| Multiobjective programming | | |
| Network methods: CPM and PERT | | |
| Game theory | | |

*Modern or nontraditional optimization techniques*

Genetic algorithms
Simulated annealing
Ant colony optimization
Particle swarm optimization
Neural networks
Fuzzy optimization

Methods of Operation Research


Level 1: General problem
Problem
Level 2: Objective classification
Single objective
Multiple objectives
Level 3: Problem classification
Unconstrained
Constrained
Level 4: Variable classification
Continuous
Integer/discrete
Mixed
Level 5: Function classification
Linear or nonlinear
Convex or nonconvex
Differentiable or nondifferentiable

# INTRODUCTION

1. **Genichi Taguchi**, (January 1, 1924 – June 2, 2012) was an engineer and statistician.
2. Dr. Genechi Taguchi is a Japanese scientist who spent much of his professional life researching ways to improve the quality of manufactured products.
3. Taguchi methods have been controversial among some conventional Western statisticians, but others have accepted many of the concepts introduced by him as valid extensions to the body of knowledge.

# INTRODUCTION

4. After World Wat· II, the Japanese telephone system was badly damaged and dysfunctional, subsequently he was appointed as head of Japan's newly formed Electrical Communications Laboratories (ECL) of Nippon Telephone and Telegraph Company.
5. Much of his research at ECL involved developing a comprehensive quality improvement methodology that included use of the DOE technique.
6. Taguchi's concept was adopted by many companies, including Toyota, Nippon Denso, Fuji Film and other Japanese firms.

# INTRODUCTION

7. Here are some of the major contributions that Taguchi has made to the quality improvement world:
    1. The Quality Loss Function
    2. Orthogonal Arrays and Linear Graphs
    3. Robustness

# WHY TAGUCHI'S DOE?

1. The quality engineering method that Taguchi proposed is commonly known as the Taguchi method or Taguchi approach.
2. His approach is a new experimental strategy in which he utilizes a modified and standardized form of DOE.
3. Taguchi approach is a form of DOE with special application principles.
4. For most experiments practiced in the industry today, the difference between DOE and the Taguchi approach is in the method of application.

# WHAT IS NOVEL IN TAGUCHI'S DOE?

1. Taguchi showed that DOE could be used not only to improve quality, but also to quantify the improvements made in terms of savings in economy aspect.
2. To make the technique easier and friendlier to apply, Taguchi standardized the application method.
3. For laying out experiments, he created a number of special orthogonal arrays, each of which is used for a number of experimental situations.

# WHAT IS NOVEL IN TAGUCHI'S DOE?

4. To analyze the results of the experiments for the purpose of determining the design solution that produces the best quality.
5. He introduced signal-to-noise ratio (S/N) for analysis of repeated results helps experimenters easily assure a design is robust to the influence of uncontrollable factors.

# NEED FOR TAGUCHI'S DoE

1. Optimisation of processes and formulations
2. Reduction in the variation of products and processes i.e. improved robustness
3. Investigation of process variables
4. Investigation of noise variables
5. Reduced costs and improved efficiency

# BASICS OF DOE

1. In order to draw statistically sound conclusions from the experiment, it is necessary to integrate simple and powerful statistical methods into the experimental design methodology.
2. In the context of DOE in manufacturing, one may come across two types of process variables or factors: qualitative and quantitative.
3. For quantitative factors, one must decide on the range of settings and how they are to be measured and controlled during the experiment.
4. For example, in injection moulding process, screw speed, mould temperature, etc. are examples of quantitative factors.

# BASICS OF DOE

5. Qualitative factors are discrete in nature. Type of raw material, type of catalyst, type of supplier, etc. are examples of qualitative factors.
6. A qualitative factor generally requires more levels when compared to a quantitative factor. Here the term 'level' refers to a specified value or setting of the factor being examined in the experiment.
7. In the DOE terminology, a trial or run is a certain combination of factor levels whose effect on the output (or performance characteristic) is of interest.

# BASICS OF DOE

8. In the context of statistics, the term ‘degrees of freedom’ is the number of independent and fair comparisons that can be made in a set of data.
9. For example, consider the heights of two students, say John and Kevin. If the height of John is $H_J$ and that of Kevin is $H_K$, then we can make only one fair comparison ($H_J - H_K$).
10. The number of degrees of freedom associated with each factor is equal to unity or 1 (i.e. 2−1=1).

$$\therefore \text{Degrees of freedom for a main effect} = \text{Number of levels} - 1$$

# BASICS OF DOE

11. The number of degrees of freedom for the entire experiment is equal to one less than the total number of data points or observations.
12. The degrees of freedom for an interaction is equal to the product of the degrees of freedom associated with each factor involved in that particular interaction effect.
13. The term ‘confounding’ refers to the combining influences of two or more factor effects in one measured effect.
14. Design resolution (R) is a summary characteristic of aliasing or confounding patterns.

# BASICS OF DOE

15. For designed experiments, designs of resolution III, IV and V are particularly important.
16. Design resolution identifies for a specific design the order of confounding of the main effects and their interactions.
17. Resolution III designs: These are designs in which no main effects are confounded with any other main effect, but main effects are confounded with two- factor interactions and two-factor interactions may be confounded with each other.

# BASICS OF DOE

18. Resolution IV designs: These are designs in which no main effects are confounded with any other main effect or with any two-factor interaction effects, but two-factor interaction effects are confounded with each other.
19. Resolution V designs: These are designs in which main effects are not confounded with other main effects, two-factor interactions or three-factor interactions, but two-factor interactions are confounded with three-factor interactions.

# TAGUCHI'S DESIGN OF EXPERIMENT

1. Dr. Taguchi suggested the use of Orthogonal Arrays (OA) for designing the experiments based on Latin square.
2. The difference between the number of experiments conducted between full factorial experiments and Taguchi's OA is:

| *Number of factors* | *Number of levels* | *Number of experiments* | |
|---|---|---|---|
| | | *Full factorial* | *Taguchi* |
| 3 | 2 | $2^k$ 8 | 4 |
| 7 | 2 | 128 | 8 |
| 15 | 2 | 32,768 | 16 |
| 4 | 3 | 81 | 9 |
| 13 | 3 | 1,594,323 | 27 |

# WHAT IS LATIN SQUARE

1. A Latin square is an *n x n* table filled with *n* different symbols in such a way that each symbol occurs exactly once in each row and exactly once in each column.

$$\begin{bmatrix} 1 & 2 & 3 \\ 2 & 3 & 1 \\ 3 & 1 & 2 \end{bmatrix} \qquad \begin{bmatrix} a & b & d & c \\ b & c & a & d \\ c & d & b & a \\ d & a & c & b \end{bmatrix}$$

# LATIN SQUARE vs. OA

1. Two Latin square of orders $n$ are said to be orthogonal to each other if when one is superimposed on the other, the ordered pairs $(i, j)$ of corresponding entries consists of all possible $n^2$ pairs.

Example of orthogonal Latin squares of order 3:

$$L_1 = \begin{array}{|c|c|c|} \hline 1 & 2 & 3 \\ \hline 3 & 1 & 2 \\ \hline 2 & 3 & 1 \\ \hline \end{array} \qquad L_2 = \begin{array}{|c|c|c|} \hline 1 & 3 & 2 \\ \hline 3 & 2 & 1 \\ \hline 2 & 1 & 3 \\ \hline \end{array}$$

| | | |
|---|---|---|
| (1,1) | (2,3) | (3,2) |
| (3,3) | (1,2) | (2,1) |
| (2,2) | (3,1) | (1,3) |

# TAGUCHI'S ORTHOGONAL ARRAY

***Nomenclature of arrays***

$L_a(b^c)$

$L$ = Latin square
$a$ = number of rows
$b$ = number of levels
$c$ = number of columns (factors)

Degrees of freedom associated with the OA = $a - 1$

| *Two-level series* | *Three-level series* | *Four-level series* | *Mixed-level series* |
|---|---|---|---|
| $L_4\ (2^3)$ | $L_9\ (3^4)$ | $L_{15}\ (4^5)$ | $L_{18}\ (2^1, 3^7)^{\dagger}$ |
| $L_8\ (2^7)$ | $L_{27}\ (3^{13})$ | $L_{64}\ (4^{21})$ | $L_{36}\ (2^{11}, 3^{12})$ |
| $L_{16}\ (2^{15})$ | $L_{81}\ (3^{40})$ | | |
| $L_{32}\ (2^{31})$ | | | |
| $L_{12}\ (2^{11})^*$ | | | |

* Interactions cannot be studied

† Can study one interaction between the 2-level factor and one 3-level factor

# STEPS IN TAGUCHI'S DOE

1. State the problem
2. Determine the objective
3. Determine the response and its measurement
4. Identify factors influencing the performance characteristics
5. Separate the factors into control and noise factors
6. Determine the number of levels and their values for all factors
7. Identify control factors that may interact
8. Select the orthogonal array
9. Assign factors and interactions to the columns of OA

# STEPS IN TAGUCHI’S DOE

10. Conduct the experiment
11. Analyze the data
12. Interpret the results
13. Select the optimal levels of the significant factors
14. Predict the expected results
15. Run a confirmation experiment

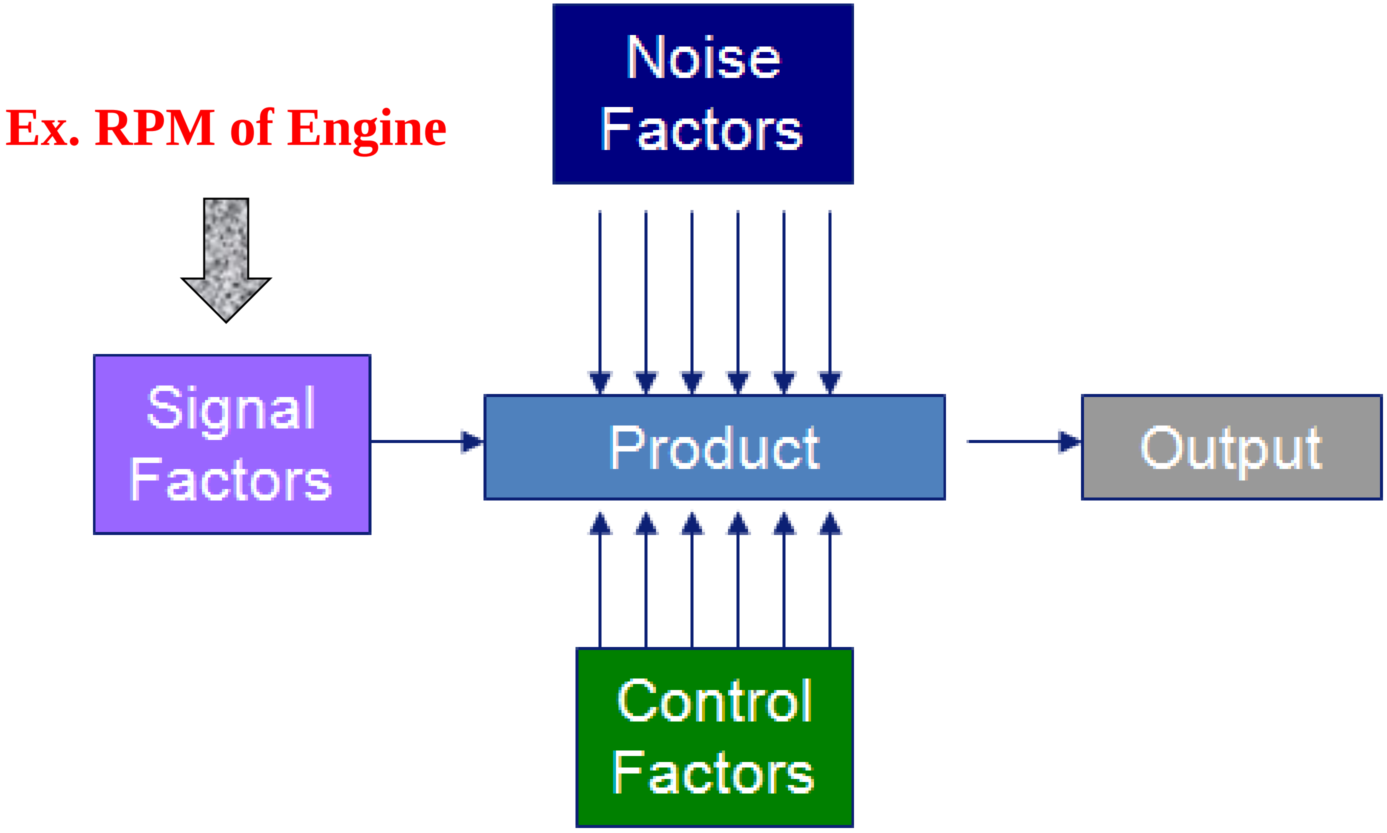
# DOE TERMINOLOGY

1. **EXPERIMENT** – It is defined as a study in which certain independent variables are manipulated, their effect on one or more dependent variables is determined.
2. **PURPOSE** – To discover something about a particular process (or) to compare the effect of several factors on some phenomena.
3. **LEVELS OF A FACTOR** – The variation of independent variable under each factor (or) number of different possible values of a factor.
4. **EFFECT OF A FACTOR** – Defined as the change of response produced by a change in the level of that factor.
5. **TREATMENT** – It means the factor.

# DOE TERMINOLOGY

6. **DEPENDENT VARIABLE**
   1. It is an outcome or response of an experiment.
   2. It is also called as response variable.
   3. Criterion used is also a dependent variable.
7. **INDEPENDENT VARIABLE (OR) FACTORS**
   1. Variables, which are varied in the experiment.
   2. Can be controlled at fixed levels.
   3. Can be varied or set at levels of our interest.
   4. Can be qualitative or quantitative and can be randomized.

# TAGUCHI'S DESIGN OF EXPERIMENT



# ORTHOGONAL ARRAY SELECTOR

| Number of Levels | | 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 |
| | 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 | | | | | | | | | | | | | | | | | | | |

# ORTHOGONAL ARRAY 2 Level Designs

**L4 (2^3)**

| Run | Columns | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 |
| 3 | 2 | 1 | 2 |
| 4 | 2 | 2 | 1 |

**L8 (2^7)**

| Run | Columns | | | | | | |
|---|---|---|---|---|---|---|---|
| | 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 |

**L12 (2^11)**

| Run | Columns | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | 1 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 |
| 4 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 2 | 1 | 1 | 2 |
| 5 | 1 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 1 |
| 6 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 1 |
| 7 | 2 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 2 | 1 |
| 8 | 2 | 1 | 2 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 |
| 9 | 2 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 1 | 1 |
| 10 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 2 |
| 11 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 1 | 2 | 2 |
| 12 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 1 | 2 | 2 | 1 |

# ORTHOGONAL ARRAY 2 Level Designs

L16 (2^15)

| Run | Columns | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 |
| 4 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 |
| 5 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 |
| 6 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 |
| 7 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 |
| 8 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 |
| 9 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| 10 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 |
| 11 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 1 |
| 12 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 2 | 1 | 2 |
| 13 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 1 |
| 14 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 |
| 15 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 |
| 16 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 1 |

# ORTHOGONAL ARRAY 3 Level Designs

**L9 (3^4)**

| Run | Columns | | | |
|---|---|---|---|---|
| | 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 |

## L27 (3^13)

| Run | Columns | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 3 | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 4 | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 3 |
| 5 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 |
| 6 | 1 | 2 | 2 | 2 | 3 | 3 | 3 | 1 | 1 | 1 | 2 | 2 | 2 |
| 7 | 1 | 3 | 3 | 3 | 1 | 1 | 1 | 3 | 3 | 3 | 2 | 2 | 2 |
| 8 | 1 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 | 3 | 3 | 3 |
| 9 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 |
| 10 | 2 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| 11 | 2 | 1 | 2 | 3 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 |
| 12 | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 |
| 13 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 2 | 3 | 1 | 3 | 1 | 2 |
| 14 | 2 | 2 | 3 | 1 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 3 |
| 15 | 2 | 2 | 3 | 1 | 3 | 1 | 2 | 1 | 2 | 3 | 2 | 3 | 1 |
| 16 | 2 | 3 | 1 | 2 | 1 | 2 | 3 | 3 | 1 | 2 | 2 | 3 | 1 |
| 17 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 | 3 | 1 | 2 |
| 18 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 2 | 3 | 1 | 1 | 2 | 3 |
| 19 | 3 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 |
| 20 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 | 3 |
| 21 | 3 | 1 | 3 | 2 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 2 | 1 |
| 22 | 3 | 2 | 1 | 3 | 1 | 3 | 2 | 2 | 1 | 3 | 3 | 2 | 1 |
| 23 | 3 | 2 | 1 | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 |
| 24 | 3 | 2 | 1 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 2 | 1 | 3 |
| 25 | 3 | 3 | 2 | 1 | 1 | 3 | 2 | 3 | 2 | 1 | 2 | 1 | 3 |
| 26 | 3 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 | 3 | 2 | 1 |
| 27 | 3 | 3 | 2 | 1 | 3 | 2 | 1 | 2 | 1 | 3 | 1 | 3 | 2 |

# ORTHOGONAL ARRAY 3 Level Designs

# ORTHOGONAL ARRAY Mixed Level Designs

L8 (2^4 4^1)

| Run | Columns | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 2 | 2 | 2 | 2 | 1 |
| 3 | 1 | 1 | 2 | 2 | 2 |
| 4 | 2 | 2 | 1 | 1 | 2 |
| 5 | 1 | 2 | 1 | 2 | 3 |
| 6 | 2 | 1 | 2 | 1 | 3 |
| 7 | 1 | 2 | 2 | 1 | 4 |
| 8 | 2 | 1 | 1 | 2 | 4 |

# ORTHOGONAL ARRAY Mixed Level Designs

L16 (2^12 4^1)

| Run | Columns | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 |
| 3 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 1 |
| 4 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 |
| 5 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 2 |
| 6 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 |
| 7 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 2 |
| 8 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 2 | 2 |
| 9 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 3 |
| 10 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 3 |
| 11 | 2 | 1 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 3 |
| 12 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 2 | 1 | 2 | 3 |
| 13 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 4 |
| 14 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 4 |
| 15 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 | 4 |
| 16 | 2 | 1 | 1 | 2 | 2 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | 4 |

# TAGUCHI'S FORMULA FOR OPTIMIZATION

For analysis, there are 3 categories of performance characteristics, (i.e.) Smaller-the-better, Larger-the-better and Nominal-the-better.

Smaller-is-the better (Minimize): $S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$

Larger-is-the better (Maximize): $S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right)$

Nominal is the best: $S/N = 10\log\left(\frac{\bar{y}}{s_y^2}\right)$

# TAGUCHI'S FORMULA FOR OPTIMIZATION

The predicted optimum response ($\mu_{pred}$) is given by

$$\mu_{pred} = \bar{Y} + (\bar{A}_2 - \bar{Y}) + (\bar{C}_2 - \bar{Y}) + (\bar{E}_1 - \bar{Y})$$

$$= \bar{A}_2 + \bar{C}_2 + \bar{E}_1 - 2\bar{Y}$$

# EXAMPLE FOR TAGUCHI'S OPTIMIZATION

# INPUT CONTROL PARAMETERS

The turning features such as depth of cut, feed rate and cutting speed were analyzed to obtain an optimal cutting conditions.

| Parameter / Level | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Cutting Speed (m/min) | 120 | 150 | 180 |
| Feed Rate (mm/rev) | 0.05 | 0.07 | 0.09 |
| Depth of Cut (mm) | 0.15 | 0.30 | 0.45 |

# TAGUCHI BASED ANALYSIS

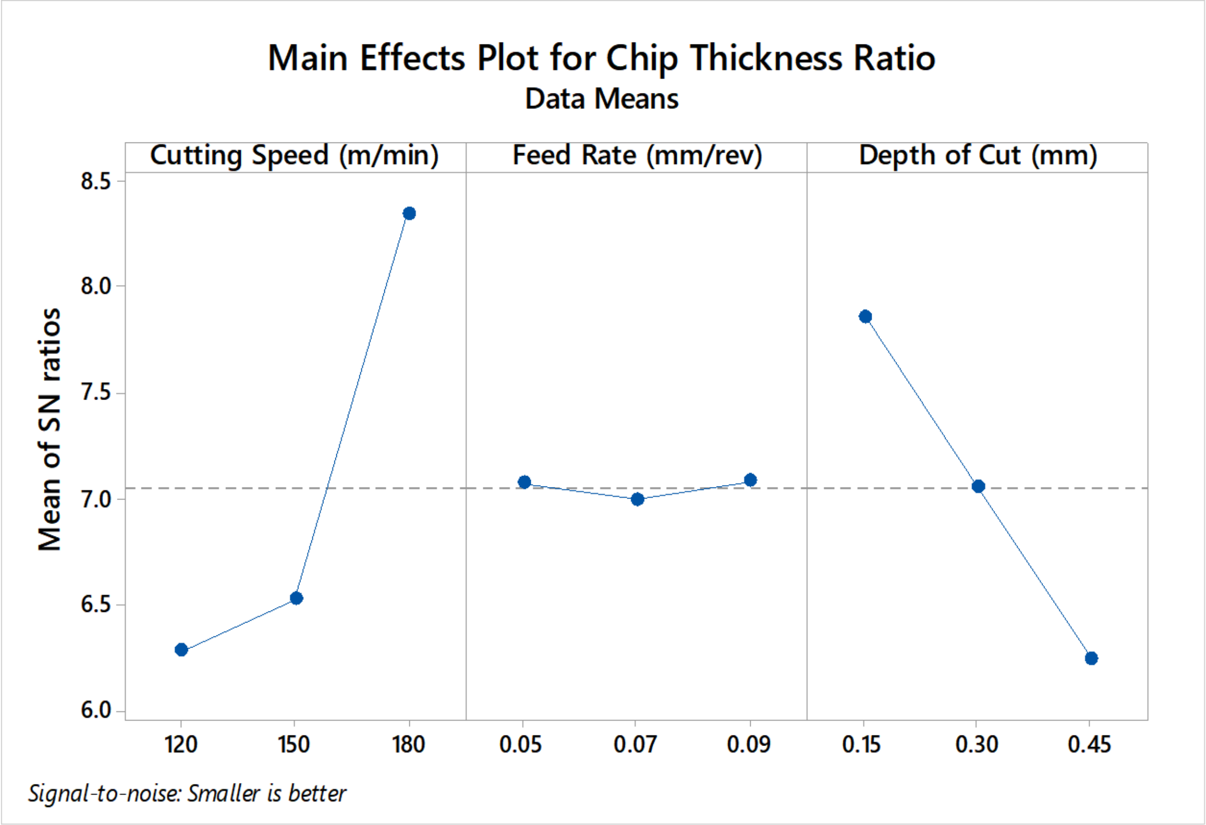
| Trial. No | Input values | | |
|---|---|---|---|
| | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) |
| 1 | 120 | 0.05 | 0.15 |
| 2 | 120 | 0.07 | 0.30 |
| 3 | 120 | 0.09 | 0.45 |
| 4 | 150 | 0.05 | 0.30 |
| 5 | 150 | 0.07 | 0.45 |
| 6 | 150 | 0.09 | 0.15 |
| 7 | 180 | 0.05 | 0.45 |
| 8 | 180 | 0.07 | 0.15 |
| 9 | 180 | 0.09 | 0.30 |

# TAGUCHI BASED ANALYSIS

| Exp. No | Uncut chip thickness (t) | Chip thickness ($t_c$) | Chip thickness ratio ($r_t$=t/$t_c$) | S/N ratio (LTB) |
|---|---|---|---|---|
| 1 | 0.36 | 0.82 | 0.44 | 7.131 |
| 2 | 0.39 | 0.79 | 0.49 | 6.196 |
| 3 | 0.45 | 0.85 | 0.53 | 5.514 |
| 4 | 0.37 | 0.78 | 0.47 | 6.558 |
| 5 | 0.42 | 0.8 | 0.52 | 5.680 |
| 6 | 0.33 | 0.76 | 0.43 | 7.331 |
| 7 | 0.30 | 0.72 | 0.42 | 7.535 |
| 8 | 0.26 | 0.75 | 0.35 | 9.119 |
| 9 | 0.29 | 0.77 | 0.38 | 8.404 |

# TAGUCHI BASED ANALYSIS

| Factors | Level 1 | Level 2 | Level 3 | Max - Min | Rank |
|---|---|---|---|---|---|
| Cutting Speed | 6.281 | 6.523 | 8.353 | 2.072 | 1 |
| Feed Rate | 7.075 | 6.998 | 7.083 | 0.085 | 3 |
| Depth of Cut | 7.860 | 7.053 | 6.243 | 1.617 | 2 |



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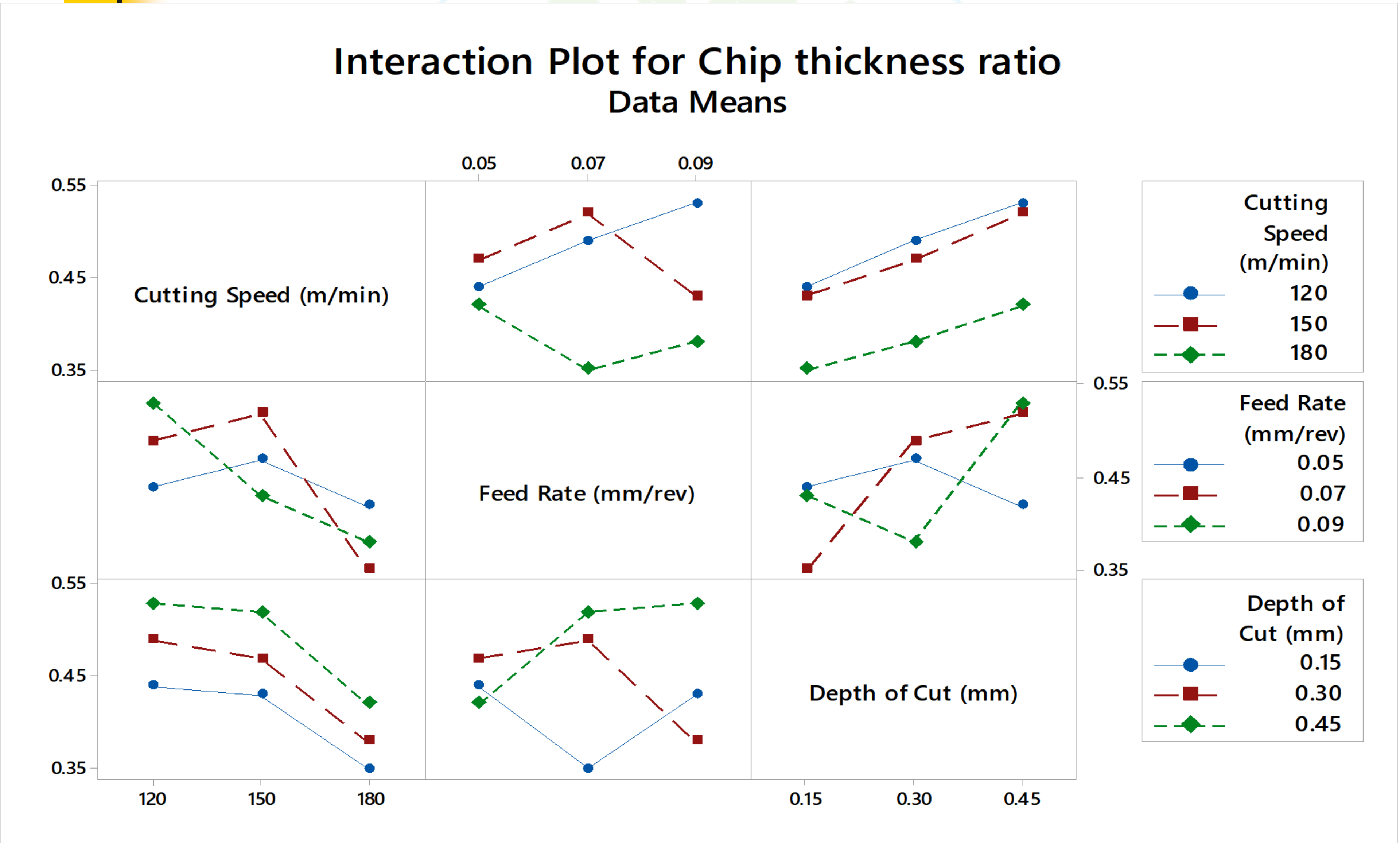

# TAGUCHI BASED ANALYSIS

| Source | DF | Adj. SS | Adj. MS | F-Value | P-Value | % Contribution |
|---|---|---|---|---|---|---|
| Cutting Speed | 2 | 0.018956 | 0.009478 | 853.00 | 0.001 | 64.13 |
| Feed rate | 2 | 0.000156 | 0.000078 | 7.00 | 0.125 | 0.53 |
| Depth of Cut | 2 | 0.010422 | 0.005211 | 469.00 | 0.002 | 35.26 |
| Error | 2 | 0.000022 | 0.000011 | | | 0.07 |
| Total | 8 | 0.029556 | | | | |

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# TAGUCHI BASED ANALYSIS – Prediction of Output S/N ratio

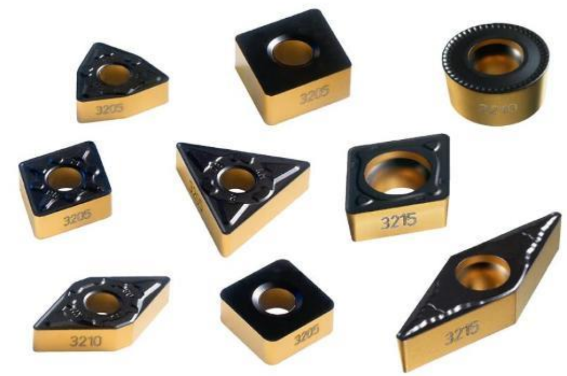
For authenticating the confirmed result, the assessed mean of Taguchi S/N ratio is calculated as, A3B2C1.

$$SNR_{em} = \mathrm{V}_{3m} + F_{3m} + D_{1m} - 2\mathrm{SNR}_m$$

$SNR_{em}$ = 8.353 + 7.083 + 7.860 - (2*7.052)

= 9.192.

# TAGUCHI – MULTIOBJECTIVE OPTIMIZATION



| Parameter / Level | Symbol | Level I | Level 2 | Level 3 |
|---|---|---|---|---|
| Cutting Tool Shape | A | C (80°) | D(55°) | S(90°) |
| Relief Angle (°) | B | 0 | 3 | 7 |
| Nose Radius (mm) | C | 0.4 | 0.8 | 1.2 |

# TAGUCHI – MULTIOBJECTIVE OPTIMIZATION

| Trial No | Cutting Insert Shape | Relief Angle (˚) | Nose Radius (mm) | ISO Insert Designation |
|---|---|---|---|---|
| 1 | C | 0 | 0.4 | CNMG 12 04 04 |
| 2 | C | 3 | 0.8 | CAMG 12 04 08 |
| 3 | C | 7 | 1.2 | CCMG 12 04 12 |
| 4 | D | 0 | 0.8 | DNMG 15 04 08 |
| 5 | D | 3 | 1.2 | DAMG 15 04 12 |
| 6 | D | 7 | 0.4 | DCMG 15 04 04 |
| 7 | S | 0 | 1.2 | SNMG 12 04 12 |
| 8 | S | 3 | 0.4 | SAMG 12 04 04 |
| 9 | S | 7 | 0.8 | SCMG 12 04 08 |

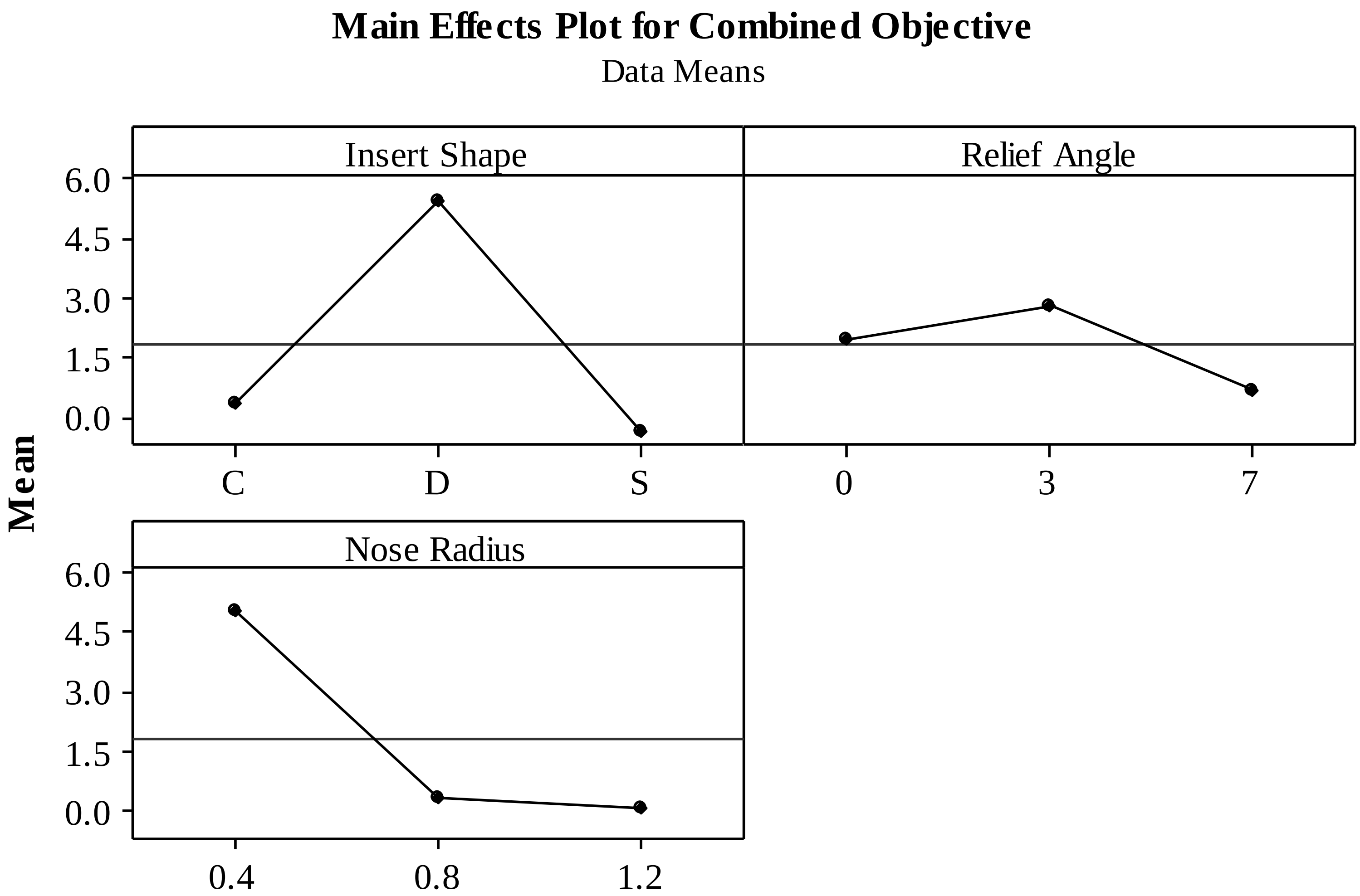
# TAGUCHI – MULTIOBJECTIVE OPTIMIZATION

| Trial No | Flank wear (mm) | Surface Roughness (µm) | Material Removal Rate (gm./min) |
|---|---|---|---|
| 1 | 0.143 | 0.687 | 0.026 |
| 2 | 0.112 | 1.898 | 0.031 |
| 3 | 0.483 | 1.702 | 0.042 |
| 4 | 0.118 | 1.560 | 0.050 |
| 5 | 0.134 | 0.814 | 0.047 |
| 6 | 0.033 | 1.007 | 0.047 |
| 7 | 0.168 | 2.504 | 0.046 |
| 8 | 0.136 | 1.245 | 0.045 |
| 9 | 0.502 | 1.689 | 0.047 |

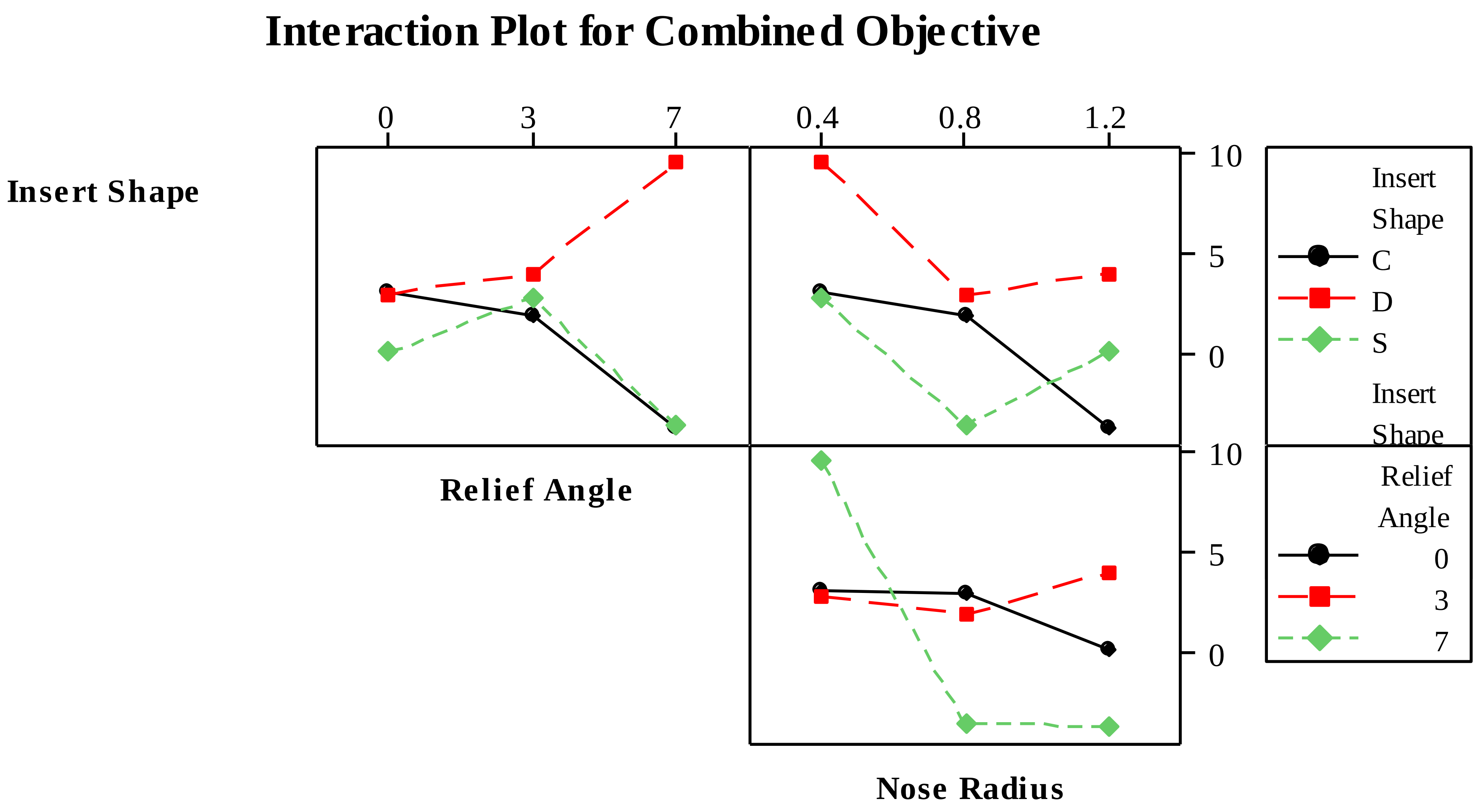
# TAGUCHI – MULTIOBJECTIVE OPTIMIZATION

| Trial No | Flank wear (A) | Surface Roughness (B) | Material Removal Rate (C) | Combined Objective (A*0.5+B*0.3+C*0.2) |
|---|---|---|---|---|
| 1 | 16.8933 | 3.26087 | -31.7005 | 3.085 |
| 2 | 19.0156 | -5.56592 | -30.1728 | 1.803 |
| 3 | 6.3211 | -4.61919 | -27.5350 | -3.732 |
| 4 | 18.5624 | -3.86249 | -26.0206 | 2.918 |
| 5 | 17.4579 | 1.78751 | -26.5580 | 3.954 |
| 6 | 29.6297 | -0.06059 | -26.5580 | 9.485 |
| 7 | 15.4938 | -7.97269 | -26.7448 | 0.006 |
| 8 | 17.3292 | -1.90339 | -26.9357 | 2.706 |
| 9 | 5.9859 | -4.55259 | -26.5580 | -3.684 |

# TAGUCHI – MULTIOBJECTIVE OPTIMIZATION



# TAGUCHI – MULTIOBJECTIVE OPTIMIZATION



# TAGUCHI – MULTIOBJECTIVE OPTIMIZATION

| Source | DF | Seq SS | Adj MS | F | P | % Contribution |
|---|---|---|---|---|---|---|
| Insert Shape | 2 | 59.544 | 29.772 | 3.49 | 0.223 | 45.27 % |
| Relief Angle | 2 | 6.937 | 3.468 | 0.41 | 0.711 | 5.28 % |
| Nose Radius | 2 | 47.761 | 23.88 | 2.80 | 0.263 | 36.37 % |
| Residual Error | 2 | 17.063 | 8.531 | | | 12.99 % |
| Total | 8 | 131.304 | | | | 100 % |

# TAGUCHI – MULTIOBJECTIVE OPTIMIZATION

# HOW TO PERFORM TAGUCHI'S DESIGN OF EXPERIMENTS AND ANALYSIS USING MINITAB – Hands on Training

# QUERIES


# THANK YOU