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The Taguchi Method and Taguchi Philosophy in Design of Experiment

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Abstract

In recent market and global requirements, the desires to provide higher level of quality in products and services for increasing market shares continues competitively among the manufacturers to ensure customer satisfaction will return with consistent orders. The important of product and process optimization has caused manufacturers focus greater attention to design optimization in order to stay competitive in the world market. The understanding on the fundamental of basic experimentation will be a starting point to improve process yield, product performance and productivity of company-wide operation. Thus, a more reliable and effective experimental approach subsequently will be the right choice to study the possible design factors that satisfy customers and process compatibility. This study presents the philosophy and method applied for Taguchi method design of experiment. The concept such as quality should be designed into the product, quality loss function, determining the optimization condition for the product or process, designing product and process that insensitive to the influence of uncontrollable factors or noise, signal-to-noise ratio and orthogonal arrays among the important terms in application of Taguchi method design of experiment. Robust Design method, also called the Taguchi Method, pioneered by Dr. Genichi Taguchi, greatly improves engineering productivity. By consciously considering the noise factors (environmental variation during the product's usage, manufacturing variation, and component deterioration) and the cost of failure in the field the Robust Design method helps ensure customer satisfaction.

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Robust Design focuses on improving the fundamental function of the product or process, thus facilitating flexible designs and concurrent engineering. Indeed, it is the most powerful method available to reduce product cost, improve quality, and simultaneously reduce development interval.

Keywords: *Robust, flexible. improvement, loss function, quality, cost, noise factors, design, strategy, signal, parameter, dynamic, design of experiment, nominal, smaller, larger, etc.*

INTRODUCTION

The super competition in the world market has created challenges to satisfy customers' needs and expectations for manufacturers and service providers, and has triggered manufacturers to reduce the costs of a product/service and reducing the loss to society.

Quality engineering has the objective of designing quality in every products and corresponding process. It directs the quality improvement efforts upstream from the manufacturing process to the design phase and therefore, referred to as an off-line quality control method. Taguchi's off-line methods are effective in improving quality and cutting costs at the same time.

In Taguchi's method, quality is measured by the deviation of a quality characteristic from its target value. A loss function is developed for the deviation. Uncontrollable factors, known as noise factors, cause such deviations and thereby lead to loss. Since the elimination of noise factors is impractical and often impossible, the Taguchi method seeks to minimize the effects of the noise and to determine the optimal level of important controllable factors based on the concept of robustness The object is create a product/process design that is insensitive to all possible combinations of the uncontrollable noise factors and is at the same time effective and cost effective as a result of setting the key controllable factors at certain levels. The foundations of Taguchi's quality engineering seem to be well accepted.

THE THEORY AND PHILOSOPHY OF TAGUCHI APPROACH

The essence of Taguchi approach is its contribution to excellent quality control in the manufacturing industries. His concept has developed engineers to see

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quality as a yard stick in their design of product and process. The philosophy which based on three fundamental concepts has greatly caused the better application and development of technology and techniques in many industries. The three concepts are:

- Quality should be designed into the product.
- It is the best to minimize the deviation from the target to achieve the quality, and products shall be designed to be insensitive to the uncontrollable factors (noise factors)
- The cost of quality is measured by the deviation from its target value and the losses should be measured system-wide

It emphasizes the importance of designing quality control into manufacturing processes. The Taguchi approach stresses that quality variation is the main enemy of quality engineering and that every effort should be made to reduce the variation in quality characteristics. Robust design is an engineering methodology for optimizing the product and process conditions which minimally sensitive to the various causes

engineering methodology for optimizing the product and process conditions which minimally sensitive to the various causes of variation and which produce high quality of product with low development and manufacturing costs . Taguchi parameter design is an important tool for robust design. In this method the tolerance design can be also classified as a robust design. Specifically robust design is identical to parameter design, but a wider sense parameter design is a subset of robust design. Two major tools used in robust design are

- Signaled-to-noise ratio which measures quality with emphasis on variation
- Orthogonal arrays which accommodate many design factors (parameters) simultaneously

Taguchi method is a powerful design of experiments which provide simple, efficient and systematic approach to optimize designs for performance, quality and cost. In building quality in the design stage, Taguchi has developed two-step process.

- Optimizing the design of the product or process by manufacturing the product in the best manner most of the time with less deviation from

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the target

- To design product and process insensitive to the influence of uncontrollable factors in ensuring less variation between the products manufactured

The optimum level of a product when performed under available operating conditions has implied that the product performance has achieved the most and the least of the target value of quality all the main factors and their influencing factors to the dependent variable. The fundamental of this technique is to improve the quality of product by minimizing the effect of the causes of variation, since variability around the expected target is allowed; the effort is to reduce the variation without eliminating the causes of variation. According to the variations that represent the noise factor are categorized into three sources:

- **Unit to unit variation:** It is caused by the variation in material, equipment performance and workmanship
- **Deterioration (internal factor):** It is wear and tear of the components and consumables items used in the process often in an industrial setting, totally removing the cause of variation can be expensive. A low cost solution is achievable by adjusting the levels and controlling the variation of factors affecting the product or process performance. The parameter design focused by Taguchi is a reaction to this expectation and the cost of experiment could be saved further by avoiding additional experiment that need to reduce variation in product and process design.

The basic approach about the design of experiment consists of four stages to such design measurement. Optimizing the design of the product means determining the right combination of ingredients or making the proper adjustment to the machine so that the best result is obtained. In Taguchi approach, the design of experiment process will considered

- Planning the experiment
- Designing the experiment Conducting the experiment and
- Analyzing the experimental results

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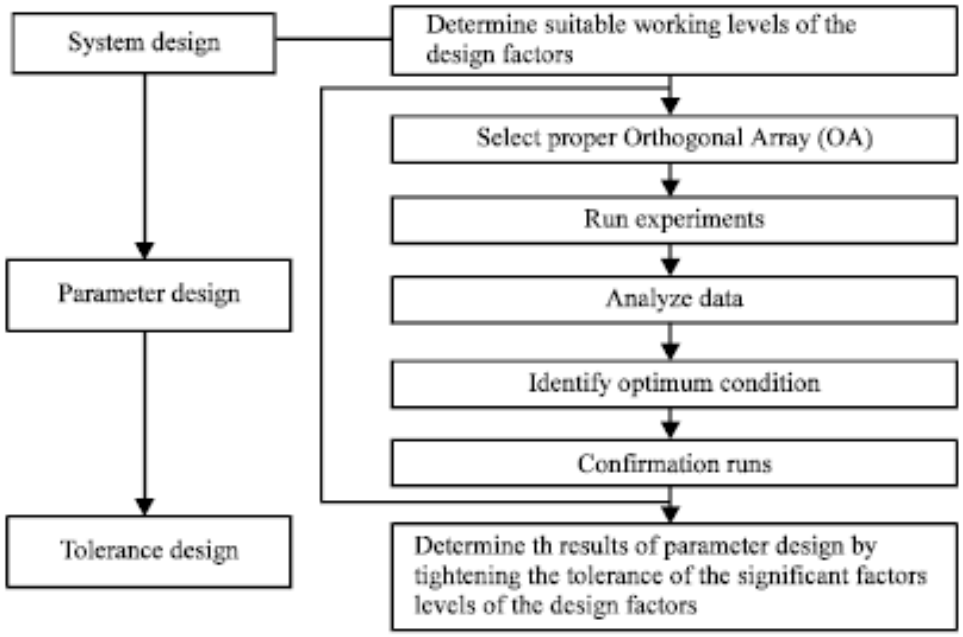

Fig. 1: Taguchi design procedure (Zhang et al., 2007)

Figure 1 The Taguchi design procedure to represent the three stages; system design, parameter design and tolerance design.

This method is very much applicable and effective when applied to experiments with multiple factors, however the preliminary knowledge in engineering or science is a prerequisite for experimenters to determine the suitable levels and design factors. Knowledge of scientific phenomena and past engineering experience with similar product designs and manufacturing processes form the basis of engineering design activity .

ADVANTAGES OF ROBUST DESIGN METHOD

Robust design

Robust design is an "engineering methodology for improving productivity during research and development so that desired quality products can be produced quickly and at low cost" Taguchi bases his method on conventional statistical tools together with some guidelines for laying out design of experiments and analyzing the results of these experiments. Taguchi's approach to quality control applies to the entire process of developing and manufacturing a product— from the initial concept, through design and engineering, to

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manufacturing and production. Taguchi methods are used to specify dimension and feature detail and normally follow DFM activities.

Robust Design method is central to improving engineering productivity pioneered by Dr. Genichi Taguchi. After the end of the Second World War, the method has evolved over the last six decades. Many companies around the world have saved hundreds of millions of dollars by using the method in diverse industries: automobiles, xerography, telecommunications, electronics, software, etc.

Over the last about 10 years many leading companies have invested heavily in the Six Sigma approach aimed at reducing waste during manufacturing and operations. These efforts have had great impact on the cost structure and hence on the bottom line of those companies. Many of them have reached the maximum potential of the traditional Six Sigma approach. What would be the engine for the next wave of productivity improvement?

Brenda Reichelderfer of ITT Industries reported on their benchmarking survey of many leading companies, "design directly influences more than 70% of the product life cycle cost; companies with high product development effectiveness have earnings three times the average earnings; and companies with high product development effectiveness have revenue growth two times the average revenue growth." She also observed, "40% of product development costs are wasted!"

These and similar observations by other leading companies are compelling them to adopt improved product development processes under the banner Design for Six Sigma. The Design for Six Sigma approach is focused on

1) Increasing engineering productivity so that new products can be developed rapidly and at low cost, and

2) Value based management.

The Taguchi method for design of experiment has become an alternative in solving these problems and is chosen as the right solution to industrial organization to improve their product and process design. The Taguchi's method which was designed to reduce the engineering experimental time and cost, stimulate the initiative and effort for product improvement and assisted the

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continuous improvement in processing capability. Its simplicity in data collection as well as practical in designing the product and process parameters makes design of experiment possible in any organization and business operation. One way to remain or stay in the market is to strengthen the new product development and the ability to overcome problem or challenge in production process in order to create the products that are satisfying the customers' expectations and, aim at customers returned for further orders. To achieve desirable product quality by design, recommends three process stages that are system design, parameter design and tolerance design.

Experimental guidance and templates which are user friendly software will help to ensure the effective application of Taguchi method at workplace to solve problems related to product design, performance and improvement of the processes. The Taguchi methodology has taken the design of experiments from exclusive world of the statistician and brought it more fully into the world of manufacturing (It emphasizes the importance of robust design and quality control into manufacturing processes.

Robust design is an engineering methodology for optimizing the product and process conditions which minimally sensitive to the various causes of variation and which produce required quality of product with low development and manufacturing costs). Taguchi parameter and tolerance design are important tool for robust design.

The Robust design method has helped reduce the development time and cost by a factor of two or better in many such problems.

In general, engineering decisions involved in product/system development can be classified into two categories:

- Error-free implementation of the past collective knowledge and experience
- Generation of new design information, often for improving product quality/reliability, performance, and cost.

While CAD/CAE tools are effective for implementing past knowledge, Robust Design method greatly improves productivity in generation of new knowledge by acting as an amplifier of engineering skills. With Robust Design, a company can rapidly achieve the full technological potential of their design ideas

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and achieve higher profits.

OBJECTIVES OF THE STUDY

- To improve quality
- To cut down costs of manufacturing
- To improve manufacturability
- To reduce product development cost
- To reduce life time costs.

TYPICAL PROBLEMS ADDRESSED BY ROBUST DESIGN

A team of engineers was working on the design of a radio receiver for ground to aircraft communication requiring high reliability, i.e., low bit error rate, for data transmission. On the one hand, building series of prototypes to sequentially eliminate problems would be forbiddingly expensive. On the other hand, computer simulation effort for evaluating a single design was also time consuming and expensive. Then, how can one speed up development and yet assure reliability?

In an another project, a manufacturer had introduced a high speed copy machine to the field only to find that the paper feeder jammed almost ten times more frequently than what was planned. The traditional method for evaluating the reliability of a single new design idea used to take several weeks. How can the company conduct the needed research in a short time and come up with a design that would not embarrass the company again in the field?

ROBUSTNESS STRATEGY

Variation reduction is universally recognized as a key to reliability and productivity improvement. There are many approaches to reducing the variability, each one having its place in the product development cycle.

By addressing variation reduction at a particular stage in a product's life cycle, one can prevent failures in the downstream stages. The Six Sigma approach has made tremendous gains in cost reduction by finding problems that occur in manufacturing or white-collar operations and fixing the immediate causes. The robustness strategy is to prevent problems through optimizing product designs and manufacturing process designs.

The manufacturer of a differential op-amplifier used in coin telephones faced the problem of excessive offset voltage due to manufacturing variability. High offset voltage caused poor voice quality, especially for phones further away from the central office. So, how to minimize field

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problems and associated cost?

There are many approaches:

1) Compensate the customers for their losses.
2) Screen out circuits having large offset voltage at the end of the production line.
3) Institute tighter tolerances through process control on the manufacturing line.
4) Change the nominal values of critical circuit parameters such that the circuit's function becomes insensitive to the cause, namely, manufacturing variation.

The approach 4 is the robustness strategy. As one moves from approach 1 to 4, one progressively moves upstream in the product delivery cycle and also becomes more efficient in cost control. Hence it is preferable to address the problem as upstream as possible. The robustness strategy provides the crucial methodology for systematically arriving at solutions that make designs less sensitive to various causes of variation. It can be used for optimizing product design as well as for manufacturing process design.

The Robustness Strategy uses five primary tools:

1) P-Diagram is used to classify the variables associated with the product into noise, control, signal (input), and response (output) factors.

2) Ideal Function is used to mathematically specify the ideal form of the signal-response relationship as embodied by the design concept for making the higher-level system work perfectly.

3) Quadratic Loss Function (also known as Quality Loss Function) is used to quantify the loss incurred by the user due to deviation from target performance.

4) Signal-to-Noise Ratio is used for predicting the field quality through laboratory experiments.

5) Orthogonal Arrays are used for gathering dependable information about control factors (design parameters) with a small number of experiments.

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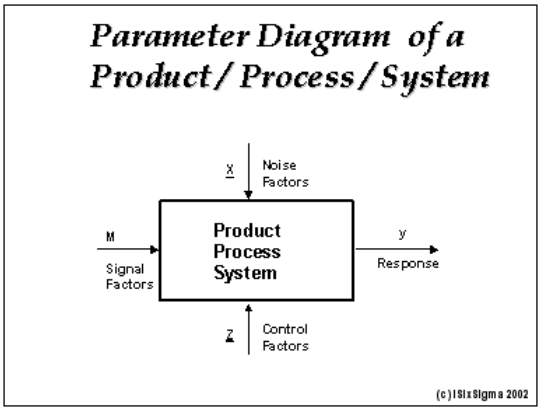
P-Diagram

P-Diagram is a must for every development project. It is a way of succinctly defining the development scope. First we identify the signal (input)

and response (output) associated with the design concept. For example, in designing the cooling system for a room the thermostat setting is the signal and the resulting room temperature is the response.



Next consider the parameters/factors that are beyond the control of the designer. Those factors are called noise factors. Outside temperature, opening/closing of windows, and number of occupants are examples of noise factors. Parameters that can be specified by the designer are called control factors. The numbers of registers, their locations, size of the air conditioning unit, insulation are examples of control factors. Ideally, the resulting room temperature should be equal to the set point temperature. Thus the ideal function here is a straight line of slope one in the signal-response graph. This relationship must hold for all operating conditions. However, the noise factors cause the relationship to deviate from the ideal.

The job of the designer is to select appropriate control factors and their settings so that the deviation from the ideal is minimum at a low cost. Such a design is called a minimum sensitivity design or a robust design. It can be achieved by exploiting nonlinearity of the products/systems. The Robust Design method prescribes a systematic procedure for minimizing design sensitivity and it is called Parameter Design.

An overwhelming majority of product failures and the resulting field costs and design iterations come from ignoring noise factors during the early design stages. The noise factors crop up one by one as surprises in the subsequent product delivery stages causing costly failures and band-aids. These problems are avoided in the Robust Design method by subjecting the design ideas to noise factors through parameter design.

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The next step is to specify allowed deviation of the parameters from the nominal values. It involves balancing the added cost of tighter tolerances against the benefits to the customer. Similar decisions must be made regarding the selection of different grades of the subsystems and components from available alternatives. The quadratic loss function is very useful for quantifying the impact of these decisions on customers or higher-level systems. The process of balancing the cost is called Tolerance Design. The result of using parameter design followed by tolerance design is successful products at low cost.

THE TAGUCHI PHILOSOPHY

According to Taguchi, "Quality is the loss imparted to the society from the time a product is shipped. " Taguchi attaches a monetary value to quality because he feels that this will make quality improvement understood by all-technical personnel as well as management . Typical examples of loss to society include failure to meet the customer's requirements and unsatisfactory performance that leads to loss of good will and reduced market share, also , the raw materials and labour depleted when making a product or rendering the service.

The purpose of quality improvement, is , then is to discover innovative methods of designing processes and products that will save society more than they cost in the long run. All products ultimately cause loss because they break and then are to be repaired / replaced due to wear and tear after normal it has given normal performance. The loss depends on the degree to which product meets the customer's requirements. Taguchi is of the opinion that the loss due to variation in the product's performance is proportional to the square of the performance characteristic 's deviation from its target value.

To achieve desirable product quality, Taguchi suggests a three-stage design operation to determine the target values and tolerances for relevant parameters in the product and the process. These three stages are as following:

1. System design,
2. Parameter design and
3. Tolerance design

1. System design

The system design stage is where new ideas, concepts and knowledge in the areas of science and engineering principles and experience are utilized to

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determine the right combination of materials, parts, processes and design factors are used to create a prototype of the product that will satisfy functional and economical specifications and also create the process that will build it.

2. Parameter design

In parameter design, the system variables are experimentally analyzed to determine how the product or process reacts to uncontrollable "noise" in the system; parameter design is the main thrust of Taguchi's approach. Parameter design involves finding optimal settings of the product process parameters in order to minimize performance variability. It aims at finding the appropriate design factor levels to make the system less sensitive to variations in uncontrollable noise factors, i.e., to make the system robust.

Taguchi defines a performance measure known as the signal to noise ratio (S/N) and tries to select the parameter levels that maximize the ratio. The term signal represents the square of the mean value of the quality characteristic, where as noise is a measure of the variability (as measured by the variance) of the characteristic.

In this way the product performs better reducing the loss to the customer.

Sources of noise:

Uncontrollable factors are known as noise factors. They cause a quality characteristic to deviate from the target value and hence create a loss to quality. In general noise arises from two sources that is internal noise and external noise.
Internal sources of noise are a result of settings of the product and process parameters for example manufacturing variations and product deterioration over time due to wear and tear. Manufacturing imperfections occur because of inevitable uncertainties in the manufacturing process. They create product to product noise and variability.

External sources of noise are those variables that are external to the product and that affect its performance. Examples are changes in such environmental conditions as humidity, temperature and dust , and variability in human operators who make the product.

In the parameter design phase, not all sources of noise can be accounted for because of the lack of knowledge concerning the factors that affect the product's performance Also, physical

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restrictions –based on the number of experiments to be performed and the number of factors that may be included in the analysis and also limit of choice of factors. In this phase, only those sources of noise that are included in the study are termed noise factors. Hence, noise factors are judiciously chosen to represent those that most impact the performance of the product.

2.1. Steps in robust parameter design. Robust Parameter design has 4 main steps:

a) Problem formulation:

This step consists of identifying the main function, developing the P-diagram, defining the ideal function and S/N ratio, and planning the experiments. The experiments involve changing the control, noise and signal factors systematically using orthogonal arrays.

b) Data collection/simulation:

The experiments may be conducted in hardware or through simulation. It is not necessary to have a full-scale model of the product for the purpose of experimentation. It is sufficient and more desirable to have an essential model of the product that adequately captures the design concept. Thus, the experiments can be done more economically.

c) Effects of control factors analysis:

The effects of the control factors are calculated in this step and the results are analyzed to select optimum setting of the control factors.

d) Prediction/Confirmation:

In order to validate the optimum conditions we predict the performance of the product design under baseline and optimum settings of the control factors. Then we perform confirmation experiments under these conditions and compare the results with the predictions. If the results of confirmation experiments agree with the predictions, then we implement the results. Otherwise, the above steps must be iterated.

3. Taguchi's Parameter design approach

Table below indicates three sources of noise (environmental variables , product deterioration , and manufacturing variables) and the various product development stages at which counter measures can be taken for each. It can be seen that building quality into the product and process at the design phase is important as the counter measures against all three sources of noise can be taken at the

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product design stage.

Moreover, as we move down stream to the manufacturing stage m only counter measures against manufacturing variations can be taken, In parameter design, there are two types of factors that affect a product's functional characteristic: control factors and noise factors. Control factors are those factors which can easily be controlled such as material choice, cycle time, or mold temperature in an injection molding process. Noise factors are factors that are difficult or impossible or too expensive to control. There are three types of noise factors: outer noise, inner noise, and between product noise. Examples of each type of noise factor and controllable factors in product and process design are listed in Table 1. Noise factors are primarily response for causing a product's performance to deviate from its target value. Hence, parameter design seeks to identify settings of the control factors which make the product insensitive to variations in the noise factors, i.e., make the product more robust, without actually eliminating the causes of variation.

Table 1: Examples of Noise and Control Factors (adapted from Byrne and Taguchi, 1987)

Factors	**Product Design**	**Process Design**
Outer Noise	Consumer's usage conditions	Ambient Temperature
	Low temperature	Humidity
	High temperature	Seasons
	Temperature change	Incoming material variation
	Shock	Operators
	Vibration	Voltage change

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	Humidity	Batch to batch variation
Inner Noise	Deterioration of parts	Machinery aging
	Deterioration of material	Tool wear
	Oxidation (rust)	Deterioration
Between Product Noise	Piece to piece variation where they are	Process to process variation where they are
	supposed to be the same, e.g.,	supposed to be the same, e.g.,
	Young's modulus	variations in feed rate
	shear modulus	
	allowable stress	
Controllable Factors	All design parameters, e.g.,	All process design parameters
	□□dimensions	All process setting parameters
	□□material selection	

Design of experiments techniques, specifically Orthogonal Arrays (OAs), are employed in Taguchi's approach to systematically vary and test the different levels of each of the control factors.

4. Tolerance design

The final and third step in Taguchi's robust design approach is tolerance design. In this, tolerances are determined/set that is , a range of admissible values – around the target values of the control parameters identified in the parameter design phase. This is done if the performance variation achieved by the settings identified in the parameter stage is not acceptable. Tolerance design occurs when the tolerances for the products or process are established to minimize the sum of the manufacturing and lifetime costs of the product or process.

In the tolerance design stage, tolerances of factors that have the largest influence on variation are adjusted only if after the parameter design stage, the target values of quality have not yet been achieved. Most engineers tend to associate quality with better tolerances, but tightening the tolerances increases the cost of the product or process because it requires better materials, components, or machinery to achieve the tighter tolerances and tolerances that are too wide will increase

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performance variation , which in turn will result in increasing the customer's costs. The objective is to determine the optimal trade off between these two costs.. Taguchi's parameter design approach allows for improving the quality without requiring better materials or parts and makes it possible to improve quality and decrease (or at least maintain the same) cost. After the parameter design stage is completed and the parameter control settings are adjusted, confirmation /verification experiments are conducted. These experiments reaffirm the degree of improvement achieved when the chosen parameter settings are used.

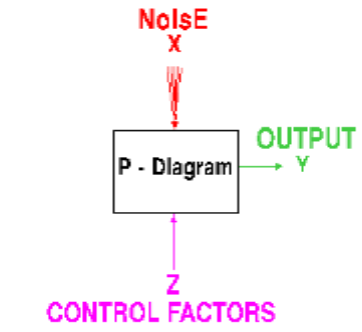
TAGUCHI'S METHOD:

Dr. Taguchi of Nippon Telephones and Telegraph Company, Japan has developed a method based on "ORTHOGONAL ARRAY" experiments which gives much reduced " variance " for the experiment with " optimum settings " of control parameters. Thus the marriage of Design of Experiments with optimization of control parameters to obtain BEST results is achieved in the Taguchi Method. "Orthogonal Arrays" (OA) provide a set of well balanced (minimum) experiments and Dr. Taguchi's Signal-to-Noise ratios (S/N), which are log functions of desired output, serve as objective functions for optimization, help in data analysis and prediction of optimum results.

Taguchi Method treats optimization problems in two categories:

[a] static problems-

Generally, a process to be optimized has several control factors which directly decide the target or desired value of the output. The optimization then involves determining the best control factor levels so that the output is at the target value. Such a problem is called as a "STATIC PROBLEM". This is best explained using a P-Diagram which is shown below ("P" stands for Process or Product). Noise is shown to be present in the process but should have no effect on the output. This is the primary aim of the Taguchi experiments - to minimize variations in output even though noise is present in the process. The process is then said to have become ROBUST.



P - Diagram for STATIC problems

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Static problem (batch process optimization) :

There are 3 Signal-to-Noise ratios of common interest for optimization of Static Problems;

(I) Smaller-The-Better

$n = -10 \text{ Log}_{10}$ [mean of sum of squares of measured data]

This is usually the chosen S/N ratio for all undesirable characteristics like "defects "etc. for which the ideal value is zero. Also, when an ideal value is finite and its maximum or minimum value is defined (like maximum purity is 100% or maximum Tc is 92K or minimum time for making a telephone connection is 1 sec) then the difference between measured data and ideal value is expected to be as small as possible. The generic form of S/N ratio then becomes,

$n = -10 \text{ Log}_{10}$ [mean of sum of squares of {measured - ideal}]

(ii)Larger-The-Better

$n = -10 \text{ Log}_{10}$ [mean of sum squares of reciprocal of measured data]

This case has been converted to SMALLER-THE-BETTER by taking the reciprocals of measured data and then taking the S/N ratio as in the smaller-the-better case.

(iii)Nominal-The-Best:

$$n = 10 \text{ Log}_{10} \frac{\text{Square of mean}}{\text{variance}}$$

This case arises when a specified value is MOST desired, meaning that neither a smaller nor a larger value is desirable.

Examples are;

1) Most parts in mechanical fittings have dimensions which are nominal-the-best type.

2) Ratios of chemicals or mixtures are nominally the best type.
   e.g. Aqua regia 1:3 of HNO3: HCL
   Ratio of Sulphur, KNO3 and Carbon in gun powder

Thickness should be uniform in deposition /growth /plating /etching..

[B] Dynamic Problems

If the product to be optimized has a signal input that directly decides the output, the optimization involves determining the best control factor levels so that the "input signal / output" ratio is closest to the desired relationship. Such a problem is called as a "DYNAMIC PROBLEM".

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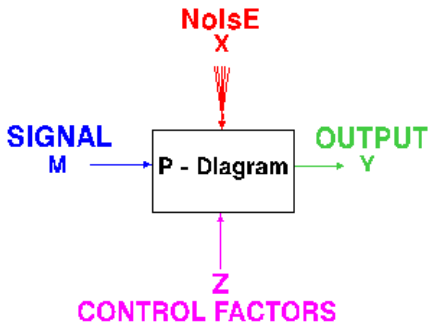
This is best explained by a P-Diagram which is shown below. Again, the primary aim of the Taguchi experiments - to minimize variations in output even though noise is present in the process- is achieved by getting improved linearity in the input/output relationship.



P - Diagram for DYNAMIC problems

DYNAMIC

Problem (Technology Development):

In dynamic problems, we come across many applications where the output is supposed to follow input signal in a predetermined manner. Generally, a linear relationship between "inputs" "output" is desirable

For example: Accelerator pedal in cars, volume control in audio amplifiers, document copier (with magnification or reduction) various types of moldings etc.

There are 2 characteristics of common interest in "follow-the-leader" or "Transformations" type of applications,

(i) Slope of the I/O characteristics

(ii) Linearity of the I/O characteristics (minimum deviation from the best-fit straight line)

Static versus Dynamic S/N ratios

In some engineering problems, the signal factor is absent or it takes a fixed value. These problems are called Static problems and the corresponding S/N ratios are called static S/N ratios. The S/N ratio described in the preceding section is a static S/N ratio.

In other problems, the signal and response must follow a function called the ideal function. In the cooling system example described earlier, the response (room temperature) and signal (set point) must follow a linear relationship. Such problems are called dynamic problems and the corresponding S/N ratios are called dynamic S/N ratios.

The dynamic S/N ratio will be illustrated in a later section using a turbine design example.

Dynamic S/N ratios are very useful for technology development, which is the process of generating flexible solutions that can be used in many products.

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The Signal-to-Noise ratios for these 2 characteristics have been defined as;

(i) Sensitivity {Slope}:

The slope of I/O characteristics should be at the specified value (usually 1).

It is often treated as Larger-The-Better when the output is a desirable characteristics (as in the case of Sensors, where the slope indicates the sensitivity).

$n = 10 \text{ Log}_{10}$ [square of slope or beta of the I/O characteristics]

On the other hand, when the output is an undesired characteristics, it can be treated as Smaller-the-Better.

$n = -10 \text{ Log}_{10}$ [square of slope or beta of the I/O characteristics]

(ii) Linearity (Larger-The-Better):

Most dynamic characteristics are required to have direct proportionality between the input and output. These applications are therefore called as "TRANSFORMATIONS". The straight line relationship between I/O must be truly linear i.e. with as little deviations from the straight line as possible.

$$n = 10 \text{ Log}_{10} \frac{\text{Square of slope or beta}}{\text{variance}}$$

Variance in this case is the mean of the sum of squares of deviations of measured data points from the best-fit straight line (linear regression).

TAGUCHI'S QUALITY LOSS FUNCTION

As per Taguchi philosophy, quality is the loss imparted to society from the time a product is shipped. The components of include the expense, waste, and lost opportunities that result when a product fails to meet the target value exactly. During production, costs such as inspection scrap and rework contribute to loss.

- The quality loss function is stated in financial terms which facilitate understanding for various entities within an organization, that is, management, engineering and production. The loss function is assumed to be proportional to the square of the deviation of the quality characteristic from the target value.

1. Quality Measurement

In quality improvement and design optimization the metric plays a crucial role. Unfortunately, a single metric does not serve all stages of product delivery.

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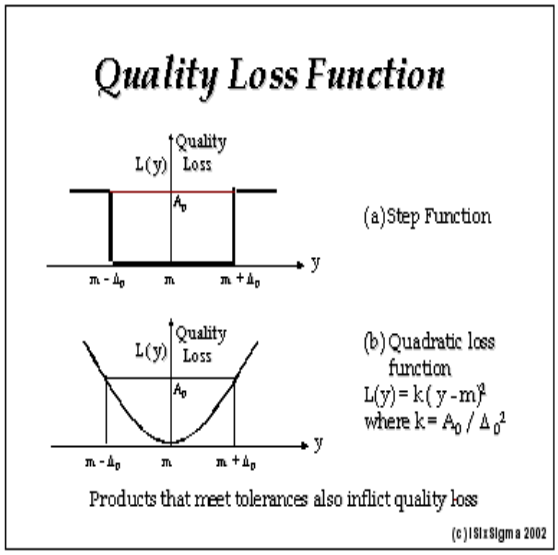
It is common to use the fraction of products outside the specified limits as the measure of quality. Though it is a good measure of the loss due to scrap, it miserably fails as a predictor of customer satisfaction. The quality loss function serves that purpose very well.



Let us define the following variables:

m: target value for a critical product characteristic

+/- $Delta_0$: allowed deviation from the target

A_0: loss due to a defective product

Then the quality loss, L, suffered by an average customer due to a product with y as value of the characteristic is given by the following equation: $L = k * (y - m)^2$

Where $k = (A_0 / Delta_0^2)$

If the output of the factory has distribution of the critical characteristic with mean m and variance s2, then the average quality loss per unit of the product is given by:

$$Q = k \{(mu - m)^2 + sigma^2 \}$$

2. Signal to Noise (S/N) Ratios

The product/process/system design phase involves deciding the best values/levels for the control factors. The signal to noise (S/N) ratio is an ideal metric for that purpose. The equation for average quality loss, Q, says that the customer's average quality loss depends on the deviation of the mean from the target and also on the variance. An important class of design optimization problem requires minimization of the variance while keeping the mean on target. Between the mean and standard deviation, it is typically easy to adjust the mean on target, but reducing the variance is difficult. Therefore, the designer should minimize the variance first and then adjust the mean on target. Among the available control factors most of them should be used to reduce variance. Only one or two control factors are adequate for adjusting the mean on target.

The design optimization problem can be solved in two steps:

1. Maximize the S/N ratio, *h*, defined as

$$h = 10 \log_{10} (h^2\sim / sigma^2)$$

This is the step of variance reduction.

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2. Adjust the mean on target using a control factor that has no effect on h. Such a factor is called a scaling factor. This is the step of adjusting the mean on target. One typically looks for one scaling factor to adjust the mean on target during design and another for adjusting the mean to compensate for process variation during manufacturing.

3. As per Taguchi, "Quality is the loss imparted to society from the time a product is shipped."

He attaches a monetary value to quality because he feels that this will make quality improvement understood by all –technical personnel as well as management. Typical examples of loss to society include failure to meet customer' requirements and unsatisfactory performance that leads to loss of good will and reduced market share. The degree to which the product or service meets customer's expectations affects magnitude of loss. Taguchi contends that the loss due to a product's variation in performance is proportional to the square of the performance characteristic's deviation from its target value.

Case: Consider the popular story of Sony and two of their television production facilities, one in the USA, the other in Japan. The color density of the televisions manufactured by Sony-USA were uniformly distributed and fell within the tolerance limits, $m \pm 5$ (where m is the target for color density), while the televisions from Sony-Japan followed a normal distribution, more televisions were on target but about 0.3% fell outside of the tolerance limits.

The color density distributions are illustrated in Figure 1. The differences in customer perceptions of quality resulted from Sony-USA paying attention only to meeting the tolerances whereas in Sony-Japan, the focus was on meeting the target and minimizing the variance around that target.

If we assign a grade to each television based on its color density as done in Figure 12, then we see that Sony- Japan produced many more Grade A sets and fewer Grade C sets in comparison to Sony-USA. Overall, a much larger portion of Sony-Japan's televisions receive higher grades then those made by Sony-USA; hence, the customer's preferred the televisions sets produced by Sony-Japan over those produced by Sony-USA.

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3. Quality loss function

Have a look at Figure 1 Color Density Distribution of Television Sets (Phadke, 1989)

To measure quality, Taguchi defines a Quality Loss Function. The quality loss function is a continuous function that is defined in terms of the deviation of a design parameter from an ideal or target value, see Figure 2b. Taguchi's view on the nature of the quality loss function represents a fundamental paradigm shift (particularly in the U.S.) in the way in which manufacturers consider whether or not a product is good. The traditional approach employed by U.S. manufacturers (as evidenced by Sony-USA) has been to use a "step function" that ensures that performance fell within the upper and lower specification limits.

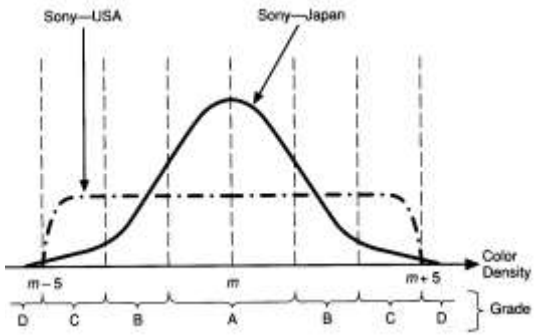

Figure 1: Color Density Distribution of Television Sets (Phadke, 1989)

Taguchi's loss function can be expressed in terms of the quadratic relationship:

$L = k (y - m) 2$

where y is the critical performance parameter value, L is the loss associated with a particular parameter y, m is the nominal value of the parameter specification, k is a constant that depends on the cost at the specification limits (can be determined conservatively by dividing the cost of scrap in Rupees , by the square of the lower or higher tolerance values). This function penalizes the deviation of a parameter from the specification value that contributes to deteriorating the performance of the product resulting in a loss to the customer. The key here is that the quality and cost of a manufactured product is influenced by the engineering design of the product as well as the process. By concentrating on product and process design that are robust i.e. less sensitive to uncontrollable factors such as temperature, humidity and manufacturing variations (noise factors), the Taguchi concept attempts to reduce the impact of noise factors rather than eliminating them. Also, manufacturing variability cannot be totally eliminated –that is incoming raw materials and components inherently exhibit variation. By dampening the effects of noise factors and by selecting the controllable factor levels that force the desirable quality characteristic to stay close to target value a robust design of the product and the process is achieved.

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Engineers have a good understanding of what the nominal size of the specification is. The usual lower and upper limits for the tolerance of a given design parameter are changed to a continuous function that presents any parameter value other than the nominal as a loss. The loss function given in is referred to as "nominal is best," but there are also expressions for cases when higher or lower values of parameters are better (Phadke, 1989).

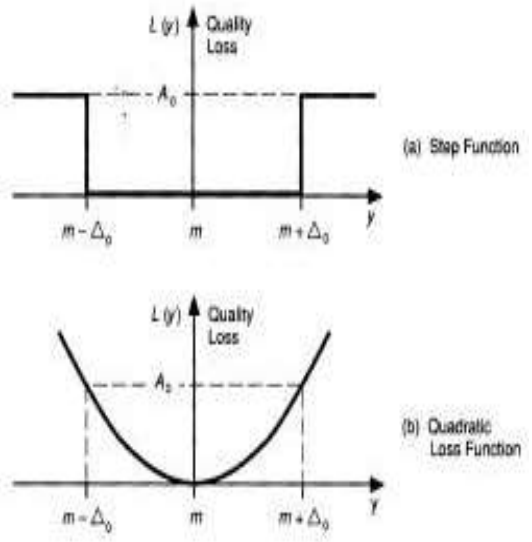

Figure 2: Quality Loss Function (Phadke, 1989)

If a large number of parts are considered, say N, the average loss per part is equal to the summation of the losses for each part, divided by the total N. The average quality loss results from deviation around the average value of y from the target and the mean square deviation of y around its own mean. The average quality loss can be expressed as:

$$L = k[S2 + (\square\square - m)2]$$

where $\square\square$ is the average value of y for the set of parts, and S2 is the variance around the average.

To minimize loss, the traditional approach is to monitor the process variables during production and adjust the process to reduce manufacturing imperfections so that response parameters fall within the specified tolerances. This method adds cost to the manufacturing process does not improve the quality of the product. Using Taguchi's approach, the average response has to be adjusted, and the variance must be reduced in order to minimize loss.

Reducing the variation is accomplished by product and process engineers who use off-line quality control techniques; adjustments to the average response are realized by process and production engineers during production using on-line quality control techniques. Within the Taguchi philosophy both quality improvement methods are considered; however, building quality into the product during the design stage (i.e., off-line) is the ultimate goal.

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STEPS IN TAGUCHI METHODOLOGY

Taguchi method is a scientifically disciplined mechanism for evaluating and implementing improvements in products, processes, materials, equipment, and facilities. These improvements are aimed at improving the desired characteristics and *simultaneously* reducing the number of defects by studying the key variables controlling the process and optimizing the procedures or design to yield the best results.

The method is applicable over a wide range of engineering fields that include processes that manufacture raw materials, sub systems, products for professional and consumer markets. In fact, the method can be applied to any process be it engineering fabrication, computer-aided-design, banking and service sectors etc. Taguchi method is useful for 'tuning' a given process for 'best' results.

Taguchi proposed a standard 8-step procedure for applying his method for optimizing any process,

8-Steps In Taguchi Methodology

Step-1: Identify The Main Function, Side Effects, And Failure Mode

Step-2: Identify The Noise Factors, Testing Conditions, And Quality Characteristics

Step-3:

Identify The Objective Function To Be Optimized

Step-4:

Identify The Control Factors And Their Levels

Step-5:

Select The Orthogonal Array Matrix Experiment

Step-6: Conduct The Matrix Experiment

Step-7: Analyze The Data,

Predict The Optimum Levels And Performance

Step-8:

Perform The Verification Experiment

And Plan The Future Action

EXPERIMENTAL DESIGN IN THE TAGUCHI METHOD

The concept of experimental design is the core of product and process design. The matrix that designates the setting of the controllable factors (design parameter) for each run or experiment is called an inner array by Taguchi. The matrix that designates the setting of uncontrollable or noise factors is called an outer array. Each run consists of a setting of the design parameters and an associated setting of the noise factors. The inner and outer arrays are

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respectively designated as the design and noise matrices.

The experimental design in Taguchi method is a set of methodology by which inherent variability of materials and manufacturing processes has been taken into account at the design stage The essence of Taguchi design is that multiple factors can be considered at once. Not only controlled factors are considered but also noise factors which exist within the production and user environment, all these are experimented to improve the yield in manufacturing and reliability in performance of the product. Taguchi design conducts balanced orthogonal experimental combinations which make Taguchi design even more effective than fractional design.

Taguchi constructed a special set of general designs for factorial experiments that covers many applications. They are orthogonal arrays with number of experiment, factors and levels for each special design orthogonal arrays. The use of these arrays helps to determine numbers of experiments needed for a given set of factors. When fixed number of levels for all factors is involved and the interaction are unimportant, standard orthogonal arrays will satisfy most experimental design needs. Taguchi method successfully resolves the difficulties in compacting experimental design by having the orthogonal arrays that represents the possible experimental condition and a standard procedure to analyze the experimental result. The Taguchi method is a concept developed base on the optimization through design of experiments, in which, experiment will be carried out and the value of quality is very much significant to discipline the way for developing a product and investigating complex problems Undoubtedly, this method has provided cost effective ways to examine and find available alternatives in design and processing issues. The activities started with brainstorming the quality characteristics and design parameters that are important to product or processes, design and conducting the experiments, analyzing the results to determine the optimum conditions and finally run the verification test at the optimum condition. The team approach and brainstorming activity in design optimization is very much consistent with the success of the design experiments as the knowledge and information on variables are synergistically extracted in deriving the benefit from Taguchi method .The preliminary understanding of the whole process will help in planning the experiment and selecting the critical factors that are to be

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tested, hence the number of experiment could be determined and time could be estimated efficiently.

Taguchi method emphasizes on having the least number of experiment to be conducted. Why larger experimentation is needed since it can be conducted in more efficient and productive ways is the principles in the Taguchi method. Taguchi method is complimented with the use of statistical process control techniques, number of factors to be controlled and which factors were most significant and dominant are quantified by analyzing the variance contributed by each factors. The statistical techniques in visualizing variation and the mean are applied to successfully make the Taguchi methodology come into effects and reality. The Taguchi method will provide information on which factors are important to be controlled and which levels are suitable to put quality characteristic on target, this will comprehend the application of the statistical quality control in ensuring process capability are maintained to the expected variation and goals. Taguchi's robust design method will allow wider manufacturing tolerances, lower grades components or materials and wider operating environment. It is a method of arriving at more reliable and durable products and process efficiently.

The benefit of improved design quality could be seen when product are produced in the production and reached to customer. The outcomes of minimal reduction in variation when product is produced with optimum combination of factors will yield consistent performance in desirable quality characteristic.

Significantly, according Phadke, the benefits of the application of Taguchi method are:

a) reduction in process variance reduction in fatal defects,
b) reduction in process time,
c) transition of design from research to manufacturing and
d) adaptation process to more precision technology.

As a results customer satisfaction is increased and costs are controlled when less warranty issues and sales are booming as expected. This is described further in its loss function approach on how to quantify cost benefits. The loss function approach is used to estimate the potential saving based on the improvement achieved during the experimentation if the product were designed to the optimum condition prescribed by the Taguchi design of

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experimental results. The improvement could be made by calculating the changes on the Mean Square Deviation (MSD) for calculating the S/N ratio. A bigger S/N ratio compare to past performance indicates improvement is attained over the product or process and this is visualized by the variation of data against the mean and target. The amount of saving is calculated by using the loss function formula which considers the cost of failure and the value of MSD. The calculation of MSD is obtained by comparing the unit's performance against the targeted performance of the quality characteristic Consequently the amount of expected saving could be estimated and process or product design could be adjusted according this goals and such decision are made to balance the profit and loss. On the another hand, Taguchi method is an efficient problem solving tools which can improve the performance of the product and process design and system with a significant achievement in experimental time and cost .

Of all the three stages of the offline quality engineering system (system design, parameter design and tolerance design), Taguchi's parameter design has proved to be the most powerful stage for process optimization. The experiment with Taguchi method is using partial factorial experiments where number of test combination is reduced into special set for designated application. The special set consists of orthogonal arrays which will determine the least and feasible number of experiment needed for a given set of factors. The total number of experiment and possible number of factors at are depicted in.

The orthogonal array designed by Taguchi only work well when there is minimal interaction among factors on the measured quality objective are independent of each other and are linear. The optimum condition still could be attained even interaction occurs between factors.

The degree of accuracy in performance estimate will depends on the degree of the complexity of interaction among all factors. Designing the experiment started with the identification of factors and effect of product and process under investigation. This could be done through cause and effect analysis in a team approach. This was explained in that a system is referred to a process, manufacturing line, an R and D environment or a given experimental situation.

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The measurement of the quality characteristic shall be determined whether it is numerical or attribute data. The design of experiment will identify factors to be studied and the orthogonal arrays that suit the number and level of the factors. Order of running the experiments shall be in random to reduce error result in experimentation. To increase the accuracy replication or repetition in experiment is emphasized in Taguchi method. Replication requires a new run of the same experiment in random order. Repetition can be accomplished when noise factors are tested at certain levels and observations can be taken by letting the noise conditions of the noise factors vary as they are naturally changed in practical situations combination. Each trial is repeated as planned before proceeding to the next trial run Sometimes it is not easy to set up an experimental conditions for noise factors, alternatively repeated.

Analysis of data is conducted by evaluating the results of the measured quality average performance at each level for all factors will be calculated and these results will be plotted to identify the main effects to the quality characteristic. It is the factorial effect that represents the difference between levels of each factor. The strongest effect is accounted by the highest S/N ratio. When required, study of interaction effect could be performed with special adoption of predicted interaction within factors in the orthogonal array of the experimentation. However, in Taguchi method consideration of factors interaction is very minimal as focus is more on the main effects. Taguchi methods do not specify any general guidelines for predicting interactions as the determination of possible interaction are known by some other means or from past experience or previous experiments As the analysis in Taguchi is measuring the variance effects of each factor with mean to be on target. The calculation base on Analysis of Variance (ANOVA) is applied extensively to quantify the effect of factor to desired quality characteristic. The result is tabulated to find the average performance at each level before the sum of square of each factor could be calculated.

IMPLEMENTATION OF ROBUST DESIGN

To implement robust design, Taguchi advocates the use of an “inner array” and “outer array” approach. The “inner array” consists of the OA that contains the control factor settings; the “outer array” consists of the OA that contains the noise factors and their settings which are under investigation. The combination of the “inner array” and

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"outer array" constitutes what is called the "product array" or "complete parameter design layout." Examples of each of these arrays are given in the case study in the next section. The product array is used to systematically test various combinations of the control factor settings over all combinations of noise factors after which the mean response and standard deviation may be approximated for each run using the following equations.

The preferred parameter settings are then determined through analysis of the "signal-to-noise" (SN) ratio where factor levels that maximize the appropriate SN ratio are optimal. There are three standard types of SN ratios depending on the desired performance response that is

- Smaller the better (for making the system response as small as possible):
- Nominal the best (for reducing variability around a target):
- Larger the better (for making the system response as large as possible):

These SN ratios are derived from the quadratic loss function and are expressed in a decibel scale. Once all of the SN ratios have been computed for each run of an experiment, Taguchi advocates a graphical approach to analyze the data. In the graphical approach, the SN ratios and average responses are plotted for each factor against each of its levels. The graphs are then examined to "pick the winner," i.e., pick the factor level which (1) best maximize SN and (2) bring the mean on target (or maximize or minimize the mean, as the case may be). Using this information, the control factors can also be grouped as follows.

1. Factors that affect both the variation and the average performanceof the product.
2. Factors that affect the variation only.
3. Factors that affect the average only.
4. Factors that do not affect either the variance or the average.

Factors in the first and second groups can be utilized to reduce the variations in the system, making it more robust. Factors in the third group are then used to adjust the average to the target value. Lastly, factors in the fourth group are set to the most economical level. Finally, confirmation tests should be run at the "optimal" product settings to verify that the predicted performance is actually realized. A demonstration of Taguchi's approach to parameter design serves as our case study in the next section.

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SUMMARY

Every experimenter develops a nominal process/product that has the desired functionality as demanded by users. Beginning with these nominal processes, he wishes to optimize the processes/products by varying the control factors at his disposal, such that the results are reliable and repeatable (i.e. show less variations).

In Taguchi Method, the word "optimization" implies "determination of BEST levels of control factors". In turn, the BEST levels of control factors are those that maximize the Signal-to-Noise ratios. The Signal-to-Noise ratios are log functions of desired output characteristics. The experiments, that are conducted to determine the BEST levels, are based on "Orthogonal Arrays", are balanced with respect to all control factors and yet are minimum in number. This in turn implies that the resources (materials and time) required for the experiments are also minimum.

Taguchi method divides all problems into 2 categories - STATIC or DYNAMIC. While the Dynamic problems have a SIGNAL factor, the Static problems do not have any signal factor. In Static problems, the optimization is achieved by using 3 Signal-to-Noise ratios - smaller-the-better, LARGER-THE-BETTER and nominal-the-best. In Dynamic problems, the optimization is achieved by using 2 Signal-to-Noise ratios - Slope and Linearity.

Taguchi Method is a process/product optimization method that is based on 8-steps of planning, conducting and evaluating results of matrix experiments to determine the best levels of control factors. The primary goal is to keep the variance in the output very low even in the presence of noise inputs. Thus, the processes/products are made ROBUST against all variations.

CONCLUSIONS

The Taguchi approach to design of experiments is an effective strategy in product and process optimization. The approach of Taguchi method is able to improve the process performance when optimum parameters setting used in the process give better output performance in terms of quality and productivity. Taguchi method will identify the possible factors for the significant effect to response variable. This approach is applicable to attribute and variable data for which they are important to be analyzed. Once the factor of an unacceptable variation is identified, follow up corrective action or preventive action can be taken to improve and prevent the problem to occur and escalate. The Taguchi

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approach is in tandem with the approach required in effective way and scientifically implemented for solving problem. The improvement made through the Taguchi method can be quantified easily by applying the loss function concept and calculation of the loss. The amount saving can be calculated, estimated saving will assist to prevent unnecessary losses and this will increase the competitiveness of the manufacturer as well as increasing the customer confidence. It is strongly recommended to use Taguchi method in industry as one of the design experiment methodology in improving the product and process quality. The great importance of its approach will enhance the production performance in quality product with minimal operating cost. Taguchi approach will result in fast decision making and are very much useful to be used in a specific and simple process.

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