TAGUCHI APPROACH TO DESIGN OF EXPERIMENTS

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Abstract: Since the early 1980's Taguchi methods to quality control have been used to optimize the process of engineering experiments. This approach has been a unique and powerful quality improvement discipline that differs from traditional practices. The general approach has far exceeded the initial quality control application and has developed in to a philosophy in its own right. This paper attempts to understand the application of Taguchi methodology to the design of experiments.

INTRODUCTION

The Taguchi approach has successfully been applied in several industrial organizations changing their outlook to quality management. It is based on three simple yet powerful fundamental concepts. Bendell & Pridmore (1989).

1. Quality should be designed into the product and not inspected into it.
2. Quality is best achieved by minimizing the deviation from target. The product should be so designed that it is immune to uncontrollable environmental factors.
3. The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

Taguchi philosophy is to design quality into the product rather than to inspect for it after its production. Quality improvement should begin at the very beginning i.e. during the design stage of the product development and should continue through the production process. Dr Taguchi observed that no amount of inspection could put quality back into the product and it only treated the symptom, therefore he argued that quality concepts should be based upon, and developed around, the philosophy of prevention. Bendell & Pridmore (1989).

TAGUCHI METHOD

The Taguchi Method is a multi-stage process, namely, (1) Systems Design, (2) Parameter Design, and (3) Tolerance Design. The following sections delineate the three-stage process suggested by Dr. Taguchi to achieve desirable product quality.

Systems Design: The focus of the systems design is on determining the suitable working levels of design factors. It includes designing and testing systems based on the researcher's judgment of selected materials, parts and technology. It also involves innovation and knowledge from applicable fields of sciences and technology.

Parameter Design: Parameter design seeks to determine the factor levels that produce the best performance of the product/process under study. The optimal condition is selected so that the influence of uncontrollable factors (noise factors) causes minimum variation of system performance. Noise – Performance Statistics (NPS) are measures of process variability that are used to identify *'Control'* factors and the combined optimal levels which minimize that variability. Signal-to-Noise ratios (S/N ratios) are also used to measure the effect of *'Noise'* on the system. A robust (insensitive) system will have a high S/N ratio.

Noise Factors: The 'noise' factors can be classified on the basis of being either internal or external to the system, as follows;

Inner Noise – is the type of variation from specification, which can be described as between product noise, which remains in the piece-to-piece, variation after the general mean level conforms to specification.

Outer Noise – is the variation, which is, imposed by circumstances, which occur after the product leaves the producer, e.g., temperature, humidity, wear and tear effects.

Tolerance Design: Tolerance design is a way to fine-tune the results of the parameter design by tightening the tolerance of factors with significant influence on the product. Such steps usually identify the need of innovation and identification of better materials, parts, machinery etc.

APPLICATION PROCEDURES

The Taguchi method is used to improve the quality of products and processes. Improved quality results when a higher level of performance is consistently obtained. The highest possible performance is obtained by determining the optimum combination of design factors. The consistency of performance is obtained by making the product/process insensitive to the influence of the uncontrollable factor. In Taguchi's approach, optimum design is determined by using design of experiment principles, and consistency of performance is achieved by carrying out the trial conditions under the influence of the noise factors.

Brainstorming: This is a necessary first step in any application. The session should include individuals with first hand knowledge of the project. All matters should be decided based on group consensus, (One person -- One vote). Design engineers, technicians and scientists with relevant experience and expertise are obvious contributors. A competent statistician should be a valuable part of the team.

It is a necessary part of the exercise at this time to have a basic statement of objectives and what is expected in terms of product specification in as much detail as possible.

Taguchi defined as quality as a characteristic that avoids loss to the society from the time the product is shipped and is measured in monetary terms. Taguchi uses a loss function – a quadratic function is normally used as in Gunter (1987). Figure 1 depicts the graphical representation of the loss function.

Figure 1:Taguchi Loss Function

Designing Experiments: Once the factors and levels have been determined in the brainstorming session, the experiments can be designed and the methods to carry them out established. The design process of the experiment involves the following steps:

__Select the appropriate orthogonal array.
__Assign factor and interaction to columns.
__Describe each trial condition.
__Decide order and repetitions of trial conditions.

Running Experiment: The experiments are then run in random order when possible.

Analyzing Results: Before analysis, the raw experimental data might have to be combined into an overall evaluation criterion. This is particularly true when there are multiple criteria of evaluation. Analysis is performed to determine the following:

__The optimum design.
__Influence of individual factors.
__Performance at the optimum condition.
__Relative influence of individual factors, etc.

Running Confirmation Experiment(s): Running the experiments at the optimum condition is the necessary final step. Once the confirmatory experiment is over it is necessary to do two other things:
An accurate costing of the effects of the optimal level of perimeters of the product is carried out and also a detailed report is presented on the findings to make use of in other similar products.

THE EXPERIMENTAL DESIGN

The techniques for laying out experiments when multiple factors are involved, has been known for a long time and is popularly known as the Factorial design of experiments. This method helps the researcher to determine the possible combinations of factors and to identify the best combination. However in industrial settings it is extremely costly to run a number of experiments to test all combinations. The Taguchi approach developed rules to carry out experiments, which further simplified and standardized the design of the experiment, along with minimizing the number of factor combinations that would be required to test for the factor effects. Bendell & Pridmore (1989).

ORTHOGONAL RAYS [Bendell & Pridmore (1989); Baker et al. (1984); Wu (1986)]

The Taguchi design of experiment makes use of Orthogonal Arrays (OA) to help design the experiment. By combining the orthogonal Latin squares in a unique manner Taguchi prepared a set of common OA's to be used for a number of experimental situations. A common OA for 2-level factors is shown in Table 1.

Factors							
Tria l # A	**B**		**C**	**D**	**E**	**F**	**G**
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

Table 1: Trial Runs for an L_8 Array

This array is designated by the symbol L_8, and is used to design experiments with upto seven 2-level factors. The array has 8 rows and 7 columns; each row represents a trial condition with factor levels indicated by the numbers in the row. Each column contains four level 1 and four level 2 conditions for the factor assigned to the column. Two 2-level factors combine in four possible ways, such as, (1,1), (1,2), (2,1), and (2,2). When the two columns of an array form these combinations the same number of time, the columns are said to be balanced or orthogonal. The vertical columns correspond to the factors specified in the study.

The OA facilitates the experimental design process. While designing the experiment the most suitable array is selected, the factors assigned to the appropriate columns and the trial combinations of the experiments determined. One of the major advantages of the OA is that it helps preserve the consistency of the design, even though different researchers may assign different factors to different columns.

The OA's provide a recipe for fractional factorial experiments, which satisfy a number of situations. When a fixed number of levels for all factors are involved and the interactions are unimportant, standard OA's satisfy most experimental needs. A modification of the OA's however becomes necessary when mixed levels and interactions are present.

AN ILLUSTRATION OF TAGUCHI DESIGN

A researcher has identified three controllable factors for a plastic molding process. Each factor can be applied at two levels. The researcher wants to determine the optimum combination of the levels of these factors and to know the contribution of each to the product quality.

Scope and Size of Experiment: The scope of the study, i.e., cost and time availability, is factors that help determine the size of the experiment. The number of experiments that can be accomplished in a given period of time and the associated costs are strictly dependent on the type of project under study.

The Design: There are 3 factors, each at 2 levels, thus an L_4 array will be suitable. The L_4, OA with the spaces for the factors and their levels are shown in the table below. There are four independent experimental conditions in an L_4. These conditions are shown in the rows, Table 2. The experiments can be spelled out as, for example in Bendell & Pridmore (1989).

<table>
<tr><td colspan="2">Variable Description</td><td colspan="2">Level 1</td><td colspan="3">Level 2</td></tr>
<tr><td colspan="2">Injection Pressure</td><td colspan="2">250 psi</td><td colspan="3">350 psi</td></tr>
<tr><td colspan="2">Mold Temperature</td><td colspan="2">150 F</td><td colspan="3">200 F</td></tr>
<tr><td colspan="2">Set Time</td><td colspan="2">6 Sec</td><td colspan="3">9 sec</td></tr>
<tr><td colspan="7">Repetitions</td></tr>
<tr><td>Experi</td><td>1</td><td>2</td><td>3</td><td>1</td><td>2</td><td>3</td></tr>
</table>

ment Numbe r						
1	1 1 1 30					
2	1 2 2 25					
3	2 1 2 34					
4	2 2 1 27					

Table 2: Experimental Parameters

Randomization: Whenever possible the experiments must be run in a random order. However if multiple receptions are planned, say 3 runs for each of the 4 conditions, then the experiment could proceed in either of the following ways:

Replication: All trial conditions are run in random order and the repetitions are treated as trials.

Repetition: The original 4 runs are randomly assigned but the three successive repetitions are followed on before taking up another trial. This helps reduce set-up costs.

ANALYSIS OF RESULTS

In the Taguchi method the results of the experiments are analyzed to achieve the following objectives: (1) to establish the best or optimal condition for the product or process, (2) to establish the contribution of individual factors, and (3) to estimate the response under optimal conditions.

The contribution of individual quality influencing factors is the deciding key of the control to be enforced on the product design. A commonly applied statistical treatment - The Analysis of Variance (ANOVA) - is used to analyze the results of the OA experiment in product design, and to determine how much variation each quality-influencing factor has contributed. By studying the main effects of each of the factors, the general trends of the influence factors, towards the product, or process, can be characterized. The characteristics can be controlled, such that a lower, or a higher, value in a particular quality-influencing factor produces the preferred result. Thus, the levels of influencing factors, to produce the best results, can be predicted.

There are two different methodologies in carrying out the complete OA analysis. A common approach is to analyze the average result of repetitive runs, or a single run, through ANOVA analysis as discussed. The other approach, which is a better method for multiple runs, is to use S/N ratios for the same steps in the analysis. The objective of S/N analysis is to determine the most optimum set of the operating conditions, from variations of the influencing factors within the results. The signals, in this case, will be those factors, which are invariant. Noise are those influencing factors that are active. Details regarding the methods of OA results analysis-using ANOVA and signal-to-noise ratio can be referred to in for example Roy (1990).

APPEAL & LIMITATIONS

Taguchi's design has wide-ranging applications. Generally speaking, experimental design with OA's can be applied where there are a large number of design factors. OA's for the design of experiments, signal/noise analysis, and cost guidance based on loss function has made his approach increasingly popular among practicing engineers. Also the team approach to problem solving resulting from the method has applications beyond the production line. The salient features of the appeal of the Taguchi methodology can be summarized as providing up front improvement of quality by design and process development, measurement of quality in terms of deviation from the target (using the Loss function), problem solving technique by involving the whole team, consistency in experimental design and analysis, reduction of time and cost of experiments and reduction of product warranty and service costs by addressing them with the loss function.

The most severe limitation of the Taguchi method is the need for timing with respect to product/process development. The technique can only be effective when applied early in the design of the product/process system. After the design variables are determined and their nominal values are specified, experimental design may not be as cost effective.

AREAS OF APPLICATION

The Taguchi design is being extensively used in the industry. Literature on the methodology is full of case studies from the Automobile, Plastics, Electronics, Process and Information industries. Amongst the leading pioneers of Taguchi methodology in USA are AT&T, Bell Laboratories and ITT Corporation Gunter (1987). Case studies in the Information technology, Automobile and Process Industries are also found in Gunter (1987) and Sullivan (1987).

SUMMARY

Dr Genuchi Taguchi's method of quality engineering can be very effective when used properly. The overall system should be chosen to meet the customer's needs at the lowest cost. The parameters of the system should be chosen to minimize the system's sensitivity to variance (make the design "robust"). Finally, the tolerances for the system can be set using economic safety factors, which are based on Taguchi's loss function. These steps for engineering design can greatly improve quality and lower cost for any product.

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