TAGUCHI APPROACH TO DESIGN OPTIMIZATION FOR QUALITY AND COST: AN OVERVIEW

Resit Unal

Edwin B. Dean

INTRODUCTION

Calibrations to existing cost of doing business in space indicate that to establish human presence on the Moon and Mars with the Space Exploration Initiative (SEI) will require resources, felt by many, to be more than the national budget can afford. In order for SEI to succeed, we must actually design and build space systems at lower cost this time, even with tremendous increases in quality and performance requirements, such as extremely high reliability. This implies that both government and industry must change the way they do business. Therefore, new philosophy and technology must be employed to design and produce reliable, high quality space systems at low cost.

In recognizing the need to reduce cost and improve quality and productivity, Department of Defense (DoD) and National Aeronautics and Space Administration (NASA) have initiated Total Quality Management (TQM). TQM is a revolutionary management strategy in quality assurance and cost reduction. TQM requires complete management commitment, employee involvement, and use of statistical tools.

The quality engineering methods of Dr. Taguchi, employing design of experiments (DOE), is one of the most important statistical tools of TQM for designing high quality systems at reduced cost. Taguchi methods provide an efficient and systematic way to optimize designs for performance, quality, and cost. Taguchi methods have been used successfully in Japan and the United States in designing reliable, high quality products at low cost in such areas as automobiles and consumer electronics (Cullen and Hollingum, 1987; Logothetis and Salmon, 1988; Sullivan, 1987; Wille, 1990). However, these methods are just beginning to see application in the aerospace industry.

The purpose of this paper is to present an overview of the Taguchi methods for improving quality and reducing cost, describe the current state of applications and its role in identifying cost sensitive design parameters.

TAGUCHI ON QUALITY

Quality has been defined by many as; "being within specifications," "zero defects," or "customer satisfaction." However, these definitions do not offer a method of obtaining quality or a means of relating quality to cost. Taguchi proposes a holistic view of quality which relates quality to cost, not just to the manufacturer at the time of production, but to the customer and society as a whole (Phadke, 1989). Taguchi defines quality as, "The quality of a product is the (minimum) loss imparted by the product to the society from the time product is shipped" (Bryne and Taguchi, 1986). This economic loss is associated with losses due to rework, waste of resources during manufacture, warranty costs, customer complaints and dissatisfaction, time and money spent by customers on failing products, and eventual loss of market share.

Figure-1 illustrates the loss function and how it relates to the specification limits.
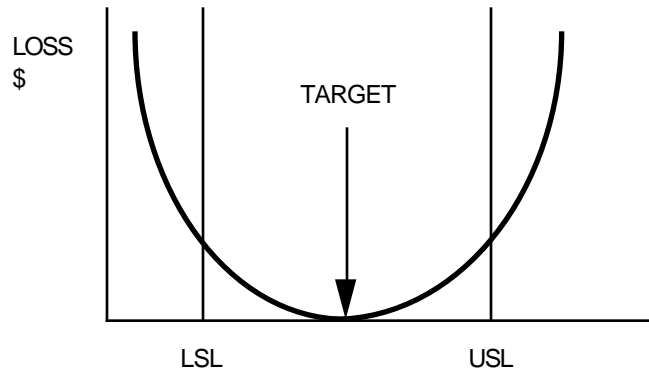
Figure-1; The Quadratic Loss Function

When a critical quality characteristic deviates from the target value, it causes a loss. In other words, variation from target is the antithesis of quality. Quality simply means no variability or very little variation from target performance (Di Lorenzo, 1990). An examination of the loss function shows that variability reduction or quality improvement drives cost down. Lowest cost can only be achieved at zero variability from target. Continuously pursuing variability reduction from the target value in critical quality characteristics is the key to achieve high quality and reduce cost.

Taguchi's quadratic loss function is the first operational joining of cost of quality and variability of product that allows design engineers to actually calculate the optimum design based on cost analysis and experimentation with the design (Teicholz, 1987).

ACHIEVING VARIABILITY REDUCTION: QUALITY BY DESIGN

Product/process design has a great impact on life cycle cost and quality. Taguchi emphasizes pushing quality back to the design stage since inspection and statistical quality control can never fully compensate for a bad design (Bendell, 1988).

The quality engineering methods of Dr. Taguchi seek to design a product/process which is insensitive or robust to causes of quality problems. The three steps of quality by design are system design, parameter design, and tolerance design (Taguchi, 1986).

System Design

System design involves the development of a system to function under an initial set of nominal conditions. System design requires technical knowledge from science and engineering.

Parameter Design

After the system architecture has been chosen, the next step is parameter design. The objective here is to select the optimum levels for the controllable system parameters such that the product is functional, exhibits a high level of performance under a wide range of conditions, and is robust against noise factors that cause variability. Noise factors are those that can not be controlled or are too expensive to control. Control factors are those parameters that can be set and maintained (design features).

Studying the design parameters one at a time or by trial and error until a first feasible design is found is a common approach to design optimization (Phadke, 1989). However, this leads either to a very long and expensive time span for completing the design or to a premature termination of the design process due to budget or schedule pressures. The result, in most cases, is a product design which is far from optimal. By

varying design parameters one at a time, the study of 13 design parameters at 3 levels would require 1,594,323 (3^{13}) possible experimental evaluations. The time and cost to conduct such a detailed study during advanced design is prohibitive. Naturally, one would like to reduce the number of experimental evaluations to a practical point, yet reach a near optimal solution. The problem is to choose an appropriate parameter configuration. Taguchi's approach to parameter design provides an answer.

Taguchi's Approach to Parameter Design

Taguchi's approach to parameter design provides the design engineer with a systematic and efficient method for determining near optimum design parameters for performance and cost (Kackar, 1985; Phadke, 1989; Taguchi 1986). The objective is to select the best combination of control parameters so that the product or process is most robust with respect to noise factors.

The Taguchi method utilizes orthogonal arrays from design of experiments theory to study a large number of variables with a small number of experiments. Using orthogonal arrays significantly reduces the number of experimental configurations to be studied. Furthermore, the conclusions drawn from small scale experiments are valid over the entire experimental region spanned by the control factors and their settings (Phadke, 1989).

Orthogonal arrays are not unique to Taguchi. They were discovered considerably earlier (Bendell, 1988). However, Taguchi has simplified their use by providing tabulated sets of standard orthogonal arrays and corresponding linear graphs to fit specific projects (ASI, 1989; Taguchi and Konishi, 1987). A typical tabulation is shown in Figure 2.

	A	B	C	D
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

Figure 2: L_9 (3^4) Orthogonal Array

In this array, the columns are mutually orthogonal. That is, for any pair of columns, all combinations of factor levels occur; and they occur an equal number of times. Here there are four parameters A, B, C, and D, each at three levels. This is called an "L_9" design, with the 9 indicating the nine rows, configurations, or prototypes to be tested. Specific test characteristics for each experimental evaluation are identified in the associated row of the table. Thus, L_9 means that nine experiments are to be carried out to study four variables at three levels. The

number of columns of an array represents the maximum number of parameters that can be studied using that array. Note that this design reduces 81 (3^4) configurations to 9 experimental evaluations.

There are greater savings in testing for the larger arrays. For example, using an L_{27} array, 13 parameters can be studied at 3 levels by running only 27 experiments instead of 1,594,323 (3^{13}).

The Taguchi method can reduce research and development costs by improving the efficiency of generating information needed to design systems that are insensitive to usage conditions, manufacturing variation, and deterioration of parts. As a result, development time can be shortened significantly; and important design parameters affecting operation, performance, and cost can be identified. Furthermore, the optimum choice of parameters can result in wider tolerances so that low cost components and production processes can be used. Thus, manufacturing and operations costs can also be greatly reduced.

Tolerance Design

When parameter design is not sufficient for reducing the output variation, the last phase is tolerance design. Narrower tolerance ranges must be specified for those design factors whose variation imparts a large negative influence on the output variation. To meet these tighter specifications, better and more expensive components and processes are usually needed. Because of this, tolerance design increases production and operations costs (Phadke, 1989).

Current Trend in Design Activity

Most American and European engineers focus on system design and tolerance design to achieve performance (Cullen and Hollingum, 1987). A common practice in aerospace design is to base an initial prototype on the first feasible design (system design); study the reliability and stability against noise factors; and correct any problems by requesting better, costlier components, and elements (tolerance design). In other words, a minimum amount of energy is spent on parameter design. As a result, the opportunity to improve quality while decreasing cost is missed. Relying on tolerance design makes products more expensive to produce and operate and relying on improved concept design requires achieving technological breakthroughs which are difficult to schedule and, hence, lead to longer development time (Phadke, 1989).

Taguchi's parameter design method is still evolving. With active research going on in Japan and U.S., it is expected that the application of the method will become widespread in the coming decade.

OVERVIEW OF THE TAGUCHI METHOD

Figure 3 provides a brief overview of the process followed by Taguchi's approach to parameter design (Phadke, 1989; Wille, 1990). The details of these steps are briefly described in the following sections.
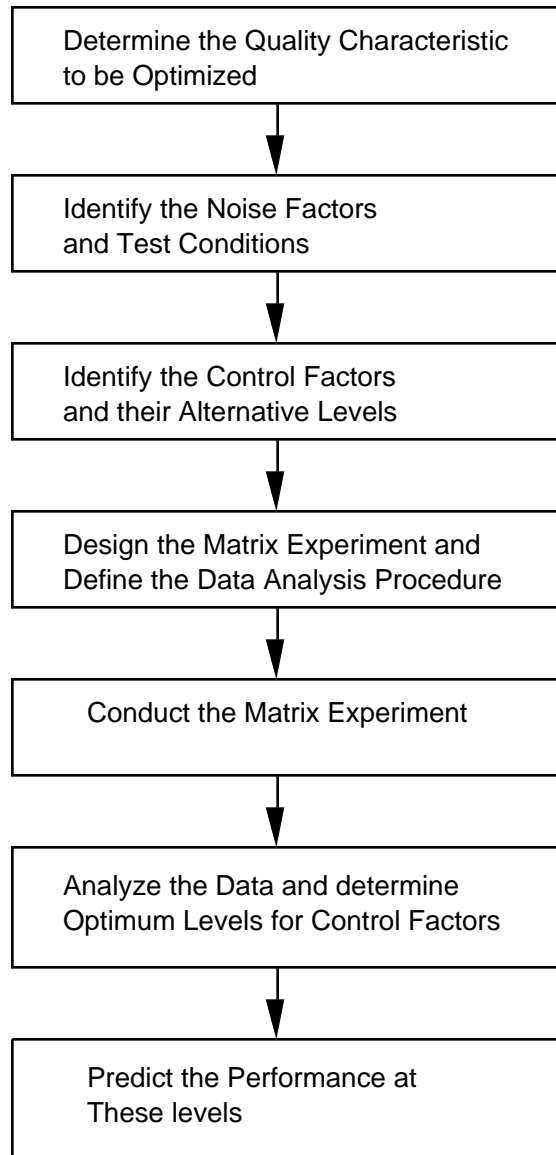
Figure 3. Flowchart of the Taguchi Method

I. Determine the Quality Characteristic to be Optimized

The first step in the Taguchi method is to determine the quality characteristic to be optimized. The quality characteristic is a parameter whose variation has a critical effect on product quality. It is the output or the response variable to be observed. Examples are weight, cost, corrosion, target thickness, strength of a structure, and electromagnetic radiation.

II. Identify the Noise Factors and Test Conditions

The next step is to identify the noise factors that can have a negative impact on system performance and quality. Noise factors are those parameters which are either uncontrollable or are too expensive to control. Noise factors include variations in

environmental operating conditions, deterioration of components with usage, and variation in response between products of same design with the same input.

III. Identify the Control Parameters and Their Alternative Levels

The third step is to identify the control parameters thought to have significant effects on the quality characteristic. Control (test) parameters are those design factors that can be set and maintained. The levels (test values) for each test parameter must be chosen at this point. The number of levels, with associated test values, for each test parameter define the experimental region.

IV. Design the Matrix Experiment and Define the Data Analysis Procedure

The next step is to design the matrix experiment and define the data analysis procedure. First, the appropriate orthogonal arrays for the noise and control parameters to fit a specific study are selected. Taguchi provides many standard orthogonal arrays and corresponding linear graphs for this purpose (Taguchi and Konishi,1987).
After selecting the appropriate orthogonal arrays, a procedure to simulate the variation in the quality characteristic due to the noise factors needs to be defined. A common approach is the use of Monte Carlo simulation (Phadke, 1989). However, for an accurate estimation of the mean and variance, Monte Carlo simulation requires a large number of testing conditions which can be expensive and time consuming. As an alternative, Taguchi proposes orthogonal array based simulation to evaluate the mean and the variance of a product's response resulting from variations in noise factors (Bryne and Taguchi, 1986; Phadke, 1989; Taguchi, 1986). With this approach, orthogonal arrays are used to sample the domain of noise factors. The diversity of noise factors are studied by crossing the orthogonal array of control factors by an orthogonal array of noise factors (Bendell, 1988), as shown in Figure 4. The results of the experiment for each combination of control and noise array experiment are denoted by $Y_{i,j}$.
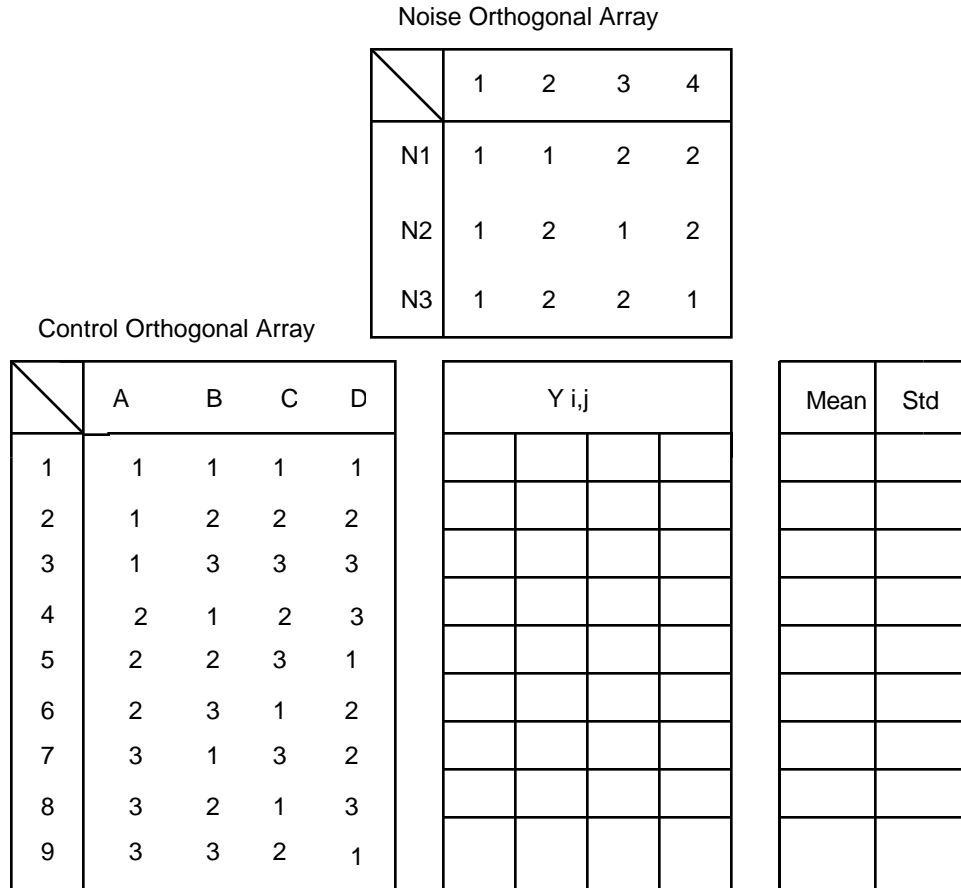
Noise Orthogonal Array

	1	2	3	4
N1	1	1	2	2
N2	1	2	1	2
N3	1	2	2	1

Control Orthogonal Array

	A	B	C	D		Y i,j				Mean	Std
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							

Figure 4:   Orthogonal Array Based Simulation Algorithm

V. Conduct the Matrix Experiment

The next step is to conduct the matrix experiment and record the results. The Taguchi method can be used in any situation where there is a controllable process (Meisl, 1990; Phadke, 1989; Wille, 1990). The controllable process can be an actual hardware experiment, systems of mathematical equations, or computer models that can adequately model the response of many products and processes.

VI. Analyze the Data and Determine the Optimum Levels

After the experiments have been conducted, the optimal test parameter configuration within the experiment design must be determined. To analyze the results, the Taguchi method uses a statistical measure of performance called signal-to-noise (S/N) ratio borrowed from electrical control theory (Phadke, 1989). The S/N ratio developed by Dr. Taguchi is a performance measure to choose control levels that best cope with noise (Bryne and Taguchi, 1986; Phadke, 1989). The S/N ratio takes both the mean and the variability into account. In its simplest form, the S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). The S/N equation depends on the criterion for the quality characteristic to be optimized. While there are many different possible S/N ratios, three of them are considered standard and are generally applicable in the situations below (Bryne and Taguchi, 1986; Phadke, 1989);

- Biggest-is-best quality characteristic (strength, yield),
- Smallest-is-best quality characteristic (contamination),
- Nominal-is-best quality characteristic (dimension).

Whatever the type of quality or cost characteristic, the transformations are such that the S/N ratio is always interpreted in the same way: the larger the S/N ratio the better. As an example, Figure 5 presents plots of S/N for two control parameters (temperature) t1 and t2, studied at 3 levels. An examination of the S/N plots reveal that parameter level setting for t2 has a larger effect on the quality characteristic then t1. Clearly both parameters should be set at level one to optimize the quality characteristic.
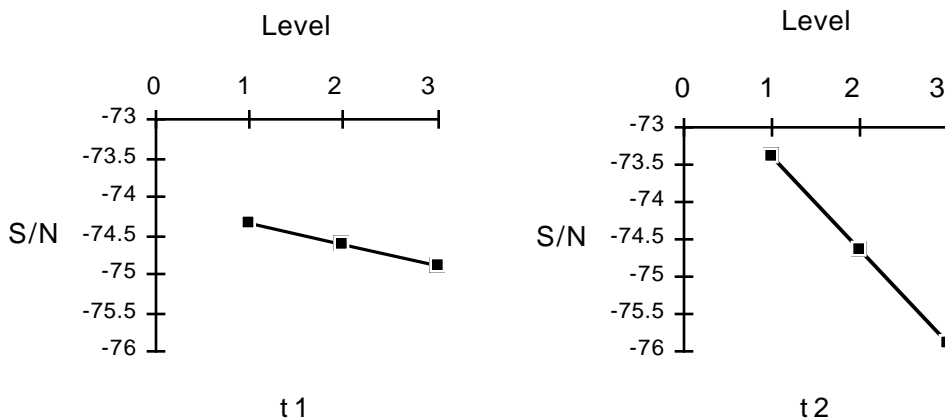

Figure 5. Examples of S/N Ratios for two control Parameters

VII. Predict the Performance at These Levels

Using the Taguchi method for parameter design, the predicted optimum setting need not correspond to one of the rows of the matrix experiment. This is often the case when highly fractioned designs are used (Bryne and Taguchi, 1986; Phadke, 1989). Therefore, as the final step, an experimental confirmation is run using the predicted optimum levels for the control parameters being studied.

CONCLUSIONS

An overview of the Taguchi method has been presented and the steps involved in the method were briefly described. Overall, the Taguchi method is a powerful tool which can offer simultaneous improvements in quality and cost. Furthermore, the method can aid in integrating cost and engineering functions through the concurrent engineering approach required to evaluate cost over the experimental design.

The Taguchi method emphasizes pushing quality back to the design stage, seeking to design a product/process which is insensitive or robust to causes of quality problems. It is a systematic and efficient approach for determining the optimum experimental configuration of design parameters for performance, quality, and cost. Principal benefits include considerable time and resource savings; determination of important factors affecting operation, performance and cost; and quantitative recommendations for design parameters which achieve lowest cost, high quality solutions.

REFERENCES

American Supplier Institute Inc (ASI), 1989, "Taguchi Methods: Implementation Manual", ASI, Dearborn, MI.

Bendell, A., 1988, "Introduction to Taguchi Methodology", <u>Taguchi Methods: Proceedings of the 1988 European Conference:</u>, Elsevier Applied Science, London, England, pp. 1-14.

Bryne, D., M. and Taguchi, S.,1986, "The Taguchi Approach to Parameter Design", ASQC Quality Congress Transactions, Anaheim, CA, p 168.

Cullen J. and Hollingum, J., 1987. <u>Implementing Total Quality</u>, Springer-Verlag, New York, N.Y.

Di Lorenzo, R. D. 1990, "The Monetary Loss Function - or Why We need TQM", Proceedings of the International Society of Parametric Analysts,12th Annual Conference, San Diego, CA, pp 16-24.

Kackar, Raghu, 1985, "Off-Line Quality Control, Parameter Design, and the Taguchi Method", Journal of Quality Technology, Vol. 17, No.4, pp. 176-188.

Logothetis N. and Salmon J. P., 1988, "Tolerance Design and Analysis of Audio-Circuits", <u>Taguchi Methods: Proceedings of the 1988 European Conference:</u>, Elsevier Applied Science, London, England, pp. 161-175.

Meisl, C. J., 1990, "Parametric Cost Analysis in the TQM Environment", Paper presented at the 12th Annual Conference of <u>International Society of Parametric Analysts,</u> San Diego, CA.

Sullivan, L. P., 1987. "The Power of Taguchi Methods", <u>Quality Progress</u>, June, pp 76-79.

Phadke, S. M., 1989. <u>Quality Engineering Using Robust Design,</u> Prentice Hall, Englewood Cliffs, N.J.

Taguchi, G., 1986. <u>Introduction to Quality Engineering</u>, Asian Productivity Organization (Distributed by American Supplier Institute Inc., Dearborn, MI).

Taguchi, G. and Konishi, S., 1987. <u>Orthogonal Arrays and Linear Graphs</u>, American Supplier Institute Inc., Dearborn, MI.

Teicholz, E. and Orr, J., N., 1987, <u>Computer Integrated Manufacturing Handbook</u>, McGraw-Hill, New York, N. Y.

Wille, R., 1990, "Landing Gear Weight Optimization Using Taguchi Analysis", Paper presented at the 49th Annual International Conference of <u>Society of Allied Weight Engineers Inc</u>, Chandler, AR.