An Overview of Taguchi Method: Evolution, Concept and Interdisciplinary Applications

Samruddhi Rao, Pragati Samant, Athira Kadampatta, Reshma Shenoy

Abstract— This paper presents an overview of Taguchi Method, encompassing all major features which include evolution, concept, design steps, vital considerations, analysis and its interdisciplinary applications. In our approach we trace the evolution of this method with time to identify the vital concepts that contributed to its present formulation, thereby stating the significance of this method over other conventional techniques. A detailed study of design steps and analysis is presented. It also focuses on the applications of this method in diverse fields and states the benefits provided due to its employment. An attempt is also made to analyze the effectiveness of this method in combination with other methods thus highlighting its usage in both isolated and synergistic approaches. It thus reinforces the vitality of this method as an efficient tool of Robust Design.

Index Terms— ANOVA ,Fuzzy logic, Orthogonal Array, quality characteristic, quality loss function, robust design, Signal-to-Noise ratio

1 Introduction

Taguchi method was developed by Genichi Taguchi the father of quality engineering, who successfully integrated powerful applied statistical methods into engineering processes for achieving greater stability and capability. His was a proactive approach based on measurement, analysis, prediction and prevention and it focused primarily on, designing quality into products and processes rather than inspecting into them(Ross, 1988) . This method lays great emphasis on responsiveness towards customer's satisfaction.

Taguchi realized and appreciated the vitality of producing an outcome on target and concluded that, excessive variation in performance was the root cause of poor quality and was counterproductive to the society at large. He further stated that these variations in performance or deviation from target would manifests itself as inevitable loss to the society through early wear out , difficulty in integrating or interfacing with other parts, servicing, the need to include safety margins etc which if ignored would lead to customer dissatisfaction and loss of company reputation. In other words Taguchi accentuated the importance of reducing process variability around a specified target value and then bringing the process mean on target. This can be accomplished only by making processes insensitive to various sources of noise and the method is called Robust Parameter Design (Phadke, 1989).

Instead of reducing variation in individual components by specifying tighter tolerances, Taguchi addresses the issue by careful selection of design parameters called factors, resulting in a more robust design that is capable of withstanding variations from unwanted sources. In order to achieve this he proposed an effective and an efficient method to determine the feasible combination of design parameters that reduces variability in product responses. Hence Taguchi method of experimental design is a powerful approach to optimizing designs for performance, quality and cost (Ross, 1988; Peace, 1993).

Section II consists of evolution of the method followed by Section III which describes the basic concept behind Taguchi Method. Section IV explains various application domain of this method followed by Section V concluding our observation.

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2 Evolution

The concept of quality has evolved with time, it today has become a philosophy encompassing all issues and engaging all individuals within an organization. It is no longer a simple result of an inspection process, but needs to be a company-wide management philosophy. Thus making quality improvement programs an integral part of the strategic planning process of many successful companies (McKeown, 1992). In the past Inspection was the only method to ensure conformity to specific requirements, but the growth in production yields during the Industrial Revolution posed the demand for an upgraded quality control mechanism In 1911, the concept of quality took a huge leap forward with the contributions of Frederick W. Taylor who introduced several important concepts such as Functional specialization, Process analysis of time and motion and Quality control inspection etc[1].Taylor's contribution thus served to be the precursors in the evolution of quality management and control. While the focus was primarily on productivity gains during Taylor's time, in the 1920s, Dr. Walter Shewhart defined quality control as a proactive function rooted in process, rather than relying strictly on reactive measures resulting from inspection. He applied statistical theory to the management of quality, and developed the first modern control chart and demonstrated that eliminating variation in the process leads to a good standard of end products. In order to eliminate variation the cause of variation was to be first identified for which the effects of various controlling factors needs to be studied. Traditionally, the effect of a particular factor was studied by varying one factor at a time. This tradition was provided a fundamental break in the 1920's when Sir RA Fisher, a British statistician suggested varying of all factors simultaneously in what is known as Design of Experiments[DOE]. In this method a deliberate change is made in one or more process factors (input variables), in order to observe the corresponding changes in the output or response factors. It is also assumed that all input variables interact with each other[1]. Thus DOE investigates all possible interactions between inputs at the same time. The data obtained is further analyzed to provide valid and objective conclusions. This method is also termed as Full- factorial experiments and involves a big round of tests. In order to slim down the amount of work Fractional factorial DOEs were used, in which only a sufficiently chosen fraction of the treatment combinations required for the complete factorial experiment was selected to be run, although the savings obtained were marginal, such as a factor of two or four. A potential solution to this problem was provided with the invention of Orthogonal Arrays in the 1940's in Britain, using which a very small subset of all possible combinations were tested thereby reducing the computational effort to a large extent.

Finally in the 1950's Genichi Taguchi successfully applied Sir Fisher' s Design of Experiments and Orthogonal Arrays to effective product development deriving the benefits of both the method. He also encouraged noisy inputs and incorporated their effects during experimentation, thus making the product or process Robust [3].

3 CONCEPT OF ROBUST DESIGN

A product is said to be of best quality when it meets customer satisfaction. Taguchi method, thus, never estimates quality of a product on the basis of cost to the manufacturer alone, number of defective pieces; whether it falls within the specified limits etc. It judges on the basis of deviation observed in the product's response from the target. This response is termed as its quality characteristic. When a product fails before its expected lifespan or its responses become poorer with time, it is said to have high quality loss.[6]

The cost due to rework, warranty cost, time energy and money spent by customers for repairing, customer complaints i.e. dissatisfaction, thus eventual loss of market share and reputation of the company together is termed as quality loss. To quantify this quality loss, we have quality loss function which depends on the standard deviation (σ) and variation of product from the target (μ-μ_0) as given below:

$$Q = K' [(\mu-\mu_0)^2+\sigma^2] \quad (1)$$

Taguchi method implies that if the variation of the product from the mean is reduced, quality loss reduces. This reduction in variation is brought about by adjusting the mean nearer to the target with help of a scaling factor. Thus,
Quality loss after adjustment:

$$Q_a' = \eta = 10 \text{ Log}_{10} [\mu^2/ \sigma^2] \quad (2)$$

The ratio of $(\mu/\sigma)^2$ can be termed as signal to noise ratio since (μ) is the desired target value and $(\sigma)^2$ is the variance i.e. noise. Signal to noise ratio depends on the quality characteristic to be optimized decided for a particular experiment.[2]
The most common types are

- Smaller the better [STD]:- This is chosen for all undesirable characteristics like "defects "etc. for which the ideal value is zero.

n = -10 Log_{10} [mean of sum of squares of {measured - ideal}

- larger the better [LTB] :- This is chosen for characteristics which are desirable whose value should be as large as possible

n = -10 Log_{10} [mean of sum squares of reciprocal of measured data]

- Nominal the better[NTB] :- This is chosen when a specified value is most desired

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

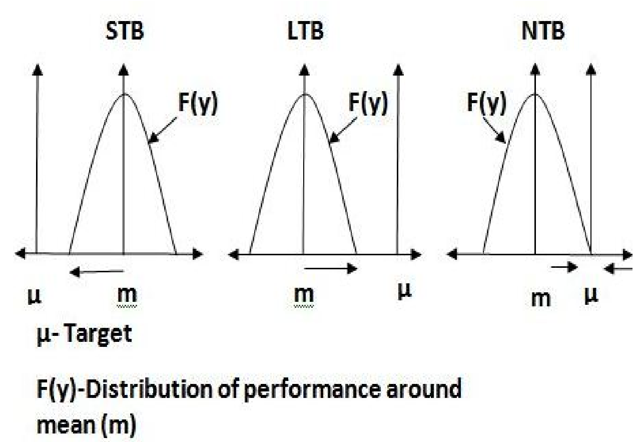

Fig. 1. Types of SNR

STB requires the performance value to go as small as possible from a threshold value and LTB value requires vice versa. But NTB requires performance value to be as near as possible to the target which is desired. Thus SNR of NTB type is appreciated and for that, quality characteristic should be accordingly selected.[7] [12]

The parameters that influence the quality characteristics are

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also called as factors. They can be of 3 types-signal factors which directly influences the intended value of the product's response (μ), noise factors which are difficult or expensive to control and cause variation (σ) in the response, control factors which are selected to minimize the sensitivity of product's response to all noise factors.[2]

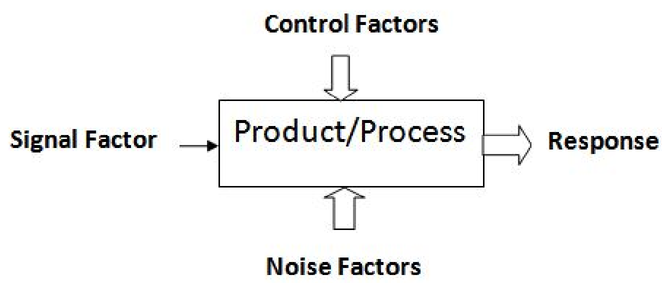

Fig. 2. Block Diagram of Product/Process

Robust design projects in which the signal factor remains constant are called static projects, while others in which user can vary signal factors are called dynamic projects.

The design of a product or process is carried out in 3 steps.

3.1 Concept Design

It involves selection of product architecture or process technology and examination of initial settings.

3.2 Parameter Design

It decides the optimum levels of control factors to maximize robustness and thereby enhances the performance. It involves the following steps:

3.2.1 Selection of parameters for experimentation

The system is analyzed to choose an appropriate quality characteristic, such that it is continuous and monotonous function, easy to measure and is a direct indicator of energy transfer in the system. The objective function i.e. the SNR is selected based on the nature of the quality characteristic. The control factors, their levels and noise factors are determined. Robustness of a product is ensured by selecting testing conditions that capture the effect of various noise factors. Also, Signal to Noise ratio (SNR) has to be defined such that it includes not only the average level of the response, but also the observed variation in its level due to noise factors.[2] The same experiment may be repeated several times to obtain different responses corresponding to deliberately introduced variation in noise factors, to take into account deterioration and external noise.[2]

3.2.2 Selection of orthogonal array for conducting experiments

Orthogonal arrays are special matrices that enable the manufacturer to choose the parameter values with minimum number of experiments. In the matrix experiment the columns of the orthogonal array represent factors to be studied and each row represents a unique combination of factor levels in individual experiments.[2]If a matrix is orthogonal, it implies that for any pair of columns all combination of factor levels occur equal number of times i.e. all factors are represented equally in all experiments. The total degree of freedom is required for the selection of a suitable orthogonal array. The degree of freedom is defined as the number of permissible variations in a process parameter to obtain a specific mean. To select an orthogonal array for experimentation, the number of rows in the array should at least be equal to the total degrees of freedom of all factors and the overall mean combined. Once the orthogonal array has been selected, experiments are performed accordingly; and SNR for each experiment is calculated and tabulated.

3.2.3 Analysis of experimental observations

Analysis of Mean (ANOM): Firstly, the overall mean value (m) for all experiments is calculated. This is a balanced value, as all levels of every factor are equally represented in the entire set of experiments. For every influencing factor, the effect of its various levels is calculated separately (m_i).The effect of a factor level is defined as the deviation of m_i from the overall mean (m).The optimum level for each factor is chosen as the one which gives highest positive effect on the mean.[2] Thus, analysis of mean is used to obtain the optimum combination of all influencing factors. The orthogonal structure of experimentation allows us to use the additive model for calculating the response for any individual combination of factors. The additive model states that combined effect of all the factor levels can be obtained by summing the deviations due to individual factor levels with the overall mean.

Analysis of Variance (ANOVA): ANOVA of a set of experiments is similar to Fourier analysis of a signal. Fourier analysis establishes the relative importance of the various harmonics that constitute a signal. It represents a signal as the addition of various independent orthogonal harmonics. ANOVA represents the overall variance in the SNR as sum of variances due to each factor and variance due to error. ANOVA is used to compute the relative importance of each factor. To maintain the quality of the product, the most significant factors should be strictly controlled.

3.2.4 Verification experiment

Once the optimum combination of different factors has been chosen, a verification experiment is performed to compare the estimated response with the observed response[10]. If they are in agreement, we adopt the optimum settings, otherwise the additive model fails and mutual dependency between the factors has to be studied.

3.2.5 Iteration method for further optimization

Experiments in Taguchi's method are performed using discrete levels of factors, which rules out the possibility of obtaining a higher SNR at any level between the initially selected levels. In order to make up for this, we perform further exper-

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imentation, selecting new levels around the optimum level determined previously. If the initial range of a factor level is extremely large, such iterations can improve the SNR significantly.

3.3 Tolerance design

It is used to reduce the tolerance of the product to most influential factors by using improved materials and by adding extra components for controlling tolerance factors.[10]

4 Applications of Taguchi Method

The robustness and simplicity of Taguchi method attributes to it finding application in a large number of diverse fields some of which are analyzed below:-

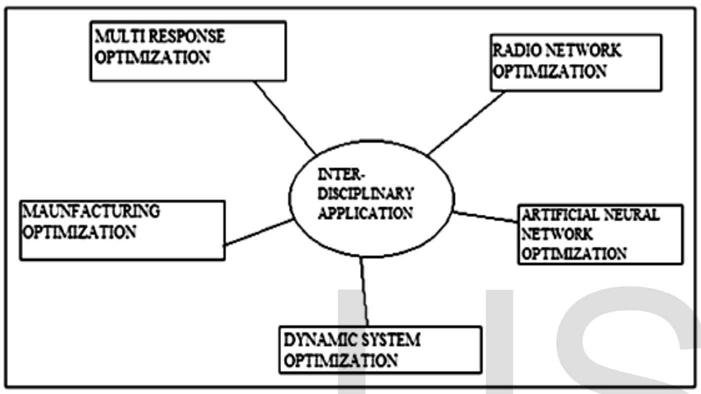

Fig . 3. Robust Design Applicability

4.1 Application in the field of Manufacturing

Taguchi's robust design technique finds its application in a number of manufacturing processes, [17] one of which is Resistance Spot welding (RSW).RSW is an efficient method of joining metallic sheet parts, used in various manufacturing processes such as automobile industries, domestic appliances etc. It uses the heating effect of electric current due to opposition provided by resistance to generate localized high temperature leading to temporary melting and fusion of the edges of metal sheets.

The quality of the joint and hence its durability depends on the welding diameter and the tensile strength of the sheet. Taguchi's robust design technique can be applied to RSW method to improve the quality of the weld by selecting optimum control factors.

The observations of the Robust design process [15] can be tabulated as below

TABLE I.OBSERVATION TABLE

Quality Characteristic	**Tensile Shear Strength**
Control Factors	Welding current Welding pressure Welding time
Factor levels	Low, Medium and High
Orthogonal array used	L9
Optimum levels for control factors	Medium current Medium pressure High weld time
SNR for initial level	9.0050dB
SNR for optimum level	13.1602dB
Improvement in SNR	4.1552 dB

Thus it can be concluded that the use of Taguchi's optimization leads to an improvement in the SNR by 4.36 dB i.e. around two fold increase in the tensile strength, due to the use of optimized factor values Also, ANOVA could be used to determine the factors that need to be strictly monitored.[16]

4.2 Application of Taguchi's method in combination with Fuzzy logic for design of multi-characteristic product

Realistic product design necessitates many quality characteristics to be optimized. The optimum combination for a particular characteristic need not be optimum for other characteristics. Relying on engineering judgment for making trade-off between several optimum factor levels can lead to avoidable degradation of some of the quality characteristics. Taguchi's method is only efficient as far as optimization of a single performance characteristic is concerned. For this purpose, immediately after the step of matrix experimentation is complete, for each experiment, it is essential to club multiple resulting SNRs into a single multi-response performance index(MRPI). This clubbing can be efficiently done using a fuzzy logic unit. This MRPI can then be considered as the single performance characteristic to be optimized.[18]

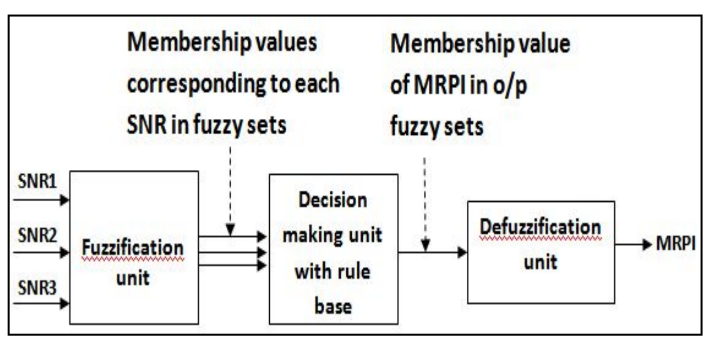

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Fig. 4 Fuzzy Logic Unit for conversion of multiple quality SNRs into a single MRPI

The fuzzy logic unit consist a knowledge base (KB) which is the collection of expert conversion rule base, required to achieve the optimum weightage to be given to various performance characteristics during combination. for every quality characteristic, fuzzy sets small (A), medium (B) and large(C) are defined separately using membership functions. For every run of the experiment, the SNRs corresponding to various quality characteristics are fed to the fuzzy logic unit, which returns a single MRPI.[19]First, a fuzzification unit maps measured input SNRs of crisp value into membership values in different classifying fuzzy sets-small, medium and large. If an SNR of the experiment, corresponding to a characteristic, is smaller as compared with the observed range of that characteristic, it gets a higher membership value in the fuzzy set 'small' and lower values in 'medium' and 'large' .Next, a fuzzy reasoning mechanism performs various fuzzy logic operations. It uses the rule base to infer the membership values into output fuzzy sets for the given fuzzy inputs. The output fuzzy sets represent classification of MRPI into very small, small, medium, large and very large values. Finally, a defuzzification unit converts the inferred fuzzy membership values into a crisp MRPI for each experiment to be used for optimization.[19]

It must be noted that the experimentation matrix with orthogonal columns can still be used for ANOM and ANOVA with MRPI as the only characteristic to be optimized. This directly estimates a single optimum combination of influencing factor levels required for the peak MRPI. Thus, combination of Taguchi's method with fuzzy logic extends and improves its applicability to design of products characterized by multiple responses.

4.3 Application in Telecommunication

Radio network consists of small geographical regions called as cell which has a base station to provide network to the use a fundamental aspect of radio network planning is the setting of the parameters that are associated with each base station, e.g., antenna tilts and angular settings. Due to limited frequency reuse spectrum, joint setting of all the parameters of the all the cells which has irregular terrain, features, regions and coverage areas becomes a challenge. Finding the optimal parameter setting for each base station that maximizes a pre-defined performance metric is a difficult problem.

Conventional radio network-planning tools use optimization methods based on local search such as simulated annealing (SA) and genetic algorithm. But major problems with these methods are their parameters require heuristic definitions for their initial values. These methods also depend on the neighboring structure of the current solution. To find an optimal value without these requirements, Taguchi methodology is used. Taguchi method uses the orthogonal array which greatly reduces the number of experiments thus saving time energy and cost.

This has been used in optimization of the following three typical cell-specific radio parameters of an LTE network: 1) the power control parameter; 2) the tilt of a transmit antenna 3) the azimuth orientation of a transmit antenna. Because Taguchi Method allows any type of parameter combinations, it can also easily be extended to jointly optimize different radio network parameters, e.g., power control parameter combination with azimuth orientation. Experiments have shown that when both algorithms were run with same optimization function and complexity Taguchi converges slightly higher optimization function.[11][14]

4.4 Dynamic systems

Systems in which, the response is required to follow the levels of the signal factor in a predefined manner are called Dynamic systems. Control systems in which the output switches abruptly between 2 states i.e. on and off are called Bang-Bang controllers. A specific example could be a temperature control circuit, primarily consisting of a sensor, control circuit and a heating element. The temperature characteristic of the sensing medium plays a decisive role in determining the response of the heating element. In addition the transient nature of the target temperature adds to the complexity making it a Doubly Dynamic problem. Taguchi method can also be applied to such type of problems, first the levels of compounded noise factor are calculated, and next for each level of signal factor the testing conditions include all levels of compounded noise factor. Regression analysis is used and for an initial setting of control factors signal to noise ratio is calculated. The same procedure is repeated for all combinations of control factors in the orthogonal array and the best combination is finally selected resulting in significant improvement in signal to noise ratio.

4.5 Artificial neural networks

An Artificial Neural Network is an information processing paradigm composed of a large number of highly interconnected processing elements called neurons. These neurons work in unison to perform the specified task. The neurons are weighted and the effect that each neuron has at decision making is dependent on the weight of that particular neutron. Taguchi methods may be applied to the training of Artificial Neural Networks to perform a specific task, such as character recognition. In order to do so weights of the neural network are made the elements of the orthogonal array. Next Taguchi method and error analysis is applied to find the optimum combination of weights for the network. Now, for character recognition each neuron is pre-assigned a specific character and it is trained to produce minimum error corresponding to that particular input. The character recognition process is initiated and the results are noted and it is concluded that Optimum selection of weights by applying Taguchi method helps the results to confirm to the above mentioned condition. It is also much faster in comparison to other algorithms and in a general character recognition problem it is up to 10 times faster than a back- propagation algorithm. Taguchi method also allows users to analyze the system and calculate the interactions between different components thus providing an effective means to examine inner operation of the network through statistics.

5 CONCLUSION

This paper thus presents a detailed overview of Taguchi Method in terms of its evolution, concept, steps involved and its interdisciplinary applications. It could be concluded that this method with its perfect amalgamation of statistical and quality control techniques was one of the effective and efficient methods of its kind to highlight the benefits of designing quality into products upstream rather than inspecting out bad products downstream. It offers a quantitative solution to identify design factors to optimize quality and reduce cost. Also the application of this method is not confined to a particular domain but also to other fields like product and service sectors. It thus is a powerful method as compared to the other intuitive and more cumbersome methods encompassing a large number of fields in terms of application

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