CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

In recent years, interest in cost of quality system has increased among Indian industries. The implementation of quality systems and other quality initiatives emphasizes the need for quality measures for performance. Therefore, there is a need for implementing the newer techniques in the Indian context. The Taguchi method is a powerful tool for improving process variability and optimization problems. Basically, the application of Statistical design of experiment and Taguchi methods by the engineering fraternity in Indian organizations is limited due to inadequate statistical knowledge.

In the present manufacturing environment, the success of the machining operation will depend on the selection of machining parameters. Optimum machining parameters are very important issues in the manufacturing environments, where economy of machining operation plays a key role in the competitive market. And this process purely depends on the application of artificial intelligent techniques which are able to solve the optimal strategies for machining operations.

Optimizing the quality of a product is a difficult task for an industry. Capital investment and machining costs of the CNC machines are very high. Even then, there is an economic way to operate CNC machine as efficiently as possible in order to obtain the invested cost. In most of the
machining processes, there is more than one response that is under investigation at the same time. It is necessary to attack these problems in such a way that multiple responses can be simultaneously optimized. Relationship between these responses is quite common. The analyst must decide which responses are most important and then determine the set of operating conditions for making the product with the overall best response. The set of operating conditions is called the optimum conditions for the process. There are a number of optimization techniques and Taguchi technique is one of the best for dealing with multiple responses in today’s manufacturing environment.

1.2 TAGUCHI METHOD

Taguchi method is a traditional approach to robust experimental design that seeks to obtain the best combination of factors/levels with the lowest societal cost solution to achieve customers’ requirement. In Taguchi’s design method, the design parameters (factors can be controlled by designers) and noise factors (factors cannot be controlled by designers such as environmental factors) influence product quality. Therefore, the Taguchi’s design method selects the levels of design parameters and reduces the effects of noise factors. That is, parameter setting should be determined with the intention that the product response (quality characteristic) has minimum variation while its mean is close to the desired target (Phadke 1989). Nevertheless, so far Taguchi method can only be used for a single response problem; it cannot be used to optimize a multi-response problem. Unfortunately, nowadays more than one quality response results from most industrial products and these products’ quality characteristics are considered by customers. In Taguchi method, to solve the multi-response problem, engineering judgment is the primary method. But, without doubt an
engineer’s judgment will increase uncertainty during the decision-making process.

Taguchi method is conventionally needed for offline quality control combining the experimental design techniques with quality or loss consideration. Three sequential stages will be included for applying Taguchi method to optimizing a product or process: (1) system design, (2) parameter design, and (3) tolerance design. Further details can be found in Peace (1993), Fowlkes and Creveling (1995) and Phadke (1989). Taguchi suggests that we can use the quadratic loss function to measure the loss for the departure of the target. The optimum parameter condition, which makes the product to be more ‘robust’ for the environmental factors and to be closer to the target, is then determined by performing the parameter design. Parameter design is also commonly referred to as ‘robust design’. Taguchi’s parameter design can be divided into two classes for system’s architecture: static and dynamic characteristics. In Taguchi’s dynamic method, there are three criteria of the performance: (1) Sensitivity; (2) Linearity and (3) Variability. To measure these three criteria, Taguchi suggests two indexes (Fowlkes and Creveling 1995; Peace 1993; Phadke 1989) to determine the optimum parameter condition and, the two indexes can be defined as the S/N ratio and sensitivity (S):

\[
S/N = 10\log_2 \frac{\beta^2}{\sigma^2} \tag{1.1}
\]

\[
S = 10\log_2 \beta^2 \tag{1.2}
\]

where the S/N ratio indicates the variability of system and S indicates the system’s sensitivity. The features of these two indexes are: the larger the best for maximizing the system’s sensitivity and minimizing the system’s variability. The philosophy of the S/N is to consider the corresponding
relation between the system’s variability when simultaneously adjusting the system’s sensitivity and, the philosophy of S considers the sensitivity only.

Taguchi techniques were developed by Taguchi and Konishi (1987). These techniques have been utilized widely in engineering analysis to optimize the performance characteristics within the combination of design parameters. Taguchi technique is also a power tool for the design of high quality systems. It introduces an integrated approach that is simple and efficient to find the best range of designs for quality, performance, and computational cost. The quality engineering methods of 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. They have been used successfully in Japan and the United States in designing reliable, high quality products at low cost in areas such as automobiles and consumer electronics (Cullen and Hollingum 1987; Logothetis and Salmon 1988; Sullivan 1987; Wille 1990). The purpose of this research is to present an overview of the Taguchi methods for improving multi-response optimization problem in a simple way and to describe the current state of applications and its role in identifying cost sensitive design parameters.

1.3 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 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).

1.3.1 System Design

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

1.3.2 Parameter Design

After the system architecture has been chosen, the next step is parameter design. The objective 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.

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 $1,594,323 \times 3^{13}$ 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.

1.3.3  **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.

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 (Taguchi and Konishi 1987).

For example, if there are four parameters A, B, C, and D, each at three levels, this is called an “L₉” 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 \( (3^{13}) \).

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.

### 1.3.4 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 tolerance design increases production and operations costs (Phadke 1989).
1.4 PROCEDURAL STEPS FOR TAGUCHI METHOD

Figure 1.1 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 1.1 Procedural steps for Taguchi method
1.4.1 Quality Characteristics to be Optimized

The first step in 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.

1.4.2 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 the same design with the same input.

1.4.3 Control Parameters and their Alternative Levels

The third step is to identify the control parameters that 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 defines the experimental region.

1.4.4 Matrix Experiment and 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 results of the experiment for each combination of control and noise array experiment are denoted by \( Y_{ij} \).

### 1.4.5 Matrix Experiment

The next step is to conduct the matrix experiment and record the results. 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.

### 1.4.6 Data Analysis and Optimum Levels

After the experiments have been conducted, the optimal test parameter configuration within the experiment design must be determined. To analyze the results, Taguchi method uses a statistical measure of performance called signal-to-noise (S/N) ratio borrowed from electrical control theory
The S/N ratio developed by 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 equation is the ratio of the mean (signal) to the standard deviation (noise). The S/N equation depends on the criterion for the quality characteristics 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.

1.4.7 Prediction of Performance

Using 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, in the final step, an experimental confirmation is run using the predicted optimum levels for the control parameters being studied.
1.5 NEED FOR THE STUDY

Over the years, researchers and industry observers have pondered over the problem of declining productivity growth rates in a cross section of Indian industries. Attempts to address this problem have led to various management initiatives designed to improve productivity. There is now a consensus that improved productivity cannot be obtained without improving quality. This has led to a surge of interest in approaches to quality management over the last decade and a half.

An overview of Taguchi method has been presented and the steps involved in the method were briefly described in the previous sections. Overall, 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.

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 to 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. Despite their contributions, the above Taguchi method shares the following limitations:

1. The optimal factor/level combination for more than one response is determined based on pure engineering experiences but the correlations among responses are not considered. Because the engineer’s judgment often leads to uncertainty
during decision making, different engineers may produce conflicting results when addressing the same problem; and

2. These procedures are developed based on the linear programming technique or other complicated mathematical algorithms thereby making them impractical for many engineering applications.

Therefore, a simple procedure is needed to solve if the responses are more.

1.6 SCOPE OF THIS STUDY

Most experiments seek to maximize the response or yield of a certain characteristic. Taguchi recommends the use of a three-stage process to achieve the desirable product quality by design, system design, parameter design and tolerance design. Parameter design can be regarded as a flexible alternative to the classical fractional factorial design and is now a widely used empirical approach in various industries. It is used to design a product or process by selecting the optimum condition of the parameter levels so that the product or process is least sensitive to the effects of noise factors.

Three types of factors are encountered when using Taguchi methods, signal factors, control factors, and noise factors. Signal factors are the factors that affect the average response. Control factors are factors that can also affect the average response but, more importantly, can affect the extent of the variability about the average response. These are set by the manufacturer and cannot be changed by the customer. Noise factors have an influence over a response but cannot be controlled in actual applications. The manufacturer does not have direct control. These can vary with the customer’s environment and usage. Three types of noise factors are in usage - outer noise, inner noise,
and product noise. Outer noise is caused by environmental conditions such as humidity, temperature, pressure, operator skills, etc. Inner noise produces variation from inside or within the product such as wear, fade of color, shrinkage, etc. Product noise is part to part variation on the product itself such as tool wear, measuring equipment, etc.

The strategy of using Taguchi method is to identify the control factors and noise factors that may affect the response of the chosen quality characteristic, and then utilize a suitable orthogonal array (OA) to layout the experiment. In this way it is possible to evaluate several factors simultaneously from a minimum number of tests. By now, Taguchi method can not optimize the multi-response problem; engineer’s judgment is the only way to solve the multi-response problem in Taguchi method. However, in most industrial products, the multi-response problem should be considered in the quality characteristics. Many studies have dealt with this problem in order to find a way to solve it and make an important contribution to real manufacturing.

In order to solve multi-response problem, a common approach is to assign a weight for each response and aggregate responses into a single measure. However, how to determine and define a weight for each response in a real case still remains difficult.

These limitations have been addressed in this study by assigning a new weight adding procedure called weight-based desirability method and weight-based Grey relation analysis. However, the limitations by applying the Eigen value as a weight in the same weights is difficult in real case. Therefore, there is ample scope in this area to eliminate the judgmental method and to find the weight assigning studies.
1.7 OBJECTIVE OF THE STUDY

The objective of the present research is to propose a new method in converting the multi-response into a single response by assigning a PCA-based weight (Eigen Value) to both Grey Relation Analysis (GRA) and Desirability methods. These methods will provide a direct solution and there is no external intervention to search for an optimal solution. In this study, new weight-based steps on grey relation analysis WBGRA and weight-based desirability method WBDM are proposed and using case study analysis the solutions are compared with the existing desirability method and grey relation analysis for solving the multi-response problems. This approach can solve any type of problem irrespective of its nature and size. This approach makes simple steps in order to achieve the optimum solutions. The experimenter can proceed with the optimization process just by having the initial conditions.

1.8 OVERVIEW OF THE THESIS

Chapter 1 discusses the background and motivation of studying the multi-response problem in the Taguchi’s approach. It also explains the scope of the study, need for the study and objective of the study in detail. Chapter 2 presents the literature review of the work done by the earlier researchers and also the problems faced by researchers and their drawbacks in solving the multi-response optimization problems. Chapter 3 discusses the case study of Wire-cut EDM operation and the proposed steps of the research work called Weight-Based Grey Relation Analysis with the existing Grey Relation Analysis. Chapter 4 explains the steps for solving multi-response optimization by weight-based desirability method with the existing desirability method. Chapter 5 discusses the application of solving multi-response optimization case studies of Injection moulding, Plate printing process and textile industry. Chapter 6 provides the conclusion. It also records the major contributions of the research work and the scope for the future work.