SIX SIGMA DESIGN THROUGH PROCESS OPTIMIZATION USING ROBUST DESIGN METHOD

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ABSTRACT

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Six Sigma or high level of process output is very common interest of world class industry. Six Sigma methodology not only ensures the quality of products but also ensures the quality of each element associated with that product, from conception to the end of the product life cycle. Because of such ensuring, Six Sigma qualities made an evolution in industry in 1990's. Now Six Sigma is almost a proven methodology for industry to produce high level quality of products. To achieve Six Sigma quality, industries need to optimize the process; there are many mathematical, engineering and statistical methods that are being used for optimizing the process. However, these methods do not always deal with a combined consideration of the effects of mean and variability of quality characteristics of the product.

One of the major steps to achieve a high level of quality is to optimize the process. It is well known that processes have many inputs, and inputs are key element to the quality of process output. Therefore, optimization of the process contributes a vital impact for Six Sigma. The proposed Taguchi robust method optimization will take both effects such as mean and variation of product quality characteristics into consideration.

In view of Dr. Taguchi's very popular phrase "loss to society", in this research we applied Taguchi method to optimize the process for Six Sigma design. We showed that a

positive gradient relationship exists between S/N ratio and process sigma. The robust design method ensures minimum variation of quality characteristics of the product or to produce almost "defects free" products. Due to such minimal variation in product, it will ensure minimum use of resources for manufacturing of product. Therefore unit cost of production will become lower and as well as it satisfies customer's implied and stated need. These are the main objectives of Six Sigma design and this research contributes to formulate a generalized and easier method to optimize the process for Six Sigma design in an industry.

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To my late ma AYSHA *KHATOON*

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LIST OF SYMBOLS

Symbol	Description
C_{PK}	Capability Index
S/N_{A2}	S/N ratio of factor A at level 2
S/N_{B2}	S/N ratio of factor B at level 2
S/N_{C1}	S/N ratio of factor C at level 1
S/N_{D2}	S/N ratio of factor D at level 2
S/N_{E1}	S/N ratio of factor E at level 1
S/N_{F1}	S/N ratio of factor F at level 1
S/N_{G1}	S/N ratio of factor G at level 1
S/N_{ave}	Average S/N ratio
m_{A2}	mean of factor A at level 2
m_{B2}	mean of factor B at level 2
m_{C1}	mean of factor C at level 1
m_{D2}	mean of factor D at level 2
m_{E1}	mean of factor E at level 1
m_{F1}	mean of factor F at level 1
m_{G1}	mean of factor G at level 1
m	Average of Mean

LIST OF ACRONYM

Acronym	Description
$B	US Dollar in Billion
5S	Sort, Set, Shine, Standardize, and Sustain
ANOVA	Analysis of Variance
ASQ	American Society for Quality
bB	Decibel
BWP	Box and Whisker Plots
CEO	Chief Executive Operations
CQE	Certified Quality Engineer
CTQ	Critical to Quality
DFEMA	Design Failure Mode and Effect Analysis
DFSS	Design for Six Sigma
DMADV	Define, Measure, Analyze, Design, Verify
DMAIC	Define, Measure, Analyze, Improve, Control
DOE	Design of Experiment
DOF	Degrees of Freedom
DPMO	Defects per Million Opportunity
DPO	Defects per unit opportunity
DPQ	Design process qualification
e	Estimated
FMEA	Failure Mode and Effect Analysis

GE	General Electric
IA	Inner array
IDOV	Identify, Design, Optimization, Verify
ISO	International Organization for Standardization
LSL	Lower specification limit
LW	Left whisker
ND	Not disclosed
OA	Orthogonal array
PDC/SA	Plan, Do, Check/Study, Act
PM	Project Metrics
PPM	Parts per million
QFD	Quality function deployment
RSM	Response Surface Method
RW	Right whisker
S/N	Signal to Noise
SPC	Statistical Process Control
SS	Six Sigma
Stdev	Standard deviation
TQC	Total Quality Control
TQM	Total Quality Management
USL	Upper specification limit

CHAPTER 1

INTRODUCTION

Six Sigma has a systematic framework for quality improvement and business excellence has been popularized for more than a decade [27]. Six Sigma was introduced in 1980's for improving manufacturing processes. The central idea behind Six Sigma is that we can measure how many " defects " we have in a process and systematically figure out how to eliminate the defects and get as close as possible to the perfect product. The sigma level provides the metric for performance monitoring and translating this into some sort of financial benefits (Appendix – I) [11]. Subir Chowdhury presents a striking address in that he states " most companies spend only 5 percent of their budget on design, but design typically accounts for 70 percent of the cost of the product – partly because 80 percent of quality problems are unwittingly design into the product itself ". Since product is the output of the process, the process should be optimized to get almost perfect output. In order to manufacture defect free products that have less variation, Taguchi's robust design may be employed to reduce such variation of the product. The main philosophy of robust design is to develop processes that consistently produce products to the target with a minimal variation [47] and reach to Six Sigma.

1.1 QUALITY ENGINEERING

1.1.1 Quality – Quality is a subjective term for which each person has his or her own definition. In technical usage, quality can have two meanings: 1) The characteristics of a product or service that bear on its ability to satisfy stated or implied needs. 2) A product or service free of deficiencies [70].

Various quality researchers define quality such as

- Fitness for use (Juran, 1964), conformance to specifications (Juran, 1988).
- Conformance to requirements (Crosby, 1979).
- Aims at the needs of the customer, present and future (Deming, 1986).
- Quality is best achieved by minimizing the deviation from the target, not a failure to confirm to specifications (Taguchi, 1986).

The ideal quality a customer can receive is that every product delivers the target performance each time the product is used, under all intended-operating conditions, and throughout the product's life, with no harmful side effects [55].

1.1.2 Quality engineering

Quality engineering is the analysis of a manufacturing system at all stages to maximize the quality of the process itself and the products it produces [70]. Most renowned quality experts and philosophers like Juran (Juran Trilogy), Deming (14 points, chain reaction, Deming cycle), Crosby (four absolutes), Feigenbaum (system approach to quality, TQC), Ishikawa (father of Japanese TQC, concept of substitute quality characteristics) normally linked their significant contributions to the management aspects of quality as indicated. There are very few quality researchers who contributed to the engineering aspects of quality, like Taguchi [2]. Taguchi has developed a systematic off – line quality – control methodology through which an engineer with relatively little statistical knowledge can optimize the process and product design. The method developed by Taguchi is more engineering oriented in comparison with the other methods [2]. The components of quality engineering are shown in figure 1.1 [2]. Figure 1.1 places our interest in this research, which focuses on robust design for process, in the context of the broader scope of Quality Engineering.

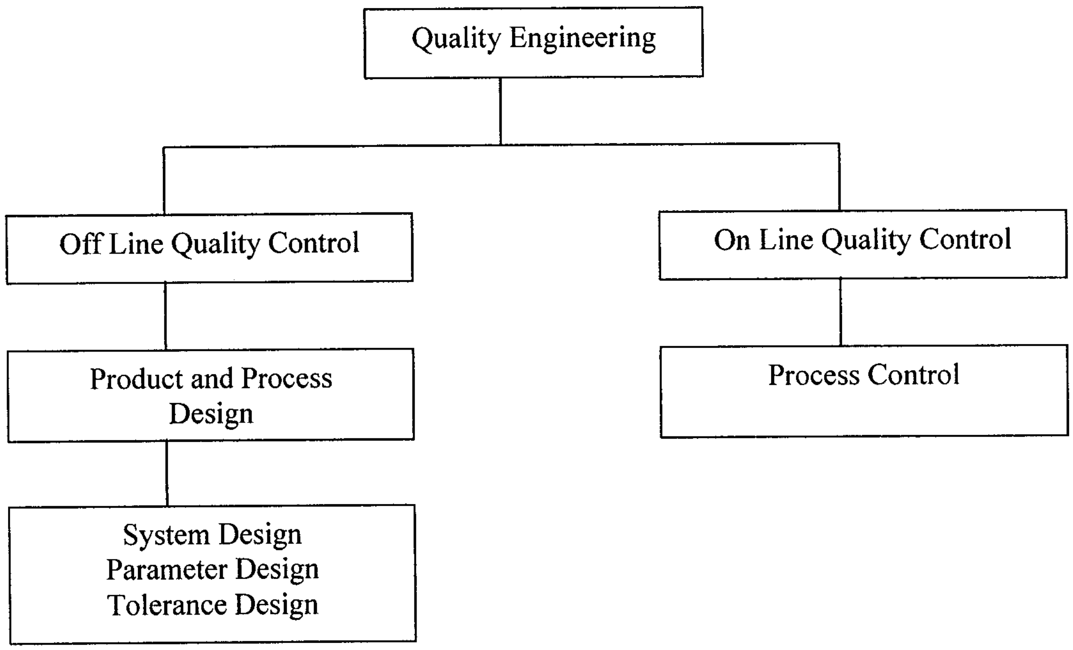


Figure 1.1 Components of quality engineering

1.2 SIX SIGMA QUALITY

Six Sigma (SS) is a methodology that provides businesses with the tools to improve the capability of their business processes. This increases in performance and decreases in process variation; hence leads to reduction in defects and improvements in profits, employee moral and quality of products [70].

The term Six Sigma is generally used to indicate a process that is well controlled (i.e. ± 6 sigma from the centerline in a control chart). The term is usually associated with Motorola, which named one of its key operational initiatives " Six Sigma quality " [70].

1.2.1 History of Six Sigma

Over the past half-century various industries focused their attention to the quality of products. A large number of systems/methods have been developed in an attempt to improve the product quality in various industries. One of these methods is Six Sigma that was introduced in late 1980's. This method made substantial impact in the industry.

The concept of sigma originated by Carl Fredrick Gauss who formulated the normal distribution curve. Therefore Six Sigma roots have been introduced more than 100 years ago. Subsequently in 1920's Walter Shewhart showed that three sigma from the mean is the location where a process still requires correction. After Shewhart, many measurements standards, for example C_{pk} (process capability index) and zero defects, are introduced and in late 1980's.

Six Sigma method was introduced by Bill Smith who was an engineer at Motorola at that time. Motorola registered federally Six Sigma as a trademark (Appendix VIII). In the early and mid-1980s, with Chairman Bob Galvin at the helm, Motorola engineers conjectured that the traditional quality levels measuring defects in thousands of opportunities didn't provide enough accuracy. Instead, they switched to measure the defects per million opportunities. Motorola developed this new standard, created the methodology, and facilitated cultural change associated with it. Six Sigma helped

Motorola to realize powerful bottom-line results in their organization - in fact they documented more than $16 Billion in savings as a result of SS efforts (Appendix I).

Six Sigma has evolved over time to be more than just a quality system like TQM or ISO. It became a way of doing business. As Geoff Tennant [26] mentioned "Six Sigma is many things, and it would perhaps be easier to list all the things that Six Sigma quality is not. Six Sigma can be seen as: a vision, a philosophy, a symbol, a metric, a goal, and a methodology."

Six Sigma in many organizations simply means a measure of quality that strives for near perfection. Six Sigma is a disciplined, data-driven approach and a methodology for eliminating defects (driving towards six standard deviations between the mean and the nearest specification limit) in any process from manufacturing to transactional and from product to service. The statistical representation of Six Sigma describes quantitatively how a process is performing. To achieve Six Sigma, a process must not produce more than 3.4 defects per million opportunities. A Six Sigma defect is defined as anything outside of customer specifications. A Six Sigma opportunity is then the total quantity of chances for a defect (e.g. occurrence of defects in the diameter and length of a shaft are two chances for a defect). The fundamental objective of the Six Sigma methodology is the implementation of a measurement-based strategy that focuses on process improvement and variation reduction through the application of Six Sigma improvement projects. This is accomplished through the use of two Six Sigma sub-methodologies:

- Define, Measure, Analyze, Improve, and Control (DMAIC)
- Define, Measure, Analyze, Design, and Verify (DMADV).

The Six Sigma DMAIC processes are an improvement system for existing processes falling below the specifications and looking for incremental improvement. The Six Sigma DMADV process is an improvement system used to develop new processes or products at Six Sigma quality levels. It can also be employed if a current process requires more than just an incremental improvement.

John F Welch Jr. of General Electric (GE) CEO, states SS approach most clearly on the GE's corporate Research & Development web site as " This is the most important initiative this company has ever undertaken. It will fundamentally change our company forever."

Six Sigma is one of the proven methods since it has already improved business results (i,e. financial savings) in many industries. It should be noted that both small and big companies profited from implementing their own Six Sigma methodologies even though the Six Sigma method was originating from big companies.

The process plays an important role in any quality level such as Six Sigma. As the output of process to be considered almost perfect, it tends to produce defect free products of a process. The process is a part of a project and each project has at least one process. Generally Six Sigma design is performed on project basis instead of a process. In Six Sigma design, one firstly selects a project then goes for process idealization. In real world, whereas it is very difficult to find an ideal process, it is possible to find a near to ideal one. This near to ideal process can be termed as optimum process. The process is said to be optimum when its output or product is almost perfect with respect to all features of output or product.

1.2.2 The Role of Six Sigma in Industry

In any industry, the common language of improvement should be expressed in terms of its financial metrics. In other words, the bottom line is the profit earning. Appendix I show the financial benefits earned through Six Sigma implementations at various industries. Hence, Six Sigma methodology plays a great role in industry to assure competitiveness in the global markets. It does not only bring profits but also ensures sustainability in business.

1.2.3 The problems and criticisms associated with Six Sigma

As we observed in Appendix I, implementing Six Sigma brought large profits to a number of companies. However, the Six Sigma methodology also attracted many criticisms from various professionals and practitioners from the industry, both from the theoretical and practical viewpoints. Some of the significant criticisms, reported in the recent literature, are as follows:

- Six Sigma successes to date are impressive and well documented. The biggest risk may be the accelerating rate of technology change, and a competitive environment where processes, products and even entire markets can change before traditional quality and improvement methods have time to work their magic. The real world is complex multivariate, non- linear and chaotic [78].
- The problem is, many of the Six Sigma projects implemented by companies are flawed in one of several ways. Either they have little direct impact on the customer, do not support a comprehensive approach to continuous process improvement, and

fail to involve suppliers and customers or exhibit a combination of these shortcomings [78].

- The problem with Six Sigma projects that skewed mainly toward internal improvements is that they do not always generate better value for the customer immediately. Improvements need to produce tangible results that cause the customer to buy more, increase his loyalty to buy again and to bring other sales opportunities to the company [78].
- Most people in industry viewed SS as a statistical tool versus a complete process for continuous improvement. This myopic view of SS as merely a statistical tool limits its treat potential [3].
- Nowadays course in SS incorporates advanced level of statistical tools and methodology [45].
- Six Sigma program uses in eliminating defects rather than to meet customer satisfaction but it is important to develop knowledge of customer wants, needs and satisfaction in conjunction with production of an industry [45].
- One of the more common criticism is that it has little to offer that cannot be found elsewhere and it is simply a marketing poly [34].
- From a technical viewpoint, the normal distribution, which is considered as a model, does not adequately represent most of the processes. Other realistic process models such as log normal, student's t, etc. will make the case for Six Sigma even more emphatically because they all tend predict a much larger probability of producing a product out of the specifications [34].

- Stamatis states that Six Sigma is an appraisal tool that does nothing for presentation. Stamatis feel that quality needs to be built into design, and to not just create methods to monitor them at the manufacturing level [60].
- Latzko states that whereas two processes might achieve the Six Sigma performance, yet the loss function for one process may be 13 times greater than the other. Rather than focusing on the metric, Latzko suggests that a continual, never ending process improvement is a far better policy [60].

1.3 IMPROVEMENT OF SIX SIGMA CRITICISMS

In this study, we are motivated by a number of the criticism listed in section 1.2 in order to improve the Six Sigma methodology. Specifically we shall address to the following criticisms in our proposed methodology.

- The real world is complex multivariate, non- linear and chaotic [78].
- From a technical viewpoint, the normal distribution, which is considered as a model, does not adequately represent most of the processes. Other realistic process models such as log normal, student's t, etc. will make the case for Six Sigma even more emphatically because they all tend predict a much larger probability of producing a product out of the specifications [34].
- Six Sigma program uses in eliminating defects rather than to meet customer satisfaction but it is important to develop knowledge of customer wants, needs and satisfaction in conjunction with production of an industry [45].

- Six Sigma is an appraisal tool that does nothing for presentation. Stamatis feel that quality needs to be built into design, and not just to create methods to monitor them at the manufacturing level [60].

It appears in Six Sigma design that the process and customers have been given less attention than inward to the product defects and Six Sigma level. The process is well known to all than term's uses in SS methodologies and process play an important role in SS design. Therefore an ideal process can ensure the product quality and it meets customer satisfaction. Ideal process means optimized process that is able to produce good quality product.

Each process has inherent control, noise and signal factors as shown in figure 4.1. In Six Sigma design, only control factors have been considered. Noise factors that are unavoidable in any process or product are ignored.

In this research, we propose a model for optimization where control and noise factors should be interacted to produce a robust product. Specifically, we will use the Taguchi's approach, where we will integrate this approach into the Six Sigma design procedure. Taguchi's approach in robust design reduces the variation, and ensures that the variation due to noise will not have an effect on the quality of the product.

Robust design is a methodology for finding the optimum settings of control factors to make the product or process insensitive to noise factors [55]. Robust design is an engineering methodology for optimizing the product and process conditions which are minimally sensitive to the various causes of variation, and which produce high quality products with low development time and manufacturing cost.

Robust design is obtained through applying the Taguchi method, where control and noise factors are considered in the inner and outer arrays respectively. Defects will be considered as the response of the experiment. We optimize the process with setting appropriate level of process factors. After optimization we measure number of defects and converted the same into SS level.

1.4 TAGUCHI'S APPROACH VERSUS DOE METHODOLOGY

There has been some debate on the novelty of Taguchi's approach with respect to the well-established Design of Experiments (DOE) methodology. While DOE is concerned with research and knowledge building, Taguchi's approach is driven by practicality. It is based on the premise that engineers, not statisticians, will be performing the experiments, so an approach that is expedient and easy to apply is of value.

Most of the manufacturing industries traditionally produce their products within the upper and lower specification limits, but do not consider the variation of product quality and are not aware of their target [71, 72]. They tend to focus only on upper and lower specification limits. However, this approach is not to be found effective because it involves with much uses and wastages of resources, and hence it reduces not only quality of the products but also increases the cost of manufacturing. The Taguchi or robust design methods, on the other hand, are more concerned about the product variation and target instead of the specification limits. By applying the Taguchi method, it is possible to manufacture the product with a minimum variation at target. It does not only produce good quality products but also ensures the minimum use of available resources hence reduce manufacturing cost of an industry.

1.5 OBJECTIVE OF THIS RESEARCH

In this research we studied the process optimization for Six Sigma design in which we integrated the Taguchi robust design methodology. The objectives of the research are as follows:

1. To design an optimized process for Six Sigma that ensures to produce the higher quality level
2. To improve robustness of the process through applying the Taguchi method.
3. To determine the sigma quality level of the optimized process.

We also consider following assumptions in our proposed methodology:

1. There is no interaction of factor's effect in the process (interaction between factors are not present)
2. Process factors will be designed on the basis of robust design.
3. All data are sample data, which represent population.

1.6 OPTIMIZATION METHOD

There are several methods in optimization and some of these are –

1. Linear programming
2. Non linear programming
3. Integer programming
4. Net work programming
5. Dynamic method
6. Response surface method

7. Non linear least squares
8. Non linear equations
9. Design of experiment
10. Robust design method (Taguchi's method)

Amongst the above mentioned methods, we will use the Taguchi's DOE method to attain optimization of the process. The Taguchi method is more engineering oriented than any of the other methods [2]. The other methods are not dealing with the noise factors; we should employ Taguchi robust method because it is the only method that ensures least variation of a product due to noise [23]. Optimization through other methods may not be implemented practically because research and operational environment of the products (research environment and user condition is not the same but in the robust design gap can be reduced) are not the same [58]. Besides research nature of optimization need more resources than the other methods. Robust method, based on engineering conception, is also called parameter design [55]. Although we discussed very briefly about parameter design but we use the term "robust" in this research.

A parameter design is an experiment, which involves control and noise factors. The main strategy of the experiment is to analyze the interaction between control and noise factors to obtain the robustness. The evaluation of such interaction is called signal-to-noise ratio. There are several types of S/N ratio in Taguchi's DOE method and S/N ratio measures the level of performance as it is affected by noise factor.

1.7 CONTRIBUTIONS OF THIS RESEARCH

The contributions of this research are as follows:

- to develop a methodology for Six Sigma exploiting the robust method.
- to determine the optimized process that leads to six sigma through the Taguchi approach robust design method instead of the traditional DOE.
- to establish a graphical relationship between process sigma and signal-to-noise (S/N) ratio where we prove that robust method can be utilized for either discrete (such as Poisson's distribution) or continuous (such as normal distribution) type of data.

1.8 ORGANIZATION OF THE THESIS

This chapter introduced the concept of quality engineering and briefly presented the Six Sigma methodology. We cited various critics of Six Sigma methodology mainly coming from the practitioners from the industry. This research attempts to develop an improved Six Sigma Design methodology to address to a number of these criticisms. Chapter 2 presents a literature review on Six Sigma in which we discuss various statistical and management quality tools/methods used in designing Six Sigma and describe the Taguchi robust design method and of its applications in industry. In chapter 3, we present the simple format to select Six Sigma project team and statistical concept for selecting a project. Chapter 4 provides details of the proposed methodology, in which the robust method and its various tools are described. These tools are important for applying method to make process robust. Chapter 5 presents a computational study, where we use the S/N ratio concept for optimizing process through setting of factors level with noise interaction. Conclusion and recommendations for future work are presented in chapter 6.

CHAPTER 2

LITERATURE REVIEW

We review the literature in three groups, namely (1) Taguchi method and robust design (2) orthogonal arrays (OA) analysis and (3) Six Sigma (SS) methodology and its applications.

Despite the fact that SS method has been introduced only two decades ago, its effective business results (Appendix I) have made the method very popular in industrial world. However, the published studies in Six Sigma are very limited [42]. On the other hand, there is a vast literature in Taguchi methods and robust design as well as on OA analysis.

First we will review Taguchi and the robust method, followed by applications in industry. The whole idea of Taguchi methods started after World War II when Allies were trying to help rebuild Japan and subsequently these methods are called the "robust design method." The robust design methodology encompasses special types of experimental design (DOE). Consequently, we also review OA and its applications in robust design. Finally we review the literature on SS that contains conception, evolution, and discussion in various articles, journals and books available in the limited academic literature on SS [42].

2.1 TAGUCHI AND ROBUST METHOD

In this section we will first review the Taguchi method and its applications, and then the robust design.

2.1.1 Taguchi method and its application

Taguchi has developed a set of methods that has led to the discovery of how to reduce product and process variability without eliminating uncontrollable variables of the product or process. These methods represent a complete system that can be used in research and development as well as in product design and manufacturing. Taguchi called this approach "quality engineering", whereas most people outside of Japan referred it as the "Taguchi Method" [81]. The Taguchi method to quality is a comprehensive methodology for quality improvement for both off line and on line quality control [40]. Taguchi method provides a systematic way to improve the understanding of the process and assists industrial/manufacturing engineers to discover the key process parameters or variables, which affect the critical process or product [33]. Taguchi's philosophy is also more relevant in terms of working towards a target performance of a product or process, which essentially reflects the continuous improvement attitude [43].

The Taguchi method consists of three objectives that are [50]:

(a) Making processes insensitive to the environmental factors or other factors that are uncontrollable,

(b) Making products insensitive to variation transmitted from components and

(c) Finding levels of the process variables that force the mean to a desired value or a target value while simultaneously reducing variability around this value.

These three objectives make up what we now term as the " robust parameter design" or the "robust design." Once analysis of variance (ANOVA) and signal-to-noise (S/N) ratio have been performed, one can easily determine the significant design characteristics that contribute to the output of a process.

The Taguchi method allows experiments to be performed, prototypes to be tested on multiple factors at a time to make the products or processes insensitive to application environment as well as other unavoidable or uncontrollable factors.

Application of the Taguchi method is a very straightforward process that simultaneously verifies what control factors of the experiment significantly accounts for the variation in a given process. Shope [66] employed the Taguchi method and claimed that scrap reduced about 50% leading to a total savings of $577,800.00 per year with an investment of $3200.00 for the cost of the experiment.

Caporaletti [46] utilized Taguchi method, where spring tension improved about 14% and translated to an estimated savings of $468.00 per machine per week. The study by Caporaletti is important and relevant for this research since our methodology follows a sequence that is similar to that of Caporaletti.

Ryoichi [23] applied the Taguchi method in Aero-Engine Engineering Development; he found that the Taguchi method is the only design method where variations can be studied by a single metric known as S/N ratio, which is a scale of stability with respect to noise. Fujimoto Ryoichi pointed out [23] " variations are a cause of failure and noise is a cause of variations". The Taguchi method provides a design concept for a product or process that is immune to noise and a design method for a product that does not fail. The study of Ryoichi is also relevant in this research, in its approach to produce defect free product for achieving SS quality. Byrne [9] suggested that the technique developed by Taguchi should be applied as they are, on the other hand, Box [9] argued that some of the techniques introduced by Taguchi's are inefficient.

Hence, Taguchi methods have been successfully used in different types and sizes of industries. They contributed substantial benefits to the industries through improvement of their products such as:

a) Automotive
b) Electronics
c) Plastic
d) Process
e) Semi – conductors
f) Software
g) Telecommunications

2.1.2 Robust Design

The robust design method is defined as the process or product minimally sensitive to the uncontrolled factors. Taguchi defined robustness is the state where the technology, product or process performance is minimally sensitive to factors causing variability (either in the manufacturing or in the user's environment) [75]. As we know that Taguchi pioneers robust design, which is also called Taguchi method, in this research, we use the term "Robust Design" instead of "Taguchi Method."

The idea behind robust design, a design that has minimum sensitivity to variation of uncontrollable factors, is to improve the quality of a product by minimizing the effects of uncontrollable variables without eliminating such uncontrollable factors since the total elimination of uncontrollable factors is almost always too expensive and too difficult to achieve, if not totally impossible.

Robust design is an engineering methodology for improving productivity during research and development so that high quality products can be produced quickly and at low cost [55]. Taguchi method to quality control applies to the entire process of developing a product – from the initial concept, through design and engineering to manufacturing and production [86].

The product "robustness" is a function of a good design and zero defects suggest that when parts come in within tolerances, the product will be treated well. Parts within tolerance may miss a target rather than to hit it haphazardly. However, robust products maximize "signal–to–noise" ratios of component parts. It will be easily done by orthogonal array analysis and designer can exploit for designing robust product or process. Taguchi recognized that engineers can deliver "robust" product design that can perform their intended function at all possible settings of the application parameters in spite of manufacturing variations [36]. The above mentioned concept of robust design evolved during the second half of the twentieth century [37, 55].

Belegundu and Zhang [5] discussed the robustness of designing a mechanical system or a component considering uncertainty. The idea is to ensure quality control at the design phase by minimizing sensitivity of response to uncertain variables through selection of the design variables. Parkinson [53] discussed a general approach for robust optimal design. Bejamin [6] developed a method for a robust design system using discrete-event simulation. Orr, S., W. Folsom, L. Godin, B. Martin, and L. Peyton [52] states that there are mainly two tasks that should be performed by robust design. The first task is the measurement of quality design/development, while the second task is the efficient experimentation to find dependable information about design parameters.

Madhav S. Phadke [55] mentioned that the robust design added a new dimension to statistical experimental design that addresses

- how to reduce economically the variation of a products function in the customer environment.
- how to ensure that decisions found to be optimum during laboratory experiments will prove to be so in manufacturing and in customer environments.

Glean Stuart Peace [54] described that the Taguchi methodology uses to identify those key factors that have the greatest contribution to variation and to ascertain those settings or values that result in the least variability.

First developed and applied in Japanese industries, in late 1980's robust design gained popularity in North America and Europe [76]. The robust design method is used in many industries such as

(I) A T & T of USA [55] uses robust design to improved processes in very large-scale integrated (VLSI) circuit fabrication.

(II) Automotive supplier industry achieved quality and cost improvement through using robust design [55].

(III) Orr et al. [52] apply robust design method, to better understand and design a new product. They claim calculated savings of $300,000.00 per year for plating source against an investment of $1,140.00 and an improvement in yield from 0% to 86.7%.

(IV) Robust design method has applications not only in the engineering field but also in cash flow analysis, supply chain management, and profit planning in business [87].

2.2 ORTHOGONAL ARRAYS (OA)

The foundation for designing an experiment using the Taguchi method is the Orthogonal Array (OA) [54]. Orthogonal arrays are very efficient with relatively small amount of data and able to translate a meaningful result and conclusion. The term "orthogonal" means being balanced and not mixed. The analysis of OA is based on combining the data associated with each level for each factor or interaction. The difference in the average results for each level is the measure of the effect of that factor [54]. We discuss the details of OAs in sections 4.4 and 4.5.

2.3 SIX SIGMA (SS)

This section covers a review of the Six Sigma quality philosophy, its applications as well as the research done in this field.

2.3.1 Six Sigma quality philosophy

Six Sigma is a business initiative first supported/initiated by Motorola in the 1980's [21]. It uses common statistical tools for producing almost defect free output of a process. The objective of Six Sigma quality is to reduce process output variation so that ± Six Sigma standard deviations lie between the mean and the nearest specification limit and implication of Six Sigma in industry are profound. There are few academic papers, provides a definition of Six Sigma and discuss the importance of academic research in this area [42] but numerous texts written on Six Sigma conception, evolution, discussion. Hoerl et al.[31] mentioned that the Six Sigma improvement initiative has become extremely popular in the last several years. Faltin et al. [19] emphasised to create a business culture that goes further to offer greater assurance to investors, regulators, analyst and creditors, as well as management. Particularly in

- Corporate financial monitoring needs to be more time.
- Metrics that are more difficult to falsify must be devised.
- Malfeasance must be detectable even at levels below the corporate office.
- Common practices are needed across business units and across companies.

Six Sigma can address of the above mentioned issues and provide a uniform and disciplined framework for reliably tracking financial results and corporate governance metrics.

The strength of Six Sigma is focused on people issues including stakeholder interests, goal alignment and buy-in to ensure an outcome that exceeds stakeholder expectations [51]. The measurements used in a Six Sigma infrastructure need to drive the right behavior for all processes, not just manufacturing [22]. We need more than standard Six Sigma approaches to optimize product or service development [20]. Smith et al. [7] mentioned that the Six Sigma programs are popular, focused and effective. Many of the tools and approaches used in Six Sigma are familiar ones, with quality function deployment, benchmarking, failure mode and effects analysis, and design of experiments [59]. Harry states that even companies adverse to management fads are embracing Six sigma, believing that Six Sigma is a method of substance that will increase market share, decrease costs, and grow profit margins [29]. Six Sigma will have significant impact on the future of quality professional. The main reason for this is the success, specifically the financial success, of those companies that have implemented it wholeheartedly, most notably Motorola. Six sigma is currently getting much more favorable press in financial circles than the Total Quality Management or ISO 9000 [30]. Snee et al [68] describe that Six Sigma training is focused on improvement projects, hence the Six Sigma emphasis on project.

Six Sigma is a management innovation methodology to produce all products that are defect free based on the process data [12]. Its success to date is impressive and well documented. However, it is still expensive and time consuming to implement [78]. Six Sigma can be applied to almost any type and size of industry and represents a process, a philosophy, an attitude, and a set of tools. Obviously the process must be employed in a way that is appropriate to the size and the nature of each business and the type of product produced by the industry [69].

Six Sigma is not an "improvement methodology" [48]. It is:

a) A system of management to achieve lasting business leadership and top performance applied to benefit the business and its customers, associates, and shareholders.
b) A measure to define the capacity of any process.
c) A goal for improvement that reaches near perfection.

Six-sigma result can be achieved through a system that has few characteristics as follows:

a) Customer centricity: To know customers stated and implied need.
b) Financial results: There is enough evidence that indicates to add value in an industry.

c) Management engagement: All top management including the chief executive of operations to be involved with Six Sigma, each executive designated responsibilities with particular Six Sigma project.

d) Resource commitment: A significant number, typically 1% to 3% of the organizations staff to be engaged with Six Sigma efforts full time.

e) Execution infrastructures: There may be a hierarchy of role of responsibilities, which provides with ways to integrate Six Sigma projects and sustain the rate of improvement.

Although the results achieved and reported by the Six Sigma methodology may be regarded impressive, a recent survey [17] reflects that only 64% of organizations agree that the improvements in their productivity is due to Six Sigma. We discussed criticisms of SS in section 1.2.3, that should be kept in mind before implementing or designing SS. We should consider basic of quality element; it is critical to quality (CTQ) [38] of the product.

2.3.2 Research background

At the birthplace of Six Sigma at Motorola Corporation, they established the "Motorola University" and put their executives through executive training, Bob Galvin, Motorola's Chief Executive Officer in 1994 spent time in classroom for updating himself with Six Sigma methodology. GE's Chief Executive Officer Jack Welch describes Six Sigma as "the most challenging and potentially rewarding initiative we have ever under taken at GE" [21].

Larry Bossidy the Chief Executive Officer of Allied Signal said "The fact is, there is more reality with this (Six Sigma) than anything that has come down in a long time in business. The more you get involved with it, the more you are convinced" [21].

There is no package for Six Sigma approach or generalized approach for Six Sigma design, as there were like DMADV / IDOV / DAMIC for improving the existing process. As Deming pointed out, the 85% of the problems exist in system and 70-80% defects are due to design and rest in manufacturing is the quality problem. It is necessary to give more attention to the design of products or processes for producing good quality products.

2.3.3 The Six Sigma management paradox

To obtain Six Sigma performance we must minimize process variability, slack and redundancy by building variability, slack and redundancy in the organization [79].

Six Sigma involves extensive reduction of process variation, so that process would be capable to produce almost perfect products. There are well known practitioners having certification as Green Belt, Black Belt, and Master Black Belt. Although educational institutions do not give these certifications, these certifications bear the potential value in industries that are involved with Six Sigma.

There are practitioners of the Six Sigma process who view that robust design as a process in opposition to Six Sigma. In fact robust design is a key tool for the Six Sigma practitioners, the means for achieving higher C_p values and low the DPMO are not usually specified in the Six Sigma literature. But engineers are encouraged to use any means to achieve them and robust design is one of them [84].

Nowadays world industries are largely dependent on machinery and automation systems, which need robust systems. A robust system has been identified as a system that is insensitive to the sources of variation [32]. To develop a robust design we consider all factors & noises that are involved with the process to produce almost defect free product.

2.3.4 Six Sigma project

Project is defined as a clear and specific problem, limited but clear scope that addresses areas of improvement in quality of product or process. Lynch et al. [18] emphasised on project basis Six Sigma and mentioned that project is the backbone of SS program. Turner et al. [80] states that financial management can be expressed through a project, in SS achievement also demonstrated through financial metric rather than other terms associated with the SS design (appendix I). Hill [82] also discussed SS operational aspects on the basis of a particular project; it is directly reflecting the financial benefit of an organization. The successes of SS initiative largely depend on project and its selection procedure [62]. Phadnis et al.[67] showed project charter is one of the elements of SS. Cook-Davies [77] described factors pertaining to the success of a project in an organization. We observed that SS design project conception has been implied for reflecting financial benefit of an industry. The project is inseparable from SS design and we will provide very brief and useable information regarding SS project in chapter 3.

2.3.5 Modeling and Six Sigma design

Our literature survey shows that many published works are on the practical applications of the Six Sigma method. To this date, not much academic research has been done. Hence, it is very hard to find a generalized model for a Six Sigma design. The processes are different from industry to industry for different products. Conception or methodology varies from process to process. Applications of the Six Sigma methodology is very case dependent. The terminology used also varies from one implementation to another. For example, Honeywell uses Six Sigma plus, Motorola have ten steps for Six Sigma and so on.

Various methodologies have been used in industry for Six Sigma such as define, measure, analysis, improve and control (DMAIC) for product or process improvement, design for Six Sigma (DFSS) for design or redesign a product or process [41]. Although methodologies are different from industry to industry, their goal is the same. This goal is how to produce almost perfect product for satisfying customer need with a possible minimum cost of production. We observe that each industry tends to develop its own methodology, its own terminology, its own approach to design and implement a Six Sigma program. One of the motivations of this research is to develop a unified Six Sigma methodology that would be applicable to a wide range of industries.

2.3.6 Applications of Six Sigma

The achievements of Six Sigma normally expressed in terms of sigma level [27] and translate into some sort of financial term (Appendix I). There are lots of industries (Appendix IX) employed Six Sigma and ranging from service industries to high tech industries. The results of Six Sigma applications are very promising such as the case in GE (Appendix I). GE claimed revenue savings of $ 4.4 billion against an investment of $1.5 billion. Bolt [13] applied Six Sigma method in American Express Company and could reduce vendor visit 5.2% without any investment.

In Six Sigma design process optimization has been performed with various statistical tools such as DOE, RSM mentioned in section 1.6. Various method have been used in SS design such as identify, design, optimize, and validate (IDOV), define, measure, analyze, design, and verify (DMADV)[101], invent/innovate, develop, optimize, and verify (IIDOV), concept, design, optimize, and verify (CDOV) [113] in industry to achieve Six Sigma quality.

2.4 SUMMARY

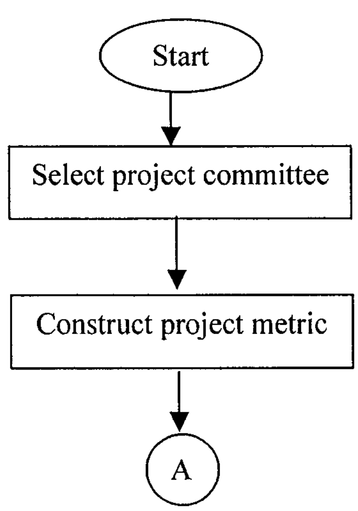
We explored various methods to obtain Six Sigma quality and studied numerous journal or books for formulating generalized model in Six Sigma design as mentioned in this chapter. We propose a robust design methodology to optimize a process, which leads to Six Sigma.

CHAPTER 3

SELECTION OF PROJECT FOR SIX SIGMA DESIGN

Experience tells us any improvement activities should be carried out in the form of project [45]. In this context, the term "Project" is defined as it consists of at least one process and represents three different areas of potential improvement, namely quality, cost, and schedule. The lifeblood of the Six Sigma initiative in any industry is the 'project' [15]. In view of industrial applications, Six Sigma emphasizes the project-by-project feature for its implementation; basically a project has concrete objectives, a beginning and an end, and provides opportunities for planning, reviewing, learning [27]. Therefore it is necessary for this research to present a very simple conception on project selection for Six Sigma before optimizing the process for Six Sigma design.

The simple form of project selection for SS flow chart is depicted in figure 3.1



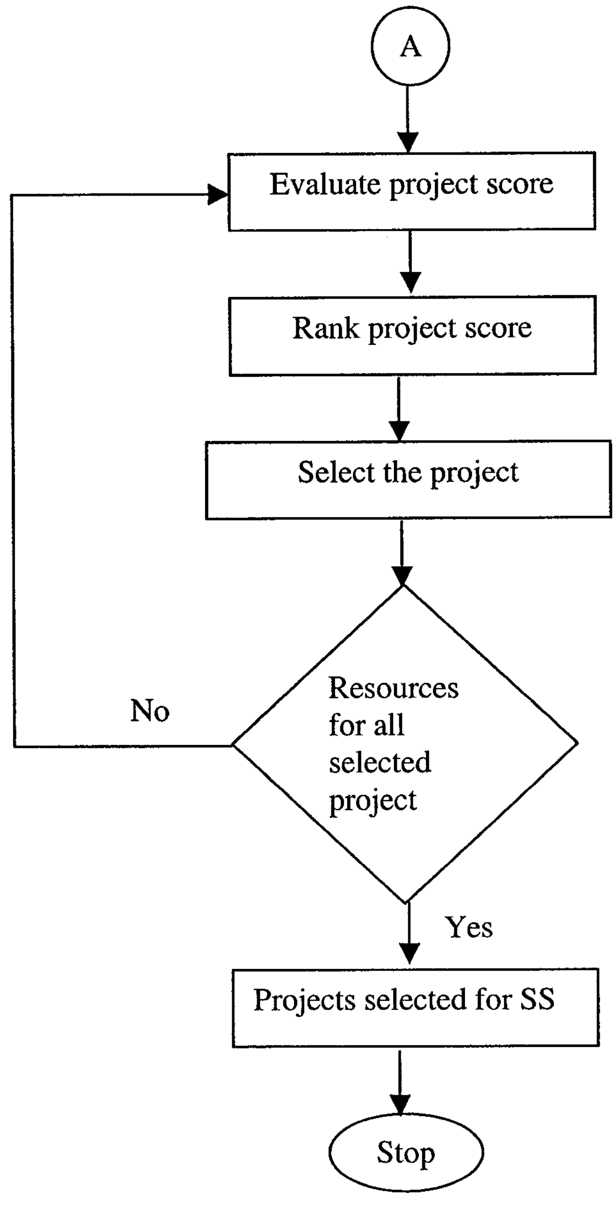


Figure 3.1 Project selection flow chart

3.1 PROJECT SELECTION FACTOR

The conception behind a Six Sigma project is to measure the financial performance of an industry within a stipulated period for the project. Six Sigma projects are categorized by the problem type as well as the savings category in which the benefits are realized. There are two groups of Six Sigma project savings: hard and soft savings [62]. Therefore the major goals of a SS project [82] are productivity improvement, business growth, and cash flow improvement. It is concerned to select a SS project with a minimal project investment and success of a project largely depends on certain factors that are associated with the project [77].

The factors that are associated with the success of a project are:

a) Factors correlate to on – time performances are,

1. Adequacy of company- wide education on the concepts of risk management.
2. Maturity of an organization's processes for assigning ownership of risk.
3. Adequacy with which a visible risk registers is maintained.
4. Adequacy of an up-to-date risk management plan.
5. Adequacy of documentation of organizational responsibilities on the project.
6. Keep project (or project stage duration) as far below three years as possible but approximately one year is better.

b) Factors related to on – cost performance are,

7. Allow changes to scope only through a mature scope change control process.
8. Maintain the integrity of the performance measurement baseline.

c) Factor related to the critical to project management success,

9. The existence of an effective delivery and management process that involves the mutual cooperation of project management and line management functions.

d) Factors critical to consistent corporate success are,

10. Portfolio – and program management practices that allows the enterprise to resource fully a suite of projects that are thoughtfully and dynamically matched to the corporate strategy and business objectives.
11. A suite of project, program and portfolio metrics that provides direct "line of sight" feedback on current project performance and anticipated future success, so that project, portfolio and corporate decisions can be aligned.
12. An effective means of "learning from experience" on projects, that combines explicit knowledge with tacit knowledge in a way that encourages people to learn and to embed that learning into continuous improvement of project management process and practices.

3.2 STEPS IN PROJECT SELECTION

In selecting a SS project there are three steps [83]:

1. Identifying and forming project selection committee / team.
2. Construct an appropriate project selection matrix.
3. To measure the output of the project.

3.3 SELECTION OF PROJECT TEAM

If every member of the project committee is aware of the success factors along with thorough knowledge of the process then it will bring great impact on the project. It is important to select the right team members and form the team. Without the appropriate team for project selection, the success of project is hard to earn. There are many guidelines to form a good team. Some of these are as follows:

1. A quality improvement team should compromise of five to seven members including the team leader.
2. Each team member should have creative and open minded, good team players, well respected among peers, and other associated with the business.
3. The team should include:
    a) Some individuals who intimately understand the current process (experts – could be at any level in the organization)
    b) Some individuals who actively use the process and work closely with customers.
    c) Some technical wizards.
    d) Some individuals who are completely objective toward the process and outcome.
    e) Customers and suppliers of the process
    f) Some individuals who are not familiar with the process (some one who brings a fresh perspective and outlook to the team)
4. Team member can always consult with customers, experts and other associated businesspersons.
5. A few guideline points to select team leader of the project team are:
    a) The team leader may be the manager or supervisor responsible for the unit where most of the changes are likely to be occurred.

b) The team leader should have some understanding and interest in the process being studied.

c) The team leader should be able to leave rank outside the door and should not be intimidating to team members because of the position within the organization.

d) The team leader should be able to communicate with other members of the team and throughout the organization.

e) The team leader should have the time and inclination to work on the project.

f) The team leader must be willingly to lead and carry a fair share of the workload.

Besides above guidelines the core responsibilities of the teams are as follows:

Team leader:

1. Taking accountability of the out come of the proposed project.
2. Planning the project.
3. Ensure minimum resources uses for the project.
4. To select appropriate methodology

Team members:

1. Dedicated to implement the project as per design.
2. Attitude to learn from others
3. Contribute to design the project.

4. To be fair to other member for sharing the project information.

3.4 CONSTRUCTION OF PROJECT METRICS (PM)

One of the most important phases in SS design is the selection of the Project Metrics (PM). The PM reflects the voice of the customer and creates a common language to all members. They should be simple, straightforward and meaningful. The idea used by the team is to identify the problem and determine the measurable / non-measurable value of the problem. Obviously, a metric should be measurable to improve the process. There are various types of methods to develop PM such as balanced or rank method. The ranking method is widely used in PM, this method is easy to create PM but it needs thorough knowledge of members to set up the rank of scale (such as scale from 0 to 10). As stated in chapter 2, project conception in SS design is inseparable from the SS design. A simple PM consists of customer issues internal and external, project and a ranking metric [83].

We provide generalize project ranking matrix, project rank, customer importance and customer relationship with project in figure 3.1, 3.2, 3.3 and 3.4 respectively.

Customer issues		Damaged product	Delay in delivery	Supply less parts than order	Found defect products	Delay in order processing	Response to customer	Delay in Billing	
Customer importance		X_1	X_2	X_3	X_3	X_1	X_3	0	
No.	Project	Project ranking based on customer correlation							
1	ABC	X_{11}	X_{11}	X_{33}	X_{22}	X_{11}	0	X_{33}	Y_{abc}
2	DEF	…	…	…	…	…	…	…	Y_{def}
3	GHI	…	…	…	…	…	…	…	Y_{ghi}
4	JKL	…	…	…	…	…	…	…	Yjkl
5	MNO	…	…	…	…	…	…	…	Y_{mno}

Table 3.1 Project ranking matrix

Project Number	Project Score	Project Rank
4	Y_{ikl}	1
2	Y_{def}	2
5	Y_{mno}	3
1	Y_{abc}	4
3	Y_{ghi}	5
$Y_{ikl} > Y_{def} > Y_{mno} > Y_{abc} > Y_{ghi}$		

Table 3.2 Project rank

And for project ABC, $Y_{abc} = X_1 * X_{11} + X_2 * X_{11} + X_3 * X_{33} + X_3 * X_{22} + X_1 * X_{11} + X_3 * 0 + 0 * X_{33}$, similarly for other project metric can be obtained.

Customer importance	Relationship to customer importance
0	Not important
X_1	Important
X_2	Very important
X_3	Critical
$0<X_1< X_2< X_3$	

Table 3.3 Customer importance

Project rank	Relationship with customer issue
0	No correlation
X_{11}	Some correlation
X_{22}	Highly correlation
X_{33}	Complete correlation
$0<X_{11}< X_{22}< X_{33}$	

Table 3.4 Customer relationship with project

Besides the above ranking, it will need further assessment with respect to available resources for the selected project.

1 If resources allow meeting the cost of all project then no need to further assessment for re ranking of the project.

2 Resources are not allowed for all projects then it will need discarding the project on the basis of different statistical analysis.

3 Still the project found to be in same group statistically, and then recomputed the rank score on the basis of factor consider or choose the all projects in order from highest to lowest until resources available.

3.5 STATISTICAL ANALYSIS FOR SELECTING THE PROJECT ON THE BASIS OF PM

Any organization / industry deals with numerous projects. But it needs to assess which project will be considered to improve or develop within the available resources for SS. There are many ways to select the project of an industry. A few of them are [35]:

1. Pareto analysis
2. Box and Whisker Plot (BWP)
3. Dixon's Outlier Test

In this research Box and Whisker Plot [35] will be considered for selecting project due to the following reasons:

a) Box and Whisker Plot calculation does not depend on the data distribution (that is discrete or continuous distribution).

b) Easy to plot or graphical representation of data without higher degree of analysis.

Box and Whisker Plot is a type of plot that displays a five number summary as shown in figure 3.2, these are

- The ends of the box are the upper and lower quartiles, so the span represents inter-quartiles range;
- The vertical line inside the box is the median; and
- The lines extend to the lowest and highest observations from the box are called whiskers.

BWP is useful for finding whether data distribution is skewed or whether there is presence of unusual observations (in a set of data, a value so far removed from other values in the distribution that is can not be attributed to the random combination of chance) in the data set.

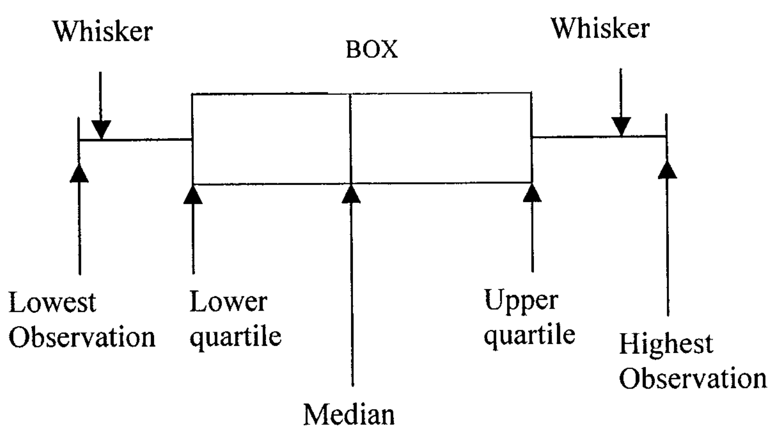


Figure 3.2 BWP

Besides these advantages, it also has some limitations such as identification of an outlier. Therefore the BWP should be applied the above PM and compare the total cost require for selecting project with the available of resources allocation for the project. We also employed this conception for generating continuous type data by MINITAB.

3.6 SUMMARY

During our review of the literature in connection with Six Sigma design, we observed that SS is basically project oriented. It is easier to evaluate a specific project rather than the work of an industry entirely. The project represents work cell of industry and it may have one or more processes. We apply customer oriented project evaluation metric, where suggest statistical selection procedure and it does not depend on data characteristic for SS design.

CHAPTER 4

TAGUCHI ROBUST DESIGN METHOD

The Taguchi Robust Design Method is a way of simultaneously analyzing and determining possible factors that may effect to the performance of the process output. This is a unique statistical experimental method, which is an off line quality control method. Quality and cost control activities performed at the product and process design stages to improve performance, productivity, reliability, and to reduce product development and life cycle cost. Consequently, to reduce variation of the product that is to reduce the defect rate, which leads to Six Sigma.

4.1 TAGUCHI METHOD

We described briefly about robust design and Taguchi method in section 2.1. The Taguchi method for optimization is used in the proposed methodology. The proposed method not only reduces variation of the product but also ensures that the product is more robust in applications environment.

4.2 ROBUST DESIGN

Robust design is based on five primary tool usages in the robust strategy [25, 56]. These are:

1. P-Diagram is used to classify the variables associated with the product into noise, control, input and response (output) as shown in figure 4.1
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 (OA) are used for gathering dependable information about control factors (design parameters) with a small number of experiments

Among the above, two important tools used in the robust design are (1) signal- to-noise ratio, which measures quality and (2) orthogonal arrays, which are used to study many design parameters simultaneously [55].

After selecting the project, we go through the process involved with the project. As per definition of robust engineering, to make the process robust, we will simultaneously control the factors and the noise to get defect free products

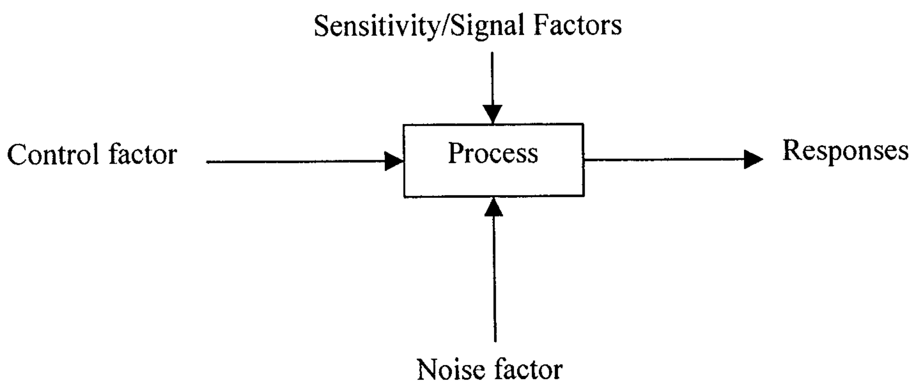


Figure 4.1 Typical diagram of a process in robust design

Development of robust engineering method will be dealt with control and noise factors as shown in above diagram of a process using Taguchi technique. Taguchi philosophy involves three ideas [50]:

1. Products and processes should be designed so that they are robust to external sources of variability.
2. Experimental design methods are an engineering tool to help accomplish this objective.
3. Operation on-target is more important than conformance to specifications.

There are three concepts are needed for representing robust design such as functional characteristics, control parameters and sources of noise.

There are two main aspects in the Taguchi method, first the behavior of a product or process is characterized in terms of parameters that are separated into two types [64,65]

I) Controllable parameters (design factor)

II) Uncontrollable parameters (noise factor)

Second, the controllable parameters are divided into those which affect the average levels of the response of interest – referred to as signal factors – and those which affect the variability in the response – referred to as control factor [1].

Control factors (also called adjustment factors) are the process inputs we intend to control in production. Engineers can change the level of control factors to adjust the output of a process and these are to optimize for minimizing noise factors.

Noise is a process input that consistently causes variation in the output measurement that is random and expected and, therefore, not controlled. Noise also is referred to as white noise, random variation, common cause variation and non-controllable variable.

Noise factors are controlled during the experiment, but are allowed to vary normally in production. Noise factors are typically difficult to control with respect to cost reason. The goal of experimentation with noise factors is to reduce the variability.

There are five sources of noise factors [40]

Variation in Hardware:

1. part variation in dimensions
2. characteristics of part changes over period of time

Variation in conditions of use:

3 due to cycle life of part

Variability due to environment condition:

4 external environment (e.g. humidity, temperature etc.)

5 internal environment created by adjacent part interaction.

4.3 OUR APPROACH TO THE BASIC MODEL

The fundamental model for any quality management is based on Shewhart / Deming cycle [8] plan, do, check/study and act (PDCA) and its cores represented in figure 4.2

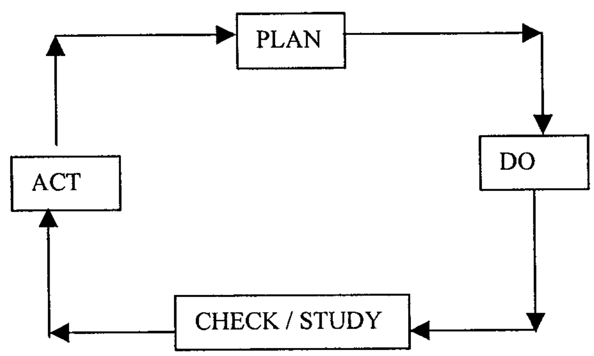


Figure 4.2 Shewhart / Deming Cycle

Plan – The plan phase deals with identifying the critical product requirement of customer and process improvement efforts are based on these critical requirements.

Do – At this phase it involves following –

1. Process variables related to improved quality should be identified.
2. To develop measures of these variables.

   and

3. To create format to collect data.

Check / Study – In the study phase to collect, process and out put data. After collecting data, summarize the data with appropriate graphic methods and interpret the findings to confirm which variables have major effect on output of the process. As significant variables are identified, statistical experiments are conducted to determine the more precise of effect variable has on quality.

Act – At end of conclusion of study phase, to select process variables believed to be the major contributor to process quality. These variables are used during the act in efforts to improve quality of the process.

In this research we propose a model to be done through Shewhart PDCA cycle to optimize the process for Six Sigma, where we apply various tools in different phases of the PDCA cycle. The process optimization steps can be summarized as follows in the PDCA model:

PLAN

(1) Identify customer needs, define dimension of quality and also define the problem.

(2) Identify critical to quality /selection of quality characteristics

(3) Prepare details analysis for determining capability and feasibility of manufacturing that is process capability studies.

(4) Identify factors/noises that influence on output of the process.

(5) To determine the number of defects of process output and measure the existing level of sigma of the process.

(6) To select level of factors and noises.

(7) Formulate the experiment, the size of OA and IA of design of experiment.

DO

(8) Experimental layout and data.

(9) Analysis

(10) Predicts factors at optimization.

CHECK / STUDY

(11) Conduct ANOVA on S/N ratio.

(12) Compare factors contribution if there is a difference between ANOVA and experimental run.

(13) ANOVA results are almost same with experimental run with respect to level and contribution of factors, then we address to fix process with the factors / noises

(14) After going manufacturing we evaluate capability / sigma level of the process, if sigma level improved then we go for next plan otherwise repeat the whole experiment for optimizing the process.

ACT

(15) Document and recommend the parameters for the process.

(16) Plan the next project.

4.4 ORTHOGONAL ARRAY (OA) APPROACH TO ROBUST DESIGN

The practical part of Six Sigma, is an umbrella of tools and techniques for identifying, quantifying and then dealing with the root causes contributing to poor quality. In robust designs, the quality is measured through signal-to-noise ratio but orthogonal arrays are applied to study many design parameters contributing to poor quality. The use of orthogonal arrays in Taguchi approach reduces the number of trials or prototypes necessary to perform an experiment.

Another advantage of OA is the relationship among the factors and investigation. For each level of any of the factors, all levels of the factors occur an equal number of items. This constitutes a balanced experiment and permits the effect of one factor under study to be separable from the effects of other factors [54].

4.5 SELECTION OF OA

The selection of OA depend on few factors as mentioned below [64] –

- The number of factors and interactions of interest.
- The number of level for factors of interest.
- The desired experimental resolution in cost limitation.

Besides above OA also should satisfy the following criterion [63] should be satisfied

$$\text{Degree of freedom (DOF) of OA} \geq \text{Total DOF required.}$$

Degree of freedom is the number of independent parameters associated with an interest that can be measured. DOF equals to one fewer than the number of level or setting for an experiment. If one factor has three levels hence DOF for the factor is two.

In our proposed experimental set-up, we have seven factors, each has two levels, and no interaction should be considered.

Therefore total DOF for factors is 7 X (number of levels –1) that is seven. This is the least requirement to select an OA; if DOF of an OA is lower than this requirement then we have to select another OA, which have higher DOF than required OA.

We run our experiment with four replications therefore the total number of experiments is thirty-two, hence DOF of OA is thirty-one. Thus it satisfies the criterion for selecting an OA for experiment.

The concept of DOF plays an important role in the statistical analysis of data and proper evaluation of any statistics derived from test significance depends upon being able to determine appropriate DOF [16].

The origin of the development of the orthogonal array is attributed to Sir R. A. Fisher of England. His early efforts apply OA to control error in the experiment. But Dr. Taguchi adapted the OA to measure not only the effect of factor interactions under study on the average result but also to determine the variation from the average.

An array can be expressed in the form of $L_A(B^C)$, where A represents number in experiment, B denotes level of each in each column and C is the total number of columns available in the OA experiment. For example $L_8(2^7)$ represents OA have eight runs, two levels in each column and total number columns available is seven. Similarly $L_{18}(2^1X3^7)$ OA have two levels in the first column where as remaining seven column contains three levels and total number of runs is eighteen in the experiment. This is sometimes called the mixed type experiment.

Orthogonal arrays are Fractional factorial designs, which minimize the number of trial run in the experiment and common OA shown in the table 4.1[1]

Orthogonal array	Number of factors	Number of levels per factor	Number of trials required by OA	Number of trials in a full factorial experiment
$L_4(2^3)$	3	2	4	8
$L_8(2^7)$	7	2	8	128
$L_9(3^4)$	4	3	9	81
$L_{12}(2^{11})$	11	2	12	2048
$L_{16}(2^{15})$	15	2	16	32768
$L_{16}(4^5)$	5	4	16	1024
$L_{18}(2^1 X 3^7)$	1 7	2 3	18	4374

Table 4.1 Common OA and compare between runs in the Full Factorial and OA

Within a column, there is an equal number of occurrences for each level. The analysis of OA is simple due to simplicity. The non-statistical expert can easily embrace it. But in full or fractional factorial design needs full depth of statistical knowledge for selecting an experiment.

The selection of an appropriate OA is a critical step in Taguchi's method [57], we select $L_8(2^7)$ and $L_4(2^2)$ OA for inner and outer array respectively.

4.6 SELECTION OF S/N RATIO

The performance characteristics (response variable) need to be controlled at both the mean and variation around the mean; it would use an objective measure that combines both of these parameters in a single metric. Taguchi defines such metric as the "signal to noise ratio (S/N)". For different types of performance characteristics the S/N is simply the ratio of the mean to the standard deviation. In general the S/N ratio will always be maximized to achieve a robust product or process design and S/N measured in decibel units.

A ratio or value formed by transforming the response data using a logarithm to help make the data more additive. Classically, S/N is an expression relating the useful part of the response to non-useful variation in the response.

Amongst metrics to be used for optimizing, the robustness of a product process S/N ratio has potential impact in design. The following are few properties of S/N ratio [64]:

1. The S/N ratio represents the variability in the response of a process or product due to noise factors.
2. The S/N ratio is not dependent on adjustment of the mean. In other words, the metric would be useful for predicting quality even if the mean value should change.
3. The S/N ratio measures relative quality characteristics, because it is to be used for comparative purposes.
4. The S/N ratio does not cause unnecessary complications such as control factor interactions.

These features of S/N ratio have great effect on optimization of a process or product. For getting the abovementioned properties it also needs thorough knowledge of engineering analysis and judgment to select proper S/N ratio.

There are two broad classes of S/N ratio, which are static and dynamic. The static S/N ratio form apply in cases where the quality characteristic target has a fixed value such as diameter of shaft or quantity of bear in a cane, etc. The dynamic S/N ratio is an extension of the static S/N ratio metrics. The dynamic S/N ratio form applies where output function vary with input function such as function of an amplifier. The static S/N ratio is common to use in Robust Design.

There are a variety of S/N ratios used in quality engineering but most common S/N ratios are:

- Smaller – the – better (STB)
- Larger – the – better (LTB)
- Nominal – the – better (NTB)

There are common features in all types of S/N ratios such as:

1. S/N ratio is always maximized.
2. S/N ratio is based the mean squared deviation or on average quality loss function.

G.1 The Smaller – the – better type S/N ratio (S/N_{STB})

The S/N_{STB} derived from smaller – the –better loss function concept and few features of this ratio are :

1. Response values or quality characteristics are continuous and non-negative.

2. The desired value of response is zero.

3. There is no scaling or adjustment factor: the goal is simply to minimize the mean and variance simultaneously.

The S/N_{STB} can be expressed as

$$S/N_{STB} = -10 \log_{10} (MSD) \quad (4.1)$$

Where

MSD – Mean square deviations.

$$MSD = 1/n * \left(\sum_{i=1}^{n} y_i^2 \right)$$
$$= [S^2 + (y)^2]$$

S – the sample variance

y – response

G.2 The Larger – the- better type S/N ratio (S/N_{LTB})

The common features of the S/N_{LTB} ratio are,

1. Response values are continuous non-negative numbers ranging from 0 to infinity.

2. The desired value of the response infinity or largest number possible.

3. This type S/N ratio has no scaling / adjustment factor.

4. The larger – the – better problems are the reciprocal of the smaller – the – better problem.

The S/N_{LTB} can be expressed as

$$S/N_{LTB} = -10 \log_{10}(MSD) \qquad (4.2)$$

Where

$$MSD = 1/n * \left(\sum_{i=1}^{n} 1/ y_i^2 \right)$$

G.3 The Nominal – the – best S/N ratio (S/N_{NTB})

There are two types of S/N_{NTB} ratio such as Type I and II.

The main characteristics of type I S/N_{NTB} ratio (S/N_{NTBI}) are as follows :

1. Response values are continuous and non-negative, ranging from zero to infinity.
2. This type of problem has a non-zero target value and zero variance when the mean response is at zero.

The S/N_{NTBI} can be expressed as

$$S/N_{NTBI} = -10 \log_{10}(S^2 / y_{ave}^2) \qquad (4.3)$$

Where

S – the sample variance

y_{ave} – average of sample response

And characteristics of type II S/N_{NTB} ratio (S/N_{NTBII}) are,

1. The response values are continuous and can take either positive or negative values.

2. The target value can be zero in this type of problem.

The type II S/N_{NTB} ratio expressed as follows –

$$(S/N_{NTBII}) = -10 \log_{10}(S^2) \quad (4.4)$$

Where, S – the sample variance

G4 Fraction defective S/N ratio (S/N_{FD})

Fraction defective S/N ratio is used when the quality characteristics are discrete type / integer nature such as number of defects. Where fraction is within 0 to 1 and the best value of fraction is zero.

The fraction defective S/N ratio can be expressed as

$$S/N_{FD} = -10 \log_{10} [p/(1-p)] \quad (4.5)$$

Where p – is the fraction defective.

Amongst of the above mentioned S/N ratio, the ***"smaller – the – better"*** type S/N ratio will be considered in order to meet the objectives such as to reduce number of defects leads to robust design and also utilize S/N_{FD} ratio to get optimize process for getting almost defect free product.

4.7 LEVEL OF QUALITY

In the SS design, the quality of products is expressed in terms of process sigma. The process sigma also represents the number of defects in opportunities. In other words, we use a level of quality, if the level of quality is Six Sigma; it indicates 3.4 defects per million opportunities. In general practice quality level improves on the project or process basis, improvement starts at where quality level is low in the industry.

The level of quality in terms of DPMO and sigma [61], are shown in figures 4.3, 4.4, and 4.5.

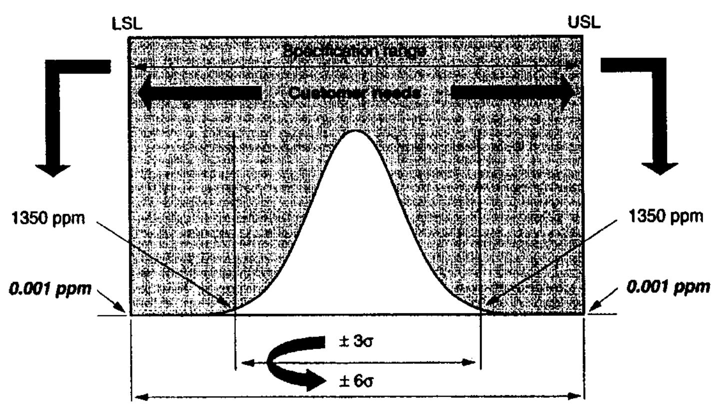


Figure 4.3 Normal distribution curve shows three and Six Sigma parametric conformance [copyright of Motorola]

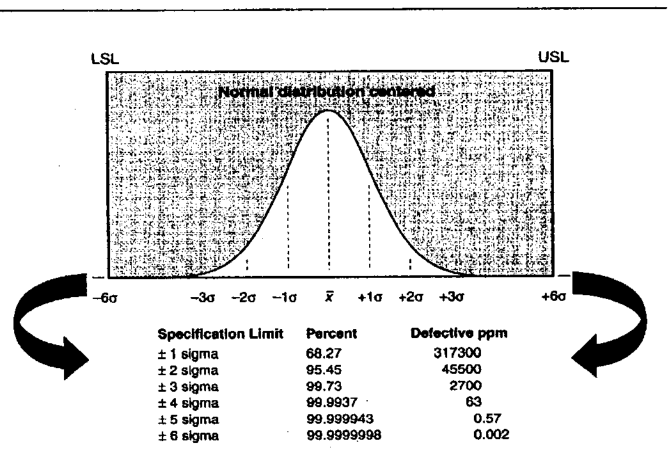


Figure 4.4 A centered normal distribution between Six Sigma limits, only two devices per billion fail to meet the specification target [copy right Motorola]

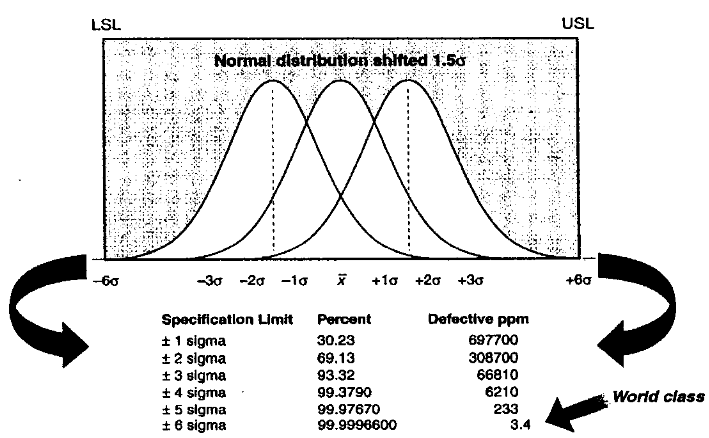


Figure 4.5 Effects of 1.5σ shift where only 3.4 ppm fails to meet specifications [copyright Motorola]

The DPMO against short and long term process sigma [26] as shown below in table 2.1 and corresponding graphical relationship also depicted in figure 4.6.

Process sigma (σ) long term	Process sigma (σ) short term	DPMO
-	0.0	933,000
-	0.5	841,000
-	1.0	691,000
0.0	1.5	500,000
0.5	2.0	309,000
1.0	2.5	159,000
1.5	3.0	66,800
2.0	3.5	22,800
2.5	4.0	6,210
3.0	4.5	1,350
3.5	5.0	233
4.0	5.5	32
4.5	6.0	3.4

Table 4.2 DPMO and short / long term process sigma

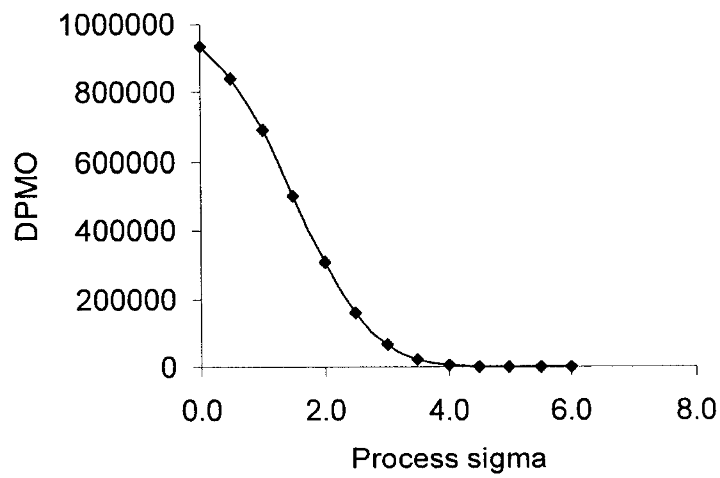


Figure 4.6 DPMO vs Process sigma (σ)

It shows that the Six Sigma goal is to produce almost defect free products for the customer. The approaches taken to reach this goal are different in different industries. For example, Motorola has ten steps for Six Sigma. Six Sigma programs, their selection and recognition processes vary dramatically from one company to the other company. The main idea of this research is to generalize the system in Six Sigma design. Although approaches taken are different, the goal of all industries is common. That is to produce defects free product for their customers. In this context, a generalized approach we propose in this research may be helpful to achieve this goal.

Six Sigma approaches are three folds. Firstly, processes important to the customer are identified and the key metrics of these processes accurately tracked over time. Secondly, acceptable limits to process performance are set, based entirely on what would deliver satisfactory quality to the real customer. Thirdly, the process capability to deliver to customer expectation is measured using sigma metric [26].

4.8 INTERACTION OF FACTORS

In real world there are interactions among the factors in processes that affect on the quality characteristics of the product. It is important to consider the interactions in planning an experiment, the failure to recognize the presence of interaction can cause in-appropriate analysis of data and such failure include important consideration in the process of optimization. The interaction effect sometimes imparts good physical quality characteristics of product instead of poor quality.

The interactions between more than two factors are very rare in practice but still there are possibilities of multi-factor interactions. It is often very difficult and expensive to identify such type of interactions, considered negligible in respect to the main effect of control factors.

Taguchi stresses the importance of focusing on main effects (the individual effects of each factor by itself) and selecting quality characteristics with good additivity so that the effects of interaction between controls are minimized (though not eliminated) and therefore need not be considered in the study [54]. Taguchi recommends to carefully defining the quality characteristic and the individual factors, which can eliminate a lot of need for incorporating interactions into the design of the experiment.

Taguchi argues that, it is not needed to consider two factors interactions explicitly. It is possible to eliminate these interactions either by correctly specifying the response and design factors or by using a sliding setting approach to choose the factor levels [50].

Besides, the process engineer, who is also an expert on the process, can acquire knowledge of the interaction effect between possible input factors from experience. Proper utilization of such knowledge or experience will allow selecting interaction effects of two factors. Factor interaction is obtained by using one column of the OA. Such as in $L_8(2^7)$ as shown in table 4.2, OA column 3,5 and 6 represent the interaction between factor of column 1 & 2, 1 & 4 and 1 & 7 respectively.

	1	2	3	4	5	6	7
Run	A	B	A X B	C	A X C	A X D	D
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 4.3 $L_8(2^7)$layout, where A, B, C and D are factors ; AXB, AXC and AXD are interactions of factor A with B, C and D respectively ; 1 [Low] and 2 [High] represents the levels of each factor and interactions.

For simplicity of the experiment in this research, interaction effects are not considered. However, the main factors of the experiment are carefully considered under assumption that there is no significant interaction action between the two factors.

4.9 QUALITY DIMENSION

We employ quality dimension for selecting critical to quality (X's) of product or process and it also reflect quality level of the product achieved through process optimization or end result of product. It is the quality characteristics of a product; a product may be excellent in one character and average in another or product exceeds all dimensions.

There are nine quality dimensions in a product and they are [24]:

1. Performance – Primary performance characteristics such as brightness, sharpness of TV picture.
2. Features – Secondary performance characteristics such as remote control car starting.
3. Conformance – Meeting specifications of industry and workmanship standards etc.
4. Reliability – Consistency of performance overtime, average time for unit to failure.
5. Durability – Useful life including repairs and service.
6. Service – Resolution of problems and complaints ease of repair and maintenance.
7. Response – Human to human interface such as courtesy of sales person.
8. Aesthetics – Sensory properties of a product such as pleasing to look at.
9. Reputation – Past performance and position in the community such

as Wal Mart stood 1st place amongst top 500 global organizations in year 2002[44].

The defect free product can ensure to meet all dimension of quality and subsequently achieved Six Sigma level quality.

4.10 SUMMARY

As we know that among the five typical tools for robust design, OA and S/N ratio brings optimization of process or product design. Both of them are discussed in section 4.5 and 4.6. We utilize these to find out optimization levels of process factors with associated noises. The entire robust design fit with the basic quality management PDCA cycle.

CHAPTER 5

DETERMINE THE OPTIMAL PROCESS FOR SIX SIGMA DESIGN USING THE ROBUST METHOD

5.1 INTRODUCTION

There are many ways to optimize processes for Six Sigma design but most of the approaches used have limitations as described in section 1.2.3. The main target of Six Sigma design is to deal with the number of defects. The characteristics of a process output depend on the factors associated with the process. Optimization of these factors will produce the best possible quality product without increasing the cost. The robust technique can be used to analyze the significance of each control factor, to evaluate the process performance, and to optimize parameters to reduce the number of defects [64].

5.2 DEFINITION OF THE OBJECTIVES AND PROCESS PARAMETERS

The main objective of our design approach is to optimize the process by setting the appropriate levels of the factors of process along with the interaction of noises. The process reaches its optimum when its output has a minimum number of defects, ideally zero-defects. Hence, reduction of the number of defects indicates improvements in the sigma level. As the main metric in the proposed methodology, we will use "Smaller-the-Better" S/N ratio.

5.3 PROCESS OPTIMIZATION

Optimization is adjusting the system or process inputs to produce the best possible average response with a minimum variability. Figure 5.1 presents a simple flow chart for process optimization.

Process is defined as a set of interrelated work activities characterized by a set of specific inputs and value added tasks that make up a procedure for a set of specific outputs [70].

The key ideas to improve sigma are either to reduce the standard deviation σ, or to center the process around the target (i.e. the mean) or both [12].

This may be represented by the following relationship –

$$[Y_1, Y_2, Y_3 \ldots \ldots \ldots Y_n] = f(X_1, X_2, X_3 \ldots \ldots \ldots X_n) \quad (5.1)$$

Where Y and X are process quality variables and process variables (independent variables) respectively. To find the best combination of quality variables (Y_1, Y_2, Y_3 … … … Y_n), we need to optimize the independent variables so that we will be able to obtain product with expected quality dimensions as per customer requirement. In our research, Y's represent as quality dimension (or " critical to quality ") and X's represent control factors. Additionally x's represent the noise factors.

Therefore the relationship can be may be represented by equation (5.2)

$$[Y_1, Y_2, Y_3 \ldots \ldots \ldots Y_n] = f(X_1, X_2, X_3 \ldots \ldots X_n) + f_1(x_1, x_2 \ldots \ldots x_n) \quad (5.2)$$

The equation 5.2 should be solved by OA in our research. We will fix the levels of X_1, X_2, X_3 … … X_n with interaction of x_1, x_2 … …x_n , which provide the best value of Y's. This means the optimal quality dimension of the process output. As an example, we can discuss the fuel delivery system in a car where fuel pump type, assembly type, rated pump flow are presenting X's, *x*'s are pump voltage level, fuel system back pressure and Y's are quantity of fuel delivered, uniform flow of fuel. The quality dimension is also defined as "critical to quality" (CTQ). CTQ is needed to transform into the product through applying appropriate method such as quality function deployment. We also provided a brief description of quality dimension in section 4.8.

In this research, we performed an experiment with interaction between control and noise factors where factors level should be determined for optimizing process.

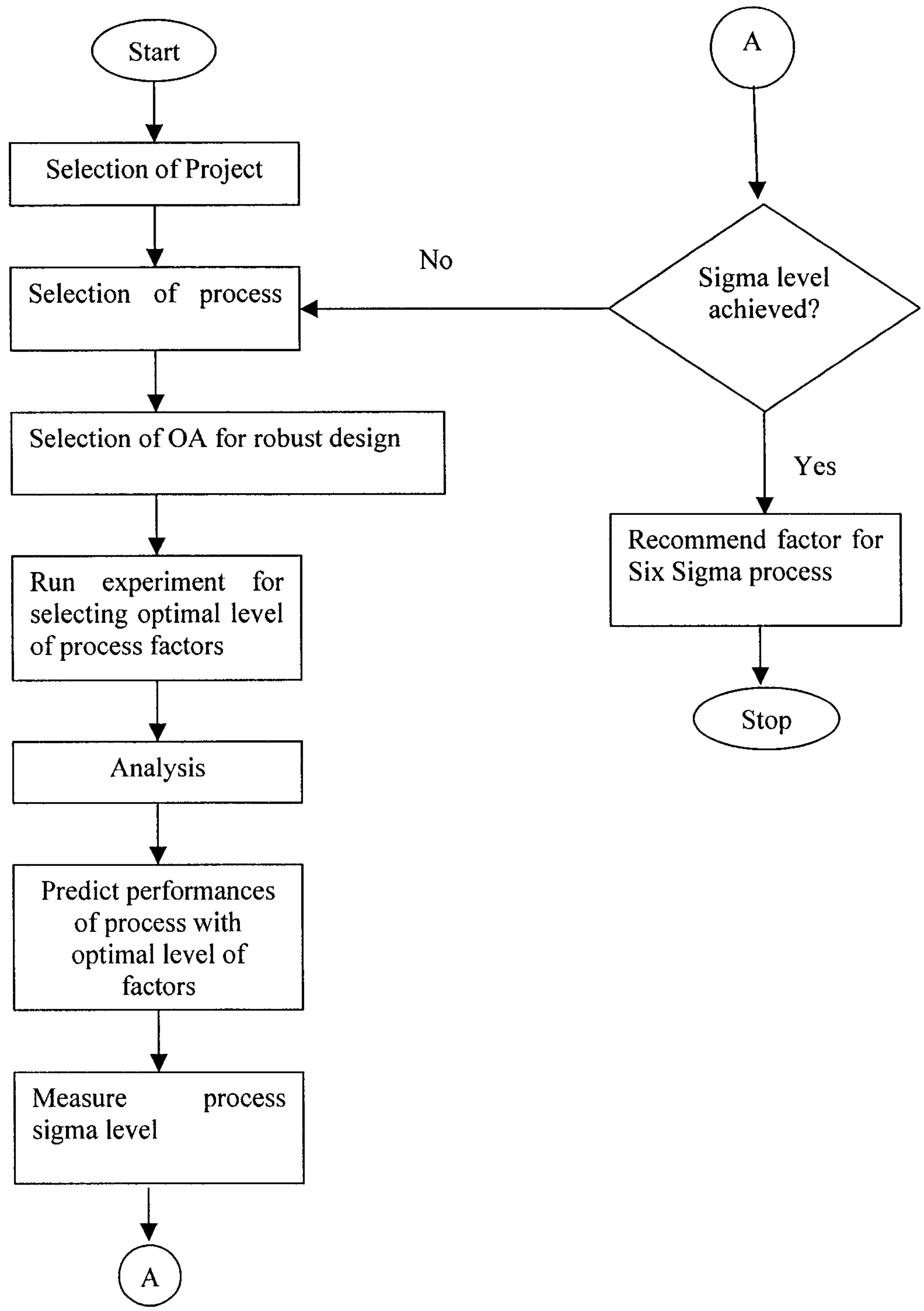


Figure 5.1 Flowchart for the optimization procedure used our approach.

The followings are the detailed explanations of the quality variables; in this approach the quality variables are identifications of the customer's wants and needs. In this section we also provide details of procedure of optimization including experimental set-up.

5.3.1 Identification of the customer needs or dimension of quality

These are the characteristics of a product and they meet stated or implied needs of a customer. The quality dimensions will be expressed in terms of either numerical (measurable) or non-numerical value. They bear ultimate satisfaction as well as loyalty of customer to the product.

5.3.2 Identification of critical to quality (CTQ) or selection of quality characteristics

The term " critical to quality " (CTQ) may also be called functional characteristics in the Robust Design. The needs and wants of the customer, those are very critical to meet, also represent the functions of the products in respect to dimensions of quality. The CTQ are measurable and it plays an important role, in developing a robust design, which requires identifying CTQ.

CTQ represent the product or service characteristics that are defined by the customer (internal or external). They may include the upper and lower specification limits or any other factors related to the product or service. A CTQ usually interpreted from a qualitative customer statement to an actionable, quantitative business specification.

To put it in layman's terms, CTQ are what the customer expects from a product, in other words, the spoken needs of the customer. The customer may often express this in plain English, but it is up to us to convert them to measurable terms using tools such as design failure mode and effect analysis (DFMEA). In order to classify the characteristics of products, we applied various techniques such as the cause-and-effect diagram to create a list of important factors to be considered. These factors are subsequently classified as controllable or uncontrollable.

5.3.3 Preparation of the detailed analysis for determining capability and feasibility of manufacturing

It can be assumed that the industry is capable to produce product as per standards to meet the customer needs. Although the industry is capable of producing product according to the standards, there is still variation exists in products and quality does not exceed the customer satisfaction. Hence, there is a scope to analyze CTQ to minimize the variation of the products which would lead to defect free product of an industry

5.3.4 Factors

As per definition of the robust design we should study two types of factors that are controllable and uncontrollable factors. They are also called design factors and noise factors respectively. The desirable result is to produce almost defect free product that leads to Six Sigma. The cause – and – effect diagram [39] is used to select factors (controllable and uncontrollable) that influence the processes of an industry.

5.3.5 Define process response and measure the sigma level of process

We measure process response as number of defects per million opportunities and translated into process sigma. The process sigma here is called the sigma level of the process. The process sigma may be defined as a measure of the amount of the process output that falls inside the externally imposed specification limits from the customer.

5.3.5.1 Process response

The responses of a process may be classified with respect to the purpose of the analysis such as process control, regulating, acceptance or rejection of lot or analysis of responses. Our research focuses on the analysis of the response and its uses in examining the relationship between a defect and its cause. The response of the process represents the facts the statistical method applied to an objective evaluation. As in Six Sigma calculation we consider number of defects is the response of the process.

5.3.5.2 Six Sigma level calculation

We employed equation 5.3 to calculate sigma quality level relationship with the 1.5 σ shift can be approximated (Schmidt & Launsby 1997) [21]

$$\text{Sigma Quality Level} = 0.8406 + (29.37 - 2.221 * \ln(\text{ppm}))^{1/2} \quad (5.3)$$

Where

Ppm – Parts per million or defects per million opportunities (DPMO)

$DPMO = DPO * 10^6$

DPO (Defect per unit opportunity) = DPU/O

O – Opportunities for a defect

DPU (Defect per Unit) = D/O

D – Defects

The following are the definitions in connection with the equation 5.3:

Defect is a product or service's non-fulfillment of an intended requirement or reasonable expectation for use, including safety considerations [70].

Unit is an object on which measurement or observation can be made. Commonly used in the sense of a "unit of product," the entity of product inspected in order to determine whether it is defective or non defective [70].

Opportunity is any area within a product, process, service, or other system where a defect could be produced or where you fail to achieve the ideal product in the eyes of the customer. In a product, the areas where defects could be produced are the parts or connection of parts within the product. In a process, the areas are the value added process steps. If the process step is not value added, such as an inspection step, then it is not considered an opportunity.

The basic Six Sigma metric is the capability index, can be expressed as follows –

$C_p = [USL - LSL] / 6\sigma$

Where USL – upper specification limit

LSL – lower specification limit

σ - is the (population) standard deviation of the process being studied

The numerator is the customer limit tolerance for a design parameter in a product or process. Sometimes it is also called functional limit of the customer and there is also factory tolerances or SPC limits that are lower than the functional limits.

The denominator is the measure of the manufacturing variability of that parameter.

From the above relationship (C_p) –

I] Through applying quality engineering tolerance range can be increased. Robust design increases the amount of variation that a particular critical parameter can have without causing the system performance to exceed the customer limit.

II] The manufacturing variability (σ) can be decreased by applying quality engineering to the manufacturing process or system.

		On target	1.5σ off the target
Quality Level	C_P	DPMO	DPMO
3σ	1	2700	66800
4σ	1.33	63	6210
5σ	1.67	0.57	233
6σ	2.00	0.002	3.4

Table 5.1 DPMO vs (C_p) with and without mean shift.

Product variability – Product variability is defined as the different kind of properties such as physical or chemical property of a product. It is important to distinguish the variability due to manufacturing process from the variability revealed when product is in use. The variability due to manufacturing process makes every characteristic of the product in each product item.

The variability seen in use can be the result of different physical phenomena affecting the characteristics considered, such as the thermal expansion, the strain due to the external loads or the effect of moisture in the dimension of some types of materials [46].

As per definition of defect, we consider number of defects for example over a period of, six month or a total number of product 100 and calculate the sigma level of the process.

To illustrate, suppose a certain CTQ of a product called "weight." The particular performance variable has been assigned a performance tolerance – an USL and LSL, respectively. Given this, it is naturally recognize that a violation of the USL would represent an overweight condition, while a failure of the LSL would constitute an underweight condition. Of course, any given unit of product can only fail one specification or the other, but not both concurrently and it can be said that the two requirements are mutually exclusive.

Now, let us hypothesize that an industry just produced and evaluated 100 units of a product. For the sake of discussion, it will be known that 2 of the units violated the LSL and 3 units failed the USL. That is occurrence of 5 defects in 100 units. However, we only recognize 100 defect opportunities. This hold true because the given specification limits (USL and LSL) are mutually exclusive. With this mind, we compute the defects-per-opportunity as $DPO = D / (U * O) = 5 / 100 = .05$. By way of transformation, it is discovered that the computed DPO is equivalent to 1.65s sigma (one-sided). By factoring the 1.50s shift we are able to approximate the equivalent short-term capability as 1.65s + 1.50s = 3.15s.

Z-shift is equal to 1.5 because this is an empirical value arrived after research done by statisticians. As it can be mathematically demonstrated [49], the "1.5 sigma shift" can be attributable solely to the influence of random sampling error. In this context, the 1.5 sigma shift is a statistically based correction for scientifically compensating or otherwise adjusting the postulated model of instantaneous reproducibility for the inevitable consequences associated with dynamic long-term random sampling error. Naturally, such an adjustment (1.5 sigma shift) is only considered and instituted at the opportunity level of a product configuration. Thus, the model performance distribution of a given CTQ can be effectively attenuated for many of the operational uncertainties encountered when planning and executing a design-process qualification.

Based on this understanding, it should be fairly evident that the 1.5 sigma shift factor can be treated as a "statistical constant," but only under certain engineering conditions. By all means, the shift factor (1.5 sigma) does not constitute a "literal" shift in the mean of a performance distribution – as many quality practitioners and process engineers falsely believe or try to postulate through uniformed speculation and conjecture. However, its judicious application during the course of engineering a system, product, service, event, or activity can greatly facilitate the analysis and optimization of "configuration repeatability."

By consistently applying the 1.5 sigma shift factor (during the course of product configuration), an engineer can meaningfully "design in" the statistical confidence necessary to ensure or otherwise assure that related performance safety margins are not violated by unknown (but anticipated) process variations. Also of interest, its existence and conscientious application has many pragmatic implications (and benefits) for reliability engineering. Furthermore, it can be used to "normalize" certain types and forms of benchmarking data in the interests of assuring a "level playing field" when considering heterogeneous products, services, and processes.

Finally 1.5 sigma offsetting viewed as a mathematical construction of normal distribution and treated as statistical constant. After calculating of improved process sigma and it is called short term sigma value, to get long term sigma value of process we subtract 1.5 from short term because short term sigma process data contains common cause of variation. But in long term process contains both common and special cause of variation. Subtracting of 1.5 sigma allows us to accommodate unavoidable sources of variation in processes or products or services.

5.3.6 Selection of factors and noise levels

We choose the level of factors and noises with respect to the capabilities of an industry and availability of resources. In this research we consider two levels such as levels 1 and 2, represented as low level and high level respectively in the experimental layout.

5.3.7 Formulating experiment

In formulating the experiment, we consider discrete type of responses that is the number of defects. It will be exploited for finding optimization of the process with the associated factors and noises.

The Smaller – the – Better type Fraction defective S/N ratio (S/N_{FD}) will be utilized for discrete type response. As number of defects will be the discrete response and it will provide the defects-per-opportunity (DPO), DPO will subsequently be converted into the sigma level of the experiment.

For inner and outer arrays, we will consider $L_8(2^7)$ and $L_4(2^2)$ hence there will be total of 32 responses and four replications for each row for different noise conditions.

The inner / outer array format is shown in table 5.2 using an $L_8(2^7)$ for the inner array and an $L_4(2^2)$ for the outer array for the noise factors.

									Noise factor(outer array , $L_4(2^3)$)					
								H	1	2	2	1		
								I	1	2	1	2		
	Control factor (inner array, $L_8(2^7)$)													
	1	2	3	4	5	6	7							
Run	A	B	C	D	E	F	G		1	2	3	4	Mean	S/N
1	1	1	1	1	1	1	1		y_{11}	y_{12}	y_{13}	y_{14}	$y_{ave(1)}$	S/N_1
2	1	1	1	2	2	2	2		y_{21}	y_{22}	y_{23}	y_{24}	…	…
3	1	2	2	1	1	2	2		y_{31}	y_{32}	y_{33}	y_{34}	…	…
4	1	2	2	2	2	1	1		y_{41}	y_{42}	y_{43}	y_{44}	…	…
5	2	1	2	1	2	1	2		y_{51}	y_{52}	y_{53}	y_{54}	…	…
6	2	1	2	2	1	2	1		y_{61}	y_{62}	y_{63}	y_{64}	…	…
7	2	2	1	1	2	2	1		y_{71}	y_{72}	y_{73}	y_{74}	…	…
8	2	2	1	2	1	1	2		y_{81}	y_{82}	y_{83}	y_{84}	$y_{ave(8)}$	S/N_8

Table 5.2 Crossed array layout for the optimization experiment.

Once S/N ratio and the averages of responses have been computed for each run, then S/N ratios have been graphically represented, and average responses have been plotted for each factor against of its levels. The graphs are to be used to select the levels of factors, which provide a maximum S/N ratio and bring the mean on the target. Using this information, the control factors can be grouped as –

a) Factors that affected both the variation and mean performance of the process output
b) Factors that affect the variation of the product only
c) Factors that affect the mean only
d) Factors that do not have any affect neither the variance nor the means

Factors in the first and second groups can be utilized to reduce the variations in the system making it more robust. The 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 basis on the best economical point of view [86].

5.4 METHODOLOGY

We use robust method, signal – to – noise ratio technique in our analysis and apply ANOVA to measure factors contribution in product / process performance. This methodology can be used for any type of distribution; response of process may be from normal or non-normal. In real world, data of process or process responses may follow any type of distribution.

5.4.1 Characteristic

Since lower number of defects is our goal to achieve the sigma level, the fraction defective lower-the-better S/N ratio characteristic (in decibels) is chosen.

The equation for this equation (4.5)

$$S/N_{FD} = -10 \log_{10} [p/(1-p)]$$

Where p – is the fraction defective and p varies from 0 to 1

and ideal value of p is zero [55].

The average number of defects

$$Y_i = 1/n *(\sum_{j=1}^{n} 1/ Y_{ij}) \qquad (5.3)$$

Where i represents ith row of inner array and j indicate as the jth column of outer array,

n = j;

The grand average

$$Y = 1/k *(\sum_{i=1}^{k} 1/ Y_i) \qquad (5.4)$$

5.4.2 Data collection

Since our research dealings with number of defects, we randomly generated data by MINITAB software as numbers of defects to run experiment through the proposed methodology.

5.5 EXPERIMENTAL LAYOUT AND DATA

The proposed experimental layout is shown in the form of Table 5.3. Our objective is to reduce the number of defects; therefore we utilize the lower-the-better S/N ratio characteristics. Since numbers of defects are of integer values, we use the fraction defective lower-the-better S/N ratio but the conception is similar to the lower-the-better S/N. High signal-to-noise ratio is always preferred in a Taguchi experiment as well as in robust design. The lower-the-better characteristic, this translates into lower process output average, improved consistency and sigma level. The equation 4.5 should be used to determine S/N for each experimental run and average of each run also find with the equation 5.3.

							OUTER ARRAY $L_4(2^2)$						
							H	1	1	2	2		
							I	1	2	1	2		
INNER ARRAY $L_8(2^7)$								Responses in PPM				S/N ratios	Mean
A	B	C	D	E	F	G							
1	1	1	1	1	1	1		425	450	380	478	33.6307	433.25
1	1	1	2	2	2	2		450	440	480	450	33.4179	455
1	2	2	1	1	2	2		478	425	440	380	33.6559	430.75
1	2	2	2	2	1	1		390	450	450	440	33.6383	432.5
2	1	2	1	2	1	2		478	478	478	480	33.1991	478.5
2	1	2	2	1	2	1		450	425	450	478	33.4587	450.75
2	2	1	1	2	2	1		390	401	450	440	33.7631	420.25
2	2	1	2	1	1	2		390	380	425	425	33.9237	405

Table 5.3 Experimental layout and with raw data (Poisson) generated by MINITAB

5.6 ANALYSIS

5.6.1 ANOVA of S/N ratio

The ANOVA of S/N ratios are shown in table 5.4. The df is the number of degrees of freedom, S is the sum of squares of sources, V is the variance of sources, F is the variance ratio, S' is the net variation and ρ is the percent contribution of source and e is the pooled estimate of experimental error [1].

ANOVA for S/N ratio						
Source	df	S	Variance (V)	F	Net Variation (S')	%
A	1	4.03E-07	0.000000403374*			
B	1	0.20304	0.203042351	49.291541543039***	0.1989231	57
C	1	0.07674	0.076735376	18.6286504037018***	0.0726162	21
D	1	0.0045	0.004500029*			
E	1	0.05291	0.052912403	12.8452704461471**	0.0487932	14
F	1	0.00116	0.001157226*			
G	1	0.01082	0.010818932*			
(e)	(4)	0.01648	0.004119213			8
Total	7	0.34917				100

* - Pooled into error

** - significant at 99% confidence level , $F_{1,4(99\%)} = 21.2$

*** - significant at 95% confidence level, $F_{1,4(95\%)} = 7.71$

Table 5.4 S/N ratio ANOVA

5.6.2 Significance of each source

The purpose of ANOVA is to determine those factors, which have strong effects on the responses of the experiment. The effect of any factor is equal to the difference between the average S/N ratios for each level. As described in section 5.3.7, we grouped factors accordingly. We observed that the factor B, C and E poses strongest effects in figure 5.3, 5.4 and 5.6. These three factors can be rank in the following order: B, C, and E. From S/N and mean effects plot we conclude that B2, C1 and E1 are the preferred settings for optimization.

The remaining factors A, D, F and G does not make significant effects as shown in figure 5.2, 5.5, 5.7 and 5.8 respectively. Hence these factors can be set either level. But theoretically we set these factors as per figure 5.2 to 5.8, which are A2, D2, F1 and G1 for prediction of S/N ratio and mean of responses.

Thus, the recommended factors level for prediction settings [54] are A2, B2, C1, D2, E1, F1 and G1.

The prediction equation for $S/N = S/N_{A2} + S/N_{B2} + S/N_{C1} + S/N_{D2} + S/N_{E1} + S/N_{F1} + S/N_{G1} - 6*S/N_{ave}$

The prediction equation for mean $= m_{A2} + m_{B2} + m_{C1} + m_{D2} + m_{E1} + m_{F1} + m_{G1} - 6*m$

The engineering significance of a statistical factor can be measured in terms of its contributing of factor [72]. The larger the percentage contribution of any factor means more can be achieved by changing the level of that factor.

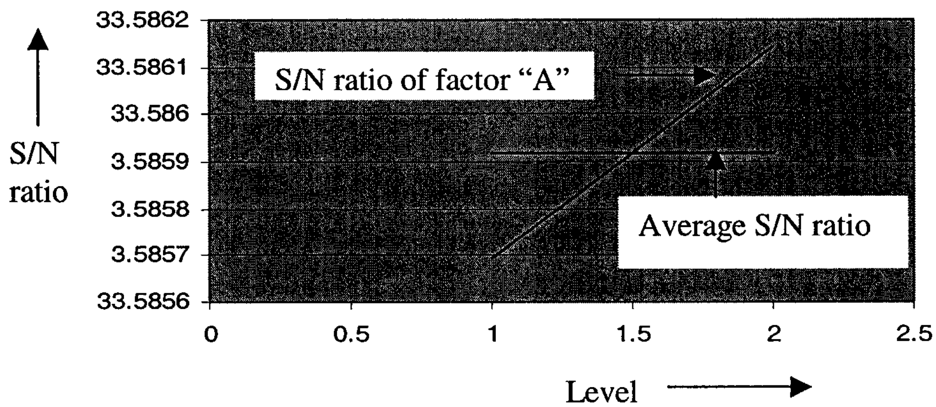


Fig. 5.2 Effects plot for S/N ratio of factor A

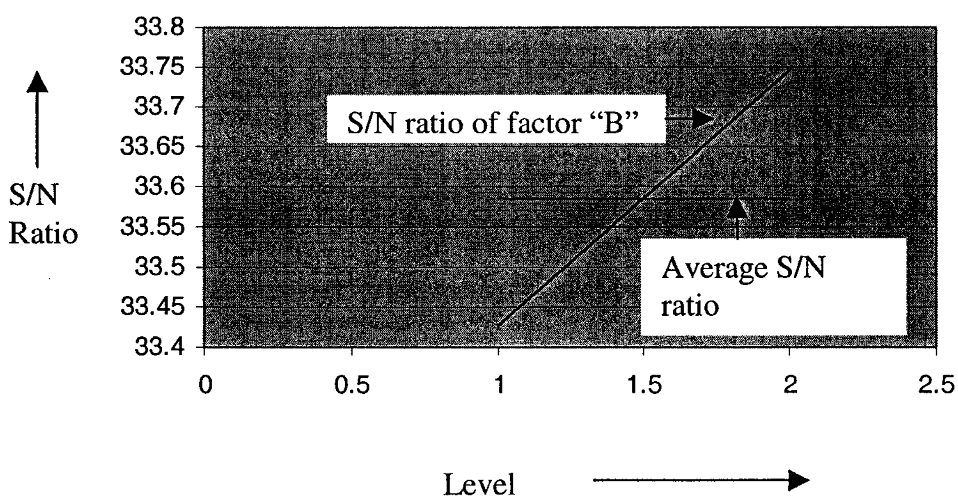


Fig. 5.3 Effects plot for S/N ratio of factor B

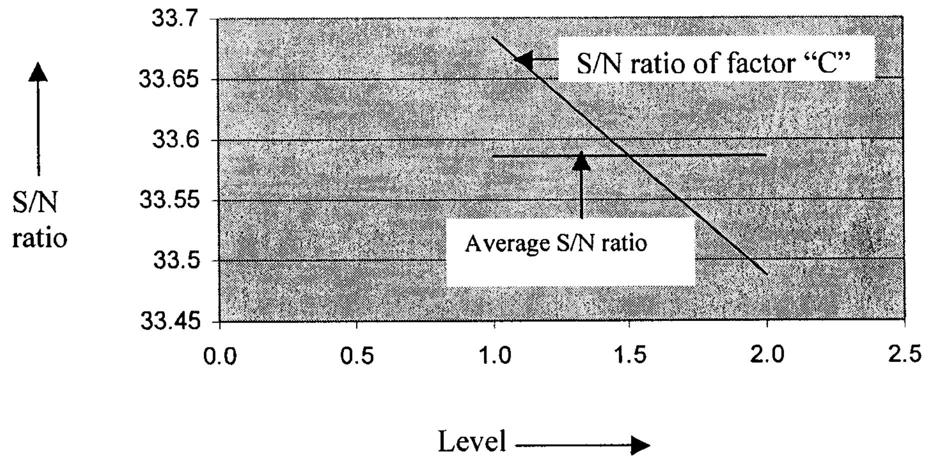


Fig. 5.4 Effects plot for S/N ratio of factor C

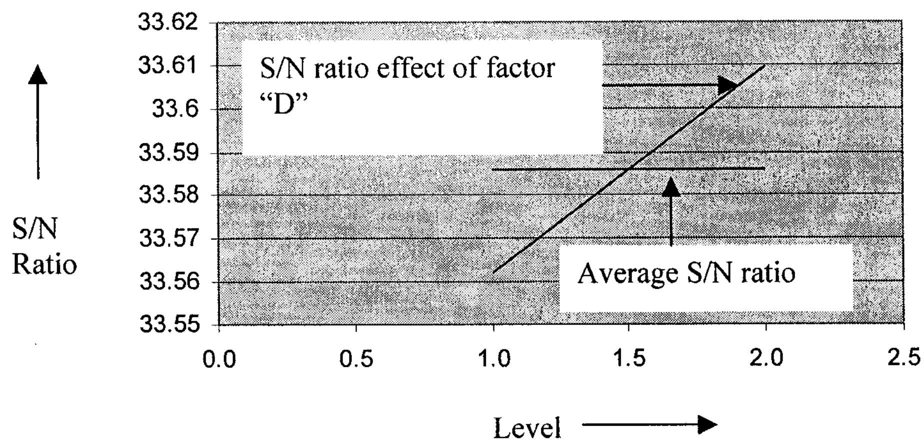


Fig. 5.5 Effects plot for S/N ratio of factor D

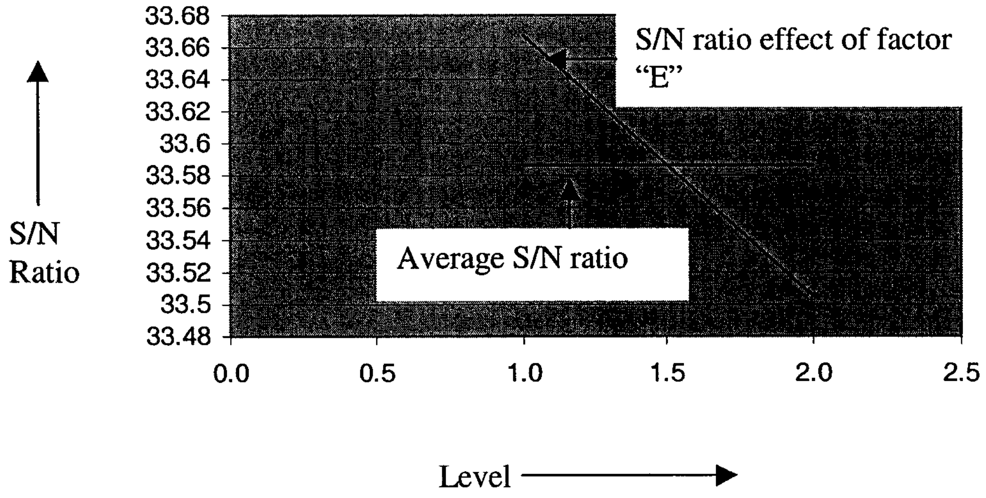


Fig. 5.6 Effects plot for S/N ratio of factor E

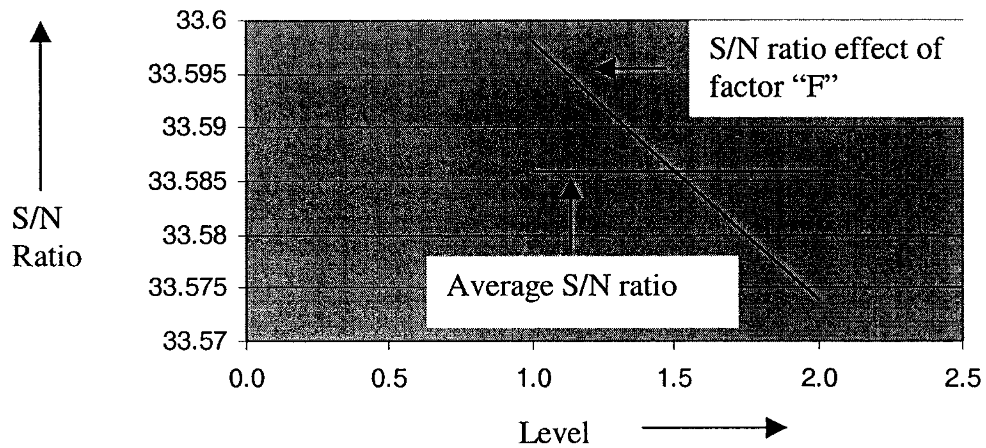


Fig. 5.7 Effects plot for S/N ratio of factor F

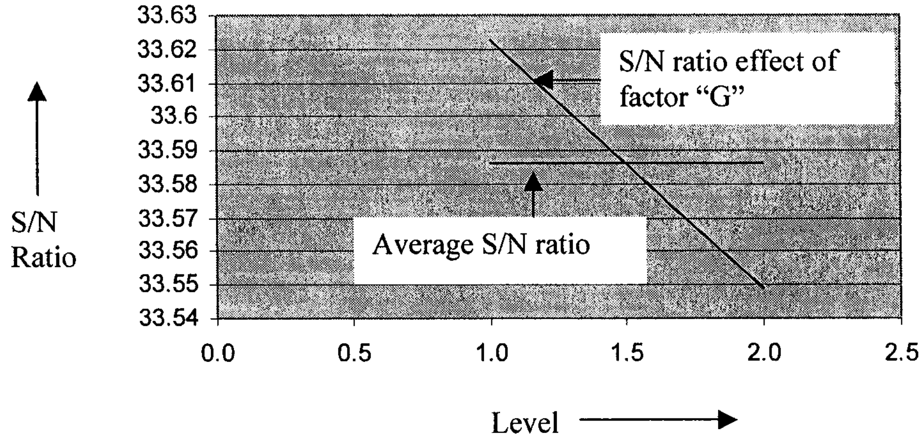


Fig. 5.8 Effects plot for S/N ratio of factor G

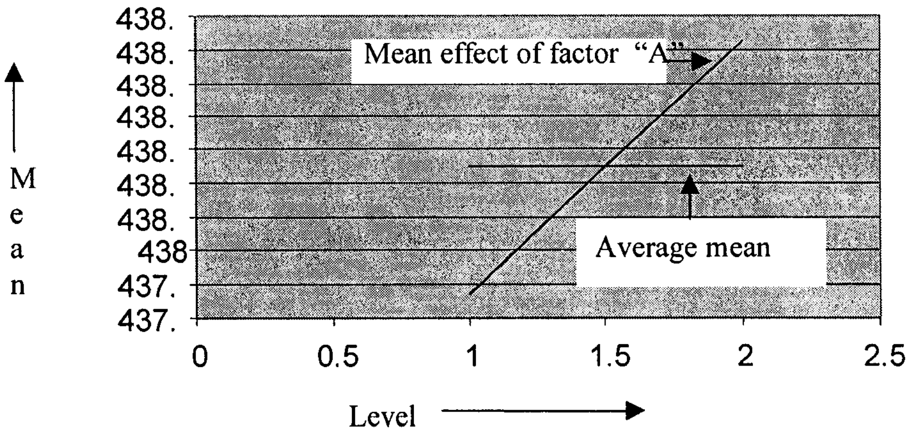


Fig. 5.9 Effects plots for mean of factor A

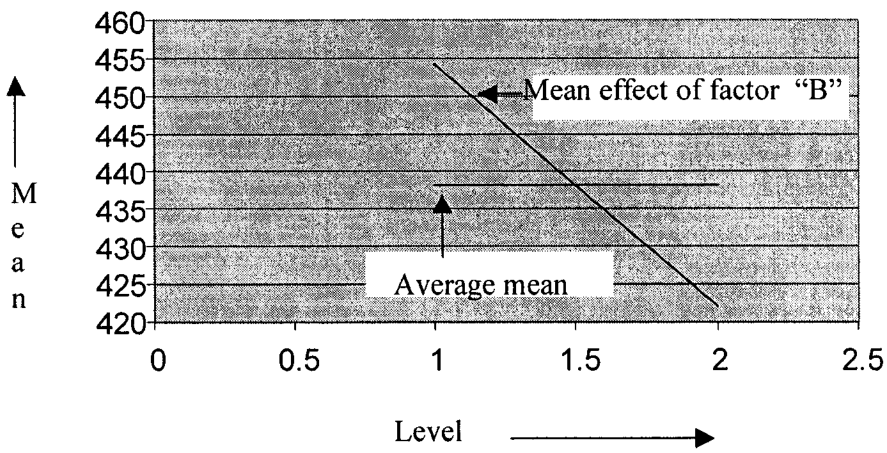


Fig. 5.10 Effects plot for mean of factor B

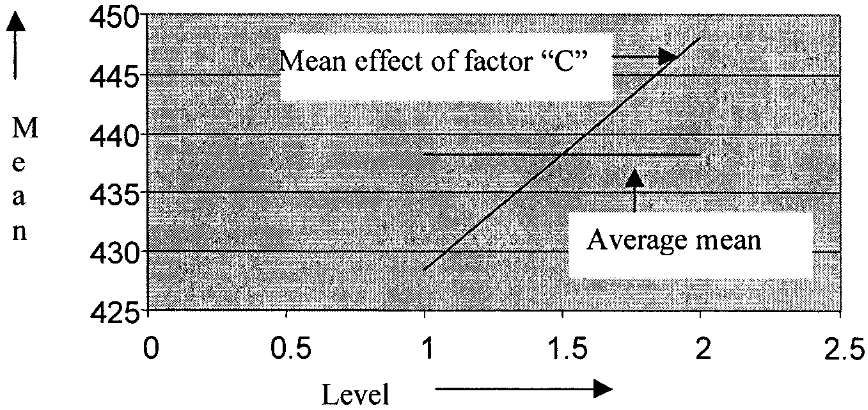


Fig. 5.11 Effects plot for mean of factor C

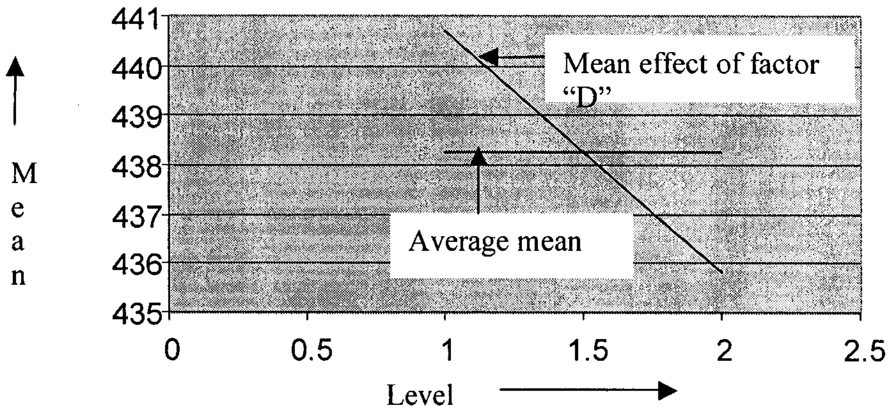


Fig. 5.12 Effects plot for mean of factor D

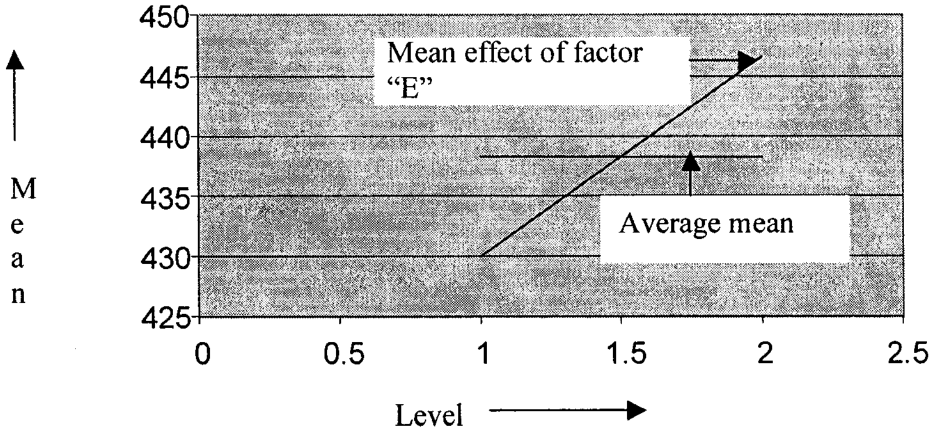


Fig. 5.13 Effects plot for mean of factor E

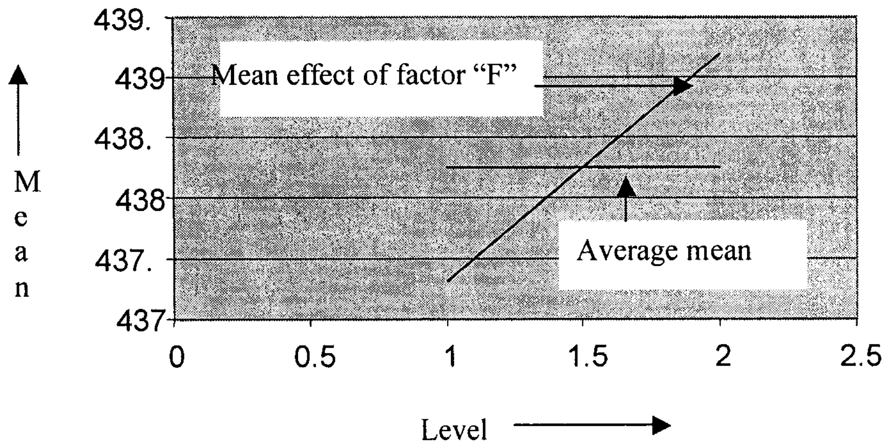


Fig. 5.14 Effects plot for mean of factor F

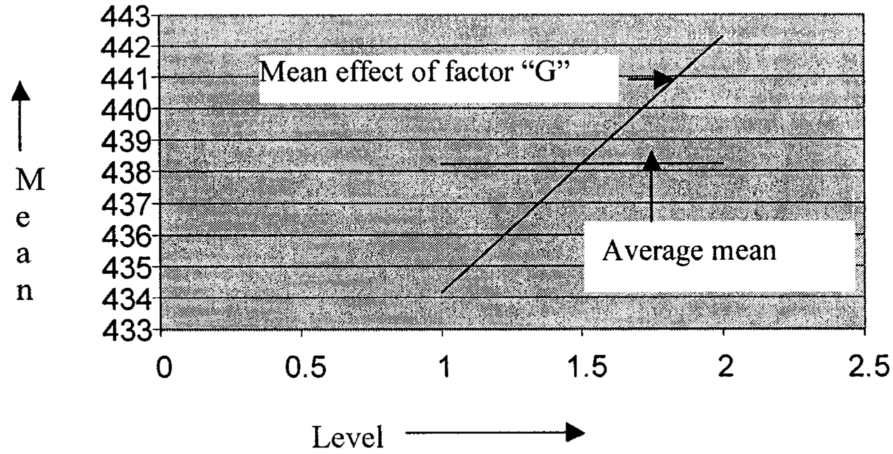


Fig. 5.15 Effects plot for mean of factor G

5.6.3 Sigma level of the experiment

We observed the strongest factors from the S/N ratio and means plot (as in figure 5.2-8 and 5.9-15) are similar to those found in ANOVA of S/N ratio analysis. Therefore our recommended setting factor levels should be employed to get improved process sigma level of the experiment. Hence process should be optimized at the prediction level of the factors.

Before optimization we have

Average defects = 438

Average S/N ratio = 33.59 dB

Process sigma = 4.82

After optimization

Average defects = 396

Average S/N ratio = 33.995 dB

Process sigma = 4.85

Process sigma calculated by using equation as described in section 5.3.5.2.and details calculations have been shown in appendix III.

5.7 EXPERIMENT WITH CONTINUOUS (NORMAL AND EXPONENTIAL) AND DISCRETE (POISSON AND BINOMIAL) DISTRIBUTED DATA

We performed experiment with data having Normal and Poisson distributions (appendix IV to VII). Detailed analytical results are shown in tables 5.5 and 5.8 respectively. It is observed that Taguchi robust design method for process optimization should be exploited for any type of distribution or any type of data.

It also reflects that the increased S/N ratio leads to improve process sigma and decrease the number of defects. These are shown in figures 5.16 to 5.19.

Assumption for data generated by MINITAB		Generated data		Before process optimization		After optimization of process		
Mean	Std ev	Mean	Stdev	Process sigma	S/N ratio	Mean	Proces s sigma	S/N ratio
513000	160	512996	197.33	1.25	-0.2258	512777	1.2519	-0.222
513000	16	512999	14.83	1.25	-0.2259	512985	1.2508	-0.2256
67000	160	67005	191.13	3	11.4377	66933	3.0066	11.4428
67000	16	66998	14.43	3	11.4382	66989	3.006	11.4388
460	160	610	159.49	4.73	32.1751	460	4.8093	33.1977
460	16	561	14.62	4.7536	32.5044	550	4.7588	32.5872

Table 5.5 Normal distribution data analysis

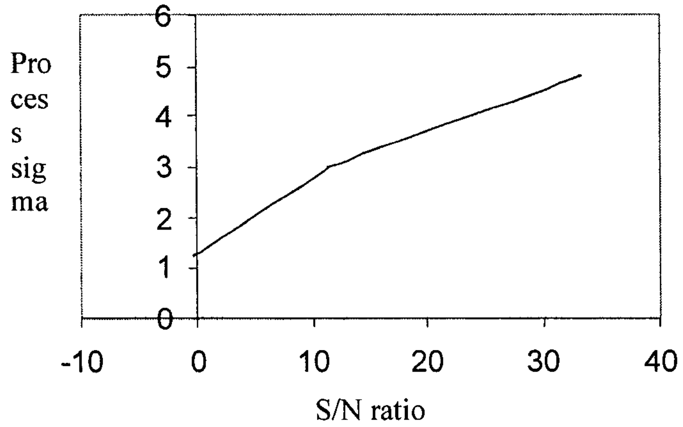


Fig 5.16 Process sigma vs. S/N ratio for normal data

Assumption for data generated by MINITAB	Generated Data	Before Optimization		After Optimization		
Mean	Mean	Process Sigma	S/N ratio	Mean	Process Sigma	S/N ratio
513000	521767	1.2	-1.32	75283	2.95	10.05
67000	74966	2.95	11.27	13534	3.71	15.69
700	1030	4.58	30.09	513	4.78	32.67
568	578	4.75	32.95	67	5.32	37.97
450	430	4.83	34.01	9	5.79	38.38

Table 5.6 Exponential distribution data analysis

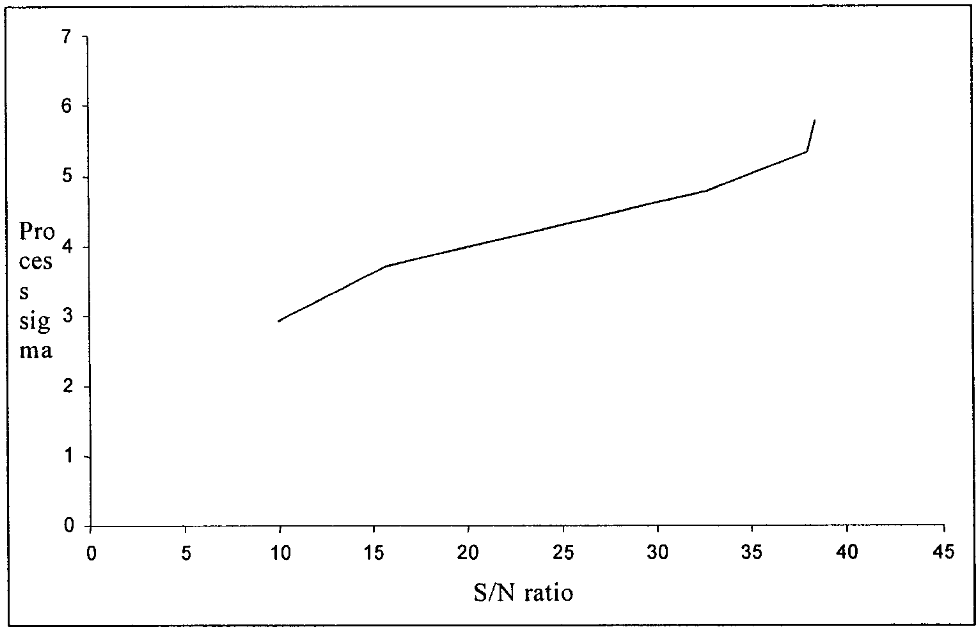


Fig 5.17 Process sigma vs. S/N ratio for Exponential distribution

Assumption for data generated by MINITAB	Generated data	Before process optimization			After optimization of process		
Mean	Mean	Mean	Process sigma	S/N ratio	Mean	Process sigma	S/N ratio
700	701	701	4.6899	31.601	664	4.7054	31.771
450	440	440	4.822	33.48	425	4.832	33.713
300	298	298	4.9274	35.316	275	4.9515	35.607
150	157	157	5.0997	38.099	141	5.1283	38.42
100	104	104	5.2058	39.98	97	5.2246	40.148
50	45	45	5.4139	43.071	44	5.417	43.253

Table 5.7 Poisson distribution data analysis

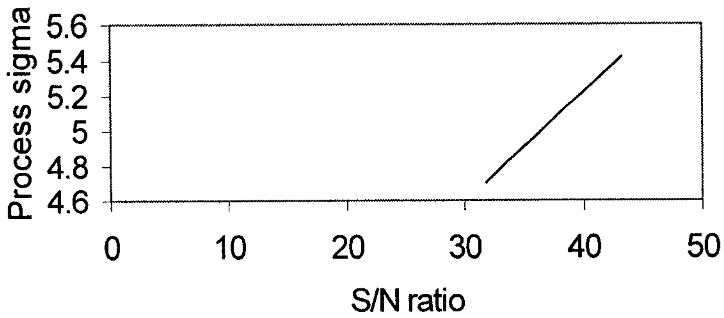


Figure 5.18 Process sigma vs. S/N ratio for Poisson distribution

Assumption for data generated by MINITAB	Generated Data	Before Optimization		After Optimization		
Mean	Mean	Process Sigma	S/N ratio	Mean	Process Sigma	S/N ratio
700	629	4.72	32.01	621	4.73	32.06
450	404	4.84	33.93	397	4.85	34.00
300	270	4.95	35.69	262	4.96	35.80
150	135	5.13	38.69	132	5.17	38.77
100	90	5.24	40.46	86	5.25	40.68
50	45	5.41	43.49	42	5.43	43.75

Table 5.8 Binomial distribution data analysis

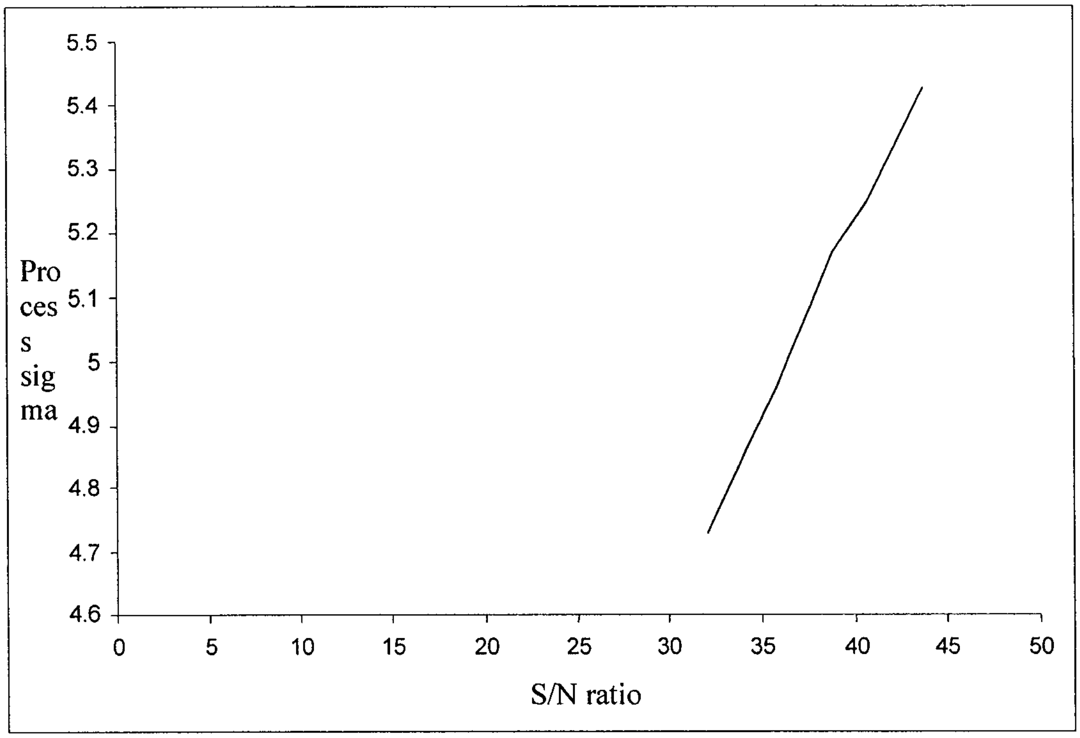


Fig 5.19 Process sigma vs. S/N ratio for Binomial distribution

We observed from figures 5.16 to 5.19 that a correlation exists between the process sigma and S/N ratio with a positive gradient. It shows that our proposed characteristic for process optimization is working with data having either discrete or continuous distributions. Therefore robust design for optimization does not depend on the nature of the process data, whereas traditional Six Sigma design assumed normal distribution of the process data. This is the major finding in our research and it is one of the techniques that can be applied on real world process data for Six Sigma design.

5.8 RECOMMEND FACTORS FOR THE PROCESS

We recommend the factors related with the process optimization in accordance with the selected characteristic of the experiment. Hence our predicted factors found in S/N ratio and ANOVA of S/N ratio should be considered as the level of the factors, which optimize the process. Subsequently we measure the sigma level with the obtained predicted value. As we employ Six Sigma in different departments (appendix II) of an industry, after finding process sigma in one project we should move to another project where sigma level is less. If sigma level is not improved or increased with the recommended parameters then we repeat the entire experiment from selection of CTQ of the product. Otherwise we documented factors that have optimized the process and ensure almost defect free product.

5.9 SUMMARY

It is observed that robust method used to reduce the number of defects through the employed basic concept of quality management tool PDAC. Since both methods are well proven in quality engineering, sigma levels achieved in process with generated responses should be employed in Six Sigma design in real world applications. Because process becomes robust or optimized therefore output of the process is also robust to the application environment.

CHAPTER 6

CONCLUSION AND FUTURE WORK

The application of the Taguchi robust design method is a very straightforward process that verifies control factors of the experiment significantly for the variation in a given process. In this method we focused on the relationship between mean of the performance characteristic and the design parameter. On the other hand, Taguchi placed equal importance on the roles of the variability and the mean. The information obtained in the experiments provides the basis of strategies for reducing the impact of noise factors on product performance. It contributes to reduce defect of product in real applications. The proposed method uses orthogonal arrays instead of the traditional DOE and it substantially reduces the use of resources for the experiment.

We observed that Taguchi robust design method has been used in various industries to improve the quality of the product. We applied the same method in optimization of process to produce robust product or to reduce defects, which reach to Six Sigma. We analyzed generated normal and non-normal data, and found the reducing trend of defects and subsequently improved process sigma level.

The research gives us insight into the quality engineering that not only ensures quality dimension of product but also provides simple way to sustain in world class competition through utilizing minimum resources.

Some of the important findings are:

- We considered the interaction between controllable and non-controllable factors and these are overlooked in Six Sigma design, since it is very difficult to ignore the noise.

- There are numerous types having different distributions of data in the real world and our method does not depend on the type of data.
- The higher S/N ratio means process sigma level will be improved and reduce number of defects.

Finally we give some avenues for further development in our work and for future research on process optimization for Six Sigma design. We used generated data that are based on assumed dispersion and mean. We observed that more dispersion data generally provide more improvement in the process sigma. But it needs further assessment.

This research is theoretical based on robust design Taguchi method and it can be applied as an optimization of process for Six Sigma design.

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Appendix I

Six Sigma and Savings by Company

Company	Year	Revenue ($B)	Invested ($B)	% Revenue Invested	Savings ($B)	% Revenue savings
Motorola						
	1986-2001	356.9(e)	ND	-	16	4.5
Allied Signal						
	1998	15.1	ND	-	0.5	9.9
GE						
	1996	79.2	0.2	0.3	0.2	0.2
	1997	90.8	0.4	0.4	1	1.1
	1998	100.5	0.5	0.4	1.3	1.2
	1999	111.6	0.6	0.5	2	1.8
	1996-1999	382.1	1.6	0.4	4.4	1.2
Honeywell						
	1998	23.6	ND	-	0.5	2.2
	1999	23.7	ND	-	0.6	2.5
	2000	25.0	ND	-	0.7	2.6
	1998-2000	72.3	ND	-	1.8	2.4
Ford						
	2000-2002	43.9	ND	-	1	2.3

Appendix II

List of six sigma uses in industry

1. Accounting Department
2. Accounts Receivable
3. Billing Department
4. Healthcare / Mental Health
5. Human Resources
6. Human Resources - Employee Turnover
7. Distribution Centers / Stock Rooms / Order Picking
8. Information Technology (IT)
9. Enterprise Resource Planning (ERP)
10. Insurance Industry
11. Inventory / Warehousing
12. Logistics / Traffic Applications
13. Logistics II Six Sigma in Retail
14. Sales Six Sigma in Sales & Marketing
15. Software
16. Voting process
17. Order Forecasting Processes
18. Small business

Appendix III

Details calculation of ANOVA for S/N ratio

Details calculation of ANOVA for S/N ratio

								OUTER ARRAY $L_4(2^2)$					
							H	1	1	2	2		
							I	1	2	1	2		
INNER ARRAY $L_8(2^7)$								Responses defects per million				S/N ratios	Mean
A	B	C	D	E	F	G							
1	1	1	1	1	1	1		425	450	380	478	33.63073	433.25
1	1	1	2	2	2	2		450	440	480	450	33.41791	455
1	2	2	1	1	2	2		478	425	440	380	33.65588	430.75
1	2	2	2	2	1	1		390	450	450	440	33.63826	432.5
2	1	2	1	2	1	2		478	478	478	480	33.1991	478.5
2	1	2	2	1	2	1		450	425	450	478	33.45868	450.75
2	2	1	1	2	2	1		390	401	450	440	33.7631	420.25
2	2	1	2	1	1	2		390	380	425	425	33.92369	405

<u>S/N ratio Calculation</u>

For 1^{st} row (experimental run)

S/N ratio = -10log(p/(1-p)

p= (425+450+380+478)/4*10^6 = 433.25X10^{-6}

Therefore, S/N for 1^{st} row = -10Xlog(433.25X10^{-6}/(1-433.25X10^{-6})) = 33.63073

Similarly we calculate S/N ratio of the remaining experimental run.

Average S/N ratio before optimization, S/N_{ave}

= (33.63073+33.41791+33.65588+33.63826+33.1991+33.45868+33.7631+33.92369)/8

= 33.5859

Average S/N ratio for factor A

A1 (average S/N ratio at level 1 of factor A), S/N_{A1}

$= (33.63073+33.41791+33.65588+33.63826)/4 = 33.5857$

Similarly $S/N_{A2} = 33.5861$

Effect of A (Delta) $= | S/N_{A1} - S/N_{A2} | = 0.0004$

S/N ratio table for responses

	A	B	C	D	E	F	G
Level 1	33.5857	33.4266	33.6839	33.5622	33.6672	33.5957	33.6227
Level 2	33.5861	33.7452	33.4880	33.6096	33.5046	33.5739	33.5491
Effect/Delta	0.0004	0.3186	0.1959	0.0474	0.1626	0.0218	0.0736

<u>Mean Calculation</u>

For 1st row (experimental run)

Average = (425+450+380+478)/4 = 433.25

Similarly we calculate average of remaining experimental run.

Average mean, m = (433.25+455+430.75+432.5+478.5+450.75+420.25+405)/8

= 438.25 = 438 (say).

Sigma Quality Level before Optimization $= 0.8406 + (29.37 - 2.221 * \ln(\text{ppm}))^{1/2}$

$= 0.8406 + (29.37 - 2.221 * \ln(438))^{1/2} = 4.82$

Average mean for factor A

A1 (average mean at level 1 of factor A), m_{A1}

= (433.25+455+430.75+432.5)/4 = 437.875

Similarly we calculate remaining average mean of each factor as noted below table.

Average mean table of responses

	A	B	C	D	E	F	G
Level 1	437.875	454.375	428.375	440.6875	429.9375	437.3125	434.1875
Level 2	438.625	422.125	448.125	435.8125	446.5625	439.1875	442.3125

Predicted equation for S/N ratio (S/N ratio after process optimization)

$= S/N_{A2} + S/N_{B2} + S/N_{C1} + S/N_{D2} + S/N_{E1} + S/N_{F1} + S/N_{G1} - 6{*}S/N_{ave}$

= 33.995dB

Predicted equation for mean (mean after process optimization)

$= m_{A2} + m_{B2} + m_{C1} + m_{D2} + m_{E1} + m_{F1} + m_{G1} - 6{*}m$

= 396.875 = 397 (say)

Sigma Level after process optimization = 4.85

Appendix III continued

ANOVA for S/N ratio						
Source	df	S	Variance (V)	F	Net Variation (S')	%
A	1	4.03E-07	0.000000403374*			
B	1	0.20304	0.203042351	49.291541543039***	0.1989231	57
C	1	0.07674	0.076735376	18.6286504037018***	0.0726162	21
D	1	0.0045	0.004500029*			
E	1	0.05291	0.052912403	12.8452704461471**	0.0487932	14
F	1	0.00116	0.001157226*			
G	1	0.01082	0.010818932*			
(e)	(4)	0.01648	0.004119213			8
Total	7	0.34917				100

* - Pooled into error

** - Significant at 99% confidence level , $F_{1,4(99\%)} = 21.2$

*** - Significant at 95% confidence level, $F_{1,4(95\%)} = 7.71$

S_A = [(Sum of A_1 S/N ratio $)^2/4$+(Sum of A_2 S/N ratio$)^2/4$] - (Sum of S/N ratio$)^2/8$ = 4.03374E-07

Variance of factor A, $V_A = S_A$/DOF of A = 4.03374E-07/1= 4.03374E-07

Total variation, S_T = (sum of squares of S/N ratio) - (total S/N ratio$)^2/8$ = 0.349167

Error Variance, V_e = 0.004119213

Variance ratio of factor B , $F_B = V_B / V_e$ = 0.20304235/0.004119213 = 49.29154

Net variation of factor B, $S'_B = S_B$ - (DOF of B X V_e) = 0.19892314

Contribution of factor B to total variation = (S'_B / S_T) X 100 = 57

Appendix IV

Normal distribution data generated by MINITAB software

I) Assumed Mean = 513000 DPMO Stdev = 160			
512781	513311	512873	512789
512969	513086	513006	513065
513058	512895	512932	513192
513381	512896	512906	512964
512604	513136	512992	512941
512872	513104	513001	513163
513202	512952	513038	513543
512697	512822	512983	512732
Generated Mean = 512996		Stdev = 197.33	
Process Sigma = 1.25			

II) Assumed Mean = 513000 DPMO Stdev= 16			
513002	512974	512987	512989
512987	513001	513015	513026
512998	513003	513027	513001
512998	513013	513005	512987
512988	513013	513018	512984
512974	513019	513007	512984
512978	512996	512987	512993
513013	512996	513022	512990
Generated Mean = 512999.2188		Stdev. = 14.829	
Process sigma = 1.25			

III) Assumed Mean = 67000 DPMO Stdev = 160						
66846		67029		67303		66776
66704		67239		66907		67146
67119		66955		66974		66856
67155		66822		67157		66492
67024		67318		67178		67154
67226		66852		66833		67005
66883		67165		67253		67026
66963		66778		67002		67045
Generated Mean = 67005.78125				Stdev = 191.13		
Process Sigma = 3						

IV) Assumed Mean = 67000 DPMO Stdev = 16			
66985	67015	66970	67005
66974	67015	67020	66987
66980	67017	66993	66995
66993	66985	67015	66998
67008	66998	66988	67023
67010	67005	67014	66993
67017	66972	67001	66991
66994	66997	67003	66990
Generated Mean = 66998 Stdev. = 14.43 Process sigma =3			

V) Assumed Mean = 568 DPMO Stdev = 160			
357	569	631	474
673	766	443	425
857	888	820	445
804	552	529	470
499	423	908	573
556	542	579	636
752	541	690	351
617	571	906	660
Generated Mean = 610 Stdev = 159.49 Process Sigma = 4.73			

VI) Assumed Mean = 568 Stdev = 16			
556	577	542	559
564	567	560	562
561	553	568	573
554	573	564	566
565	564	587	565
555	545	602	535
548	561	534	584
550	550	576	547
Generated Mean = 561 Stdev. = 14.62 Process Sigma = 4.75			

Appendix V

Poisson distributed data generated by MINITAB software

I) Assumed Mean = 700 DPMO			
643	725	690	680
701	680	671	662
666	709	691	679
696	721	715	687
678	677	664	709
707	706	709	715
718	678	665	675
723	709	674	699
Generated Mean = 691		Process Sigma = 4.694	

II) Assumed Mean = 450 DPMO			
447	459	471	457
433	449	442	425
437	448	453	425
428	443	472	421
443	481	453	458
489	473	445	456
458	446	457	431
443	414	442	459
Generated Mean = 449		Process Sigma = 4.8163	

III) Assumed Mean = 300			
315	271	305	310
324	289	272	281
280	271	299	331
267	312	267	267
287	321	312	297
332	276	322	279
304	273	284	273
281	294	294	321
Generated Mean = 294		Process Sigma = 4.93	

IV) Assumed Mean = 150 DPMO			
139	150	161	131
158	160	159	156
155	149	164	170
153	140	163	150
147	157	138	139
137	142	176	141
156	164	163	146
163	152	153	160
Generated Mean = 153		Process Sigma = 5.1064	

V) Assumed Mean = 100 DPMO			
90	113	100	94
108	97	84	109
95	103	111	99
100	91	101	113
104	83	102	115
95	100	104	94
95	102	101	96
108	113	90	105
Generated Mean = 104		Process Sigma = 5.2058	

VI) Assumed Mean = 50 DPMO			
52	42	63	49
47	50	51	51
55	45	54	63
47	51	52	57
46	44	48	40
54	45	49	56
53	37	52	48
47	55	42	36
Generated Mean = 49		Process Sigma = 5.3932	

Appendix VI

Exponential Data generated by MINITAB software

I) Assumed Mean = 513000 DPMO			
75217	689024	124024	109549
722837	71253	1665873	756979
802365	971895	248307	5513
1113197	48173	306435	69347
370952	147419	123446	267811
860883	347236	945390	54977
2000754	573299	456327	871159
451100	320359	1106464	18966
Generated Mean = 521767 DPMO Process Sigma = 1.20			

II) Assumed Mean =67000 DPMO			
105190	31399	6093	114681
298739	109817	11721	130045
102163	111812	16993	133722
6740	31829	101396	103579
161863	10512	43794	22109
246740	9364	28993	4920
15683	52695	35052	10411
131786	82478	60619	65980
Generated Mean = 74966 DPMO Process Sigma = 2.95			

III) Assumed Mean = 700 DPMO			
194	1749	3266	154
1125	2554	108	620
355	1001	1960	2652
205	47	263	3743
781	418	187	598
1130	534	1683	481
663	1071	620	377
327	2987	1019	102
Generated Mean = 1030 DPMO Process Sigma = 4.58			

VI) Assumed Mean = 568 DPMO			
295	1922	253	919
1615	890	624	37
93	447	433	66
383	115	183	81
639	208	469	26
1347	340	777	148
153	840	1481	705
1404	1171	166	268
Generated Mean = 578 DPMO Process Sigma = 4.75			

V) Assumed Mean = 450 DPMO			
1085	271	829	75
662	178	13	667
427	3	196	248
208	483	53	139
394	620	32	263
326	1046	1206	414
117	481	145	1323
190	581	912	177
Generated Mean = 430 DPMO Process Sigma = 4.83			

Appendix VII
Binomial distribution data generated by MINITAB software

I) Assumed No. trials = 700 Probability of failure = 0.1			
632	622	645	618
623	623	641	648
628	623	623	628
631	633	632	640
631	631	623	630
635	632	613	616
627	628	636	626
621	635	616	625
Generated mean trials = 629 Process sigma = 4.72			

II) Assumed No. trials = 450 Probability of failure = 0.1			
410	402	400	412
407	405	390	390
395	405	402	414
407	409	410	414
411	401	391	406
408	407	410	412
412	404	406	394
405	399	396	400
Generated mean trials = 404 Process sigma = 4.84			

III) Assumed No. trials = 300 Probability of failure = 0.1			
259	261	276	271
274	273	256	275
271	264	264	272
277	270	271	280
266	266	271	276
263	264	276	276
267	268	259	267
275	278	277	276
Generated mean trials =270 Process sigma = 4.95			

VI) Assumed No. trials = 150 Probability of failure = 0.1			
136	138	136	134
138	134	132	135
138	136	134	138
129	134	133	138
135	126	136	140
134	136	139	132
140	138	132	137
139	130	127	138
Generated mean trials = 135 Process sigma = 5.13			

V) Assumed No. trials = 100 Probability of failure = 0.1			
88	93	91	92
93	88	93	89
90	88	93	92
92	91	91	89
96	90	91	87
87	89	93	84
92	86	92	90
84	86	85	88
Generated mean trials = 90 Process sigma = 5.24			

VI) Assumed No. trials = 50 Probability of failure = 0.1			
45	44	45	45
36	46	43	46
49	44	48	42
48	44	49	47
45	43	46	45
43	44	45	44
43	43	46	44
47	44	44	45
Generated mean trials = 45 Process sigma = 5.41			

Appendix VIII

Six Sigma Trademark

The following information is reproduced from the United States Patent and Trademark Office (http://www.uspto.gov). The Trademark Electronic Search System (TESS) was last updated on Thu Aug 15 04:10:41 EDT 2002.

Word Mark	SIX SIGMA
Goods and Services	IC 016. US 038. G & S: printed publications; namely, magazines, brochures, reports and leaflets about product quality and product quality improvement programs in the fields of electronics and communications equipment manufacturing. FIRST USE: 19900130. FIRST USEIN COMMERCE: 19900130 IC 041. US 107. G & S: educational services; namely, conducting classes about product quality and product quality improvement programs for products in the fields of electronics and communications equipment and providing related instructional materials. FIRST USE: 19900130.FIRST USE IN COMMERCE: 19900130
Mark Drawing Code	(5) WORDS, LETTERS, AND/OR NUMBERS IN STYLIZED FORM
Serial Number	74199225
Filing Date	August 29, 1991

Published for Opposition	March 23, 1993
Registration Number	1813630
Registration Date	December 28, 1993
Owner	(REGISTRANT) Motorola, Inc. CORPORATION DELAWARE 1303 East Algonquin Road Schaumburg ILLINOIS 60196
Attorney of Record	JMELODY L SCHOTTLE
Prior Registrations	1647704
Type of Mark	TRADEMARK. SERVICE MARK
Register	PRINCIPAL
Affidavit Text	SECT 15. SECT 8 (6-YR).
Live/Dead Indicator	LIVE

Appendix IX
Name of Some Six Sigma Implementing Companies or Organizations

3M, A.B. Dick Company, Abbott Labs, Adolph Coors, Advanced Micro Devices, Aerospace Corp, Airborne, Alcoa, Allen Bradley, Allied Signal, Ampex, Apple Computers, Applied Magnetics, ASQC, Atmel, Baxter Pharmaseal, Beatrice Foods, Bell Helicopter, Boeing, Bombardier, Borden, Bristol Meyers - Squibb, Bryn Mawr Hospital, Campbell Soup, Cellular 1, Chevron, Citicorp, City of Austin, TX, City of Dallas, TX, Clorox, Cooper Ind, Dannon, Defense Mapping Agency, Delnosa (Delco Electronics in Mexico), Digital Equipment Corp, DTM Corp, Eastmen Kodak, Electronic Systems Center, Empak, Florida Dept. of Corrections, Ford Motor Company, GEC Marconi, General Dynamics, General Electric, Hazeltine Corp, Hewlett packard, Holly Sugar, Honeywell, Intel, Junior Achievement, Kaiser Aluminum, Kraft General Foods, Larson & Darby, Inc, Laser Magnetic Storage, Lear Astronics, Lenox China, Littton Data Systems, Lockhee Martin, Loral, Los Alamos National labs, Martin Marietta, McDonnell Douglas, Merix, Microsoft, Morton Int'l, Motorola, NASA, Nat'l Institute of Corrections, Nat'l Institute of Standards, Nat'l Semiconductor, Natural Gas Pipeline Company of America, Northrop Corp, PACE, Parkview Hospital, Pentagon, Pharmacia, PRC, Inc, Qualified Specialists, Ramtron Corp, Rockwell Int'l, Rohm & Haas, Seagate, Society of Plastics Egineers, Solar Optical, Sony, Star Quality, Storgae Tek, Symbios Logic, Synthes, Technicomp, Tessco, Texaco, Texas Commerce Bank, Texas Dept. of Transportation, Texas Instruments, Titleist, Trane, TRW, Ultratech Stepper, United States Air Force, United States Army, United technologies, UPS, USAA, Verbatim, Walbro Automotive, Walker parking, Woodward Governor, Xerox