SIX SIGMA PROJECTS AND PERSONAL EXPERIENCES

Edited by **Abdurrahman Coskun, Tamer C. İnal** and **Mustafa Serteser**

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Published by InTech
Janeza Trdine 9, 51000 Rijeka, Croatia

Publishing Process Manager Iva Lipovic
Technical Editor Teodora Smiljanic
Cover Designer Jan Hyrat
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First published June, 2011
Printed in Croatia

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Six Sigma Projects and Personal Experiences, Edited by Abdurrahman Coskun, Tamer C. İnal and Mustafa Serteser
p. cm.
ISBN 978-953-307-370-5

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Preface

After the World War II, in response to “customer satisfaction”, many of the quality improvement tools that we still use extensively today such as control charts, process capability, and value analysis were developed and widely used in a wide range of organizations from industry to health sector. Then, more recently, quality circles and total quality management have shown the power of team-based process improvement. ISO 9000 was developed as a standard for organization’s quality systems. To be certified, organizations needed to document their quality system; they improved it with reviews and audits. The identification of non-conformances and “corrective action system” to prevent reoccurrences have taken their place in an organization’s daily life. Finally today, we are talking about error-free processes, eliminating the waste, and “do it right the first time”. Strategic approaches to achieve excellence now is the main focus of Six Sigma and lean concept.

In fact, Lean and Six Sigma are two distinct management strategies; while Lean methodology focuses on creating more value with less work, Six Sigma make efforts to identify and eliminate defects in product development. Thus, Lean-Six Sigma is a marriage of these two different strategies. They both contribute to an organization’s decision-making process by reducing inefficiencies as well as increasing quality. They do not only cover defective products, but all types of defective work, unnecessary processes, and services that don’t meet customer’s needs. There is also a relationship of ISO to Six Sigma. While ISO is providing a standardization among the quality improvement tools, Six Sigma presents a way to achieve error-free processes.

Lean-Six Sigma provides principles and tools that can be applied to any kind of organizations that is aiming to measure defects and/or error rates in order to reduce the cost of products by eliminating the defects and waste.

In this book scientists from various regions of the world share their experiences and knowledge about Lean and Six Sigma methodology. The chapters in the book cover the basic principles of managing Lean and Six Sigma methodology in various disciplines of industry, business and even health sectors. We hope that this book will help employees worldwide at all levels in different organizations, who need to improve their knowledge and experience in the field of Six Sigma and Lean concept.

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Lean Six Sigma

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1. Introduction

Due to increased globalization and constant technological advances and other competitive pressures, the organizations have to accelerate the pace of change to adapt to new situations. This climate introduces opportunities and threats and Organizations have to innovate and strive for operational excellence. Six Sigma is the most popular quality and process improvement methodology which strives for elimination of defects in the processes whose origin is traced back to the pioneering and innovation work done at Motorola and its adoption by many companies including GE, Ford, General Motors, Xerox etc. The primary objective of Six Sigma is to reduce variations, in products and processes, to achieve quality levels of less than 3.4 defects per million opportunities (DPMO). The important point to be noted is reducing the defects involve measurements in terms of millions of opportunities instead of thousands. Six Sigma is a culmination of several decades of quality improvement efforts pursued by organizations world over due to pioneering work done by quality Gurus Shewart, Deming, Juran, Crosby, Ishikawa, Taguchi and others. Dr. W. Edward Deming, who is considered by many to be the "Father of modern Quality movement", was instrumental for transforming post war Japan into an economic giant because of helping for systematic introduction of quality improvement measures by Japanese companies. Dr. Deming had advocated popular quality improvement methods such as Total Quality Management (TQM), Plan-Do-Check-Act methodology, 14 point rules and elimination of 7 deadly sins and he helped organizations to achieve operational excellence with much customer focus. Later many US companies have gained much from Japanese experiences and ideas on quality improvement concepts.

The Six Sigma concepts and tools used can be traced back to sound mathematical and management principles of Gauss, Taylor, Gilberth and Ford for their contributions like Sigma and Normal distribution (Gaussian distribution),Taylor's Scientific Management, Gilberth's 'Time and Motion study' and Ford's mass production of cars using 'Assembly line ' system.

Six Sigma when coupled with 'Lean Principles' is called 'Lean Six Sigma' which professes eliminating waste in process steps by using 'Lean Tools' which is based on Toyota Production System(TPS) which enhances value in Six Sigma implementation one step further by increasing speed by identifying and removing non-value adding steps in a process.

Execution of Lean Six Sigma project uses a structured method of approaching problem solving normally described by acronym 'DMAIC' which stands for Define, Measure, Analyze, Improve and Control.

Many organizations have achieved phenomenal success by implementing Lean Six Sigma. Lean and Six Sigma are conceptually sound technically fool proof methodologies and is here to stay and deliver break through results for a long time to come. Motorola had celebrated 20 years of Six Sigma in the year 2007 and as per Sue Reynard in an article in ISixSigma-Magazine," Motorola is a company of inventions and Six Sigma which was invented at Motorola is a defect reduction methodology that aims for near perfection has changed the manufacturing game of Motorola, but it didn't stop there. As the Six Sigma has evolved during the ensuing 20 years, it had been adopted worldwide and has transformed the way business is done".

This chapter focuses and highlights overview and details of some of the important aspects of 'Lean Six Sigma' and the tools used to implement it in organizations to improve their bottom line by controlling variations in processes, reducing defects to near zero level and adopting lean principles. The chapter is organized on the following broad topics: the history of Six Sigma, the need for Six Sigma, Sigma Levels and motivation for Six Sigma, Lean thinking, Lean Six Sigma, DMAIC methodology, Six Sigma and Lean tools, and case studies on Lean Six Sigma implementations.

Six Sigma Tools are available as free open source templates which can be downloaded from the URLs which are given in the references at end of the chapter.

2. What is six sigma ?

Six Sigma is a quality improvement methodology invented at Motorola in 1980s and is a highly disciplined process improvement method that directs organizations to focus on developing and delivering near perfect products and services. Six Sigma is a statistical term that measures how far a given process deviates from perfection. The central idea behind Six Sigma is, if we are able to measure how many "defects" that exist in a process, it can be systematically figured out how to eliminate them and get close to "zero defects".

In the year 1985, Bill Smith, a Motorola Engineer coined the term 'Six Sigma', and explained that Six Sigma represents 3.4 defects per million opportunities is the optimum level to balance quality and cost. It is a real-breakthrough in quality improvement process where defects are measured against millions of opportunities instead of thousands which was the basis those days.

Leading companies are applying this bottom-line enhancing strategy to every function in their organizations. In the mid 1990s, Larry Bossidy of Allied Signal and Jack Welch of GE Saw the potential in Six Sigma and applied it in their organizations which resulted in significant cost savings in progressive years. GE reports stated that Six Sigma had delivered $300 million to its bottom line in 1997, $750 million in 1998, and $2 billion in 1999.

2.1 History of six sigma

The immediate origin of Six Sigma can be traced to its eearly roots at Motorola (Fig. 1), and specifically to Bill Smith (1929 - 1993). Bill Smith was an employee of Motorola and a Vice President and Quality Manager of Land based Mobile Product Sector, when he approached then chairman and CEO Bob Galvin in 1986 with his theory of latent defect.

The core principle of the latent defect theory is that *variation* in manufacturing processes is the main culprit for *defects*, and eliminating variation will help eliminate defects, which will in turn eliminate the wastes associated with defects, saving money and increasing customer satisfaction. Variation is measured in terms of sigma values or thresholds. The threshold determined by Smith and agreed to by Motorola is 3.4 defects per million opportunities (3.4 DPMO), which is derived from sigma shifts from specifications.

1985 Bill Smith coins the term "Six sigma" **1987 Motorola trademarks the term "Six Sigma"**

Fig. 1. Bill Smith coins the term Six Sigma at Motorola.

Motorola adopted the concepts and went on to win the first ever *Malcolm Baldrige Excellence Award* in 1988, just two years after Bill Smith's introduction of Six Sigma.

3. Describing six sigma concept

Six Sigma is a method for improving quality by removing defects and their causes in business process activities. The method concentrates on those outputs which are important to customers and translates these customer needs into measurable requirements, the so called CTQs (Critical To Quality). An indicator for the CTQs is identified and a robust measurement system is established to obtain clean and precise data relating to the process. Once this is in place, one can compare actual process behaviour to the customer-derived specification and describe this in a statistical distribution (using mean, standard deviation [σ] or other indicators, dependent on the type of distribution).

3.1 Inputs and output

The objective of the Six Sigma concept is to gain knowledge about the transfer function of the process - the understanding of the relationship between the independent input variables (Xs) and the dependent output variable (Y). If the process is modelled as a mathematical equation, where Y is a function of X, i.e. $\mathbf{Y = f(X1, X2, \ldots, Xn)}$, then the output variable (Y) can be controlled by steering the input variables (Xs).

The Six Sigma drive for defect reduction, process improvement and customer satisfaction is based on the "statistical thinking" paradigm:

- All work occurs in a system of interconnected processes.
- All processes have inherent variation.
- Data analysis is used to understand the variation and to drive process improvement decisions.

3.2 Variation

Six Sigma is all about reducing the variation of a process. The more standard deviations (σ) – an indicator of the variation of the process – that fit between the mean of the distribution and the specification limits (as imposed by the customer), the more capable is the process. A Six Sigma process means that 6 standard deviations fit on each side of the mean, between the mean and the specification limits. 6 Sigma equates in percentage terms to 99.9997% accuracy or to 3.4 defects per million opportunities to make a defect. Fig 2 illustrates how Six Sigma quality is achieved by reducing variations in a process.

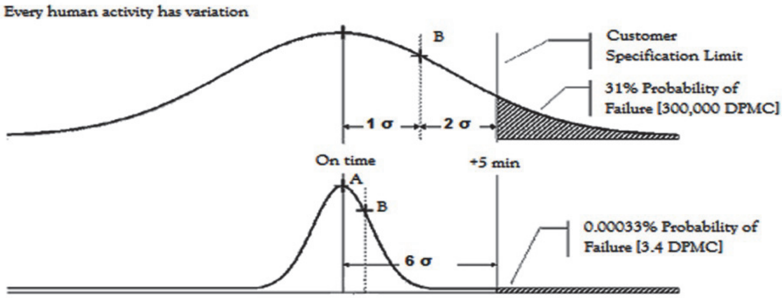

Fig. 2. Reducing variation in a process using Six Sigma

3.3 Normal curve and sigma

Six Sigma concepts can be better understood and explained using mathematical term Sigma and Normal Distribution. Sigma is a Greek symbol represented by "σ". The bell shape curve shown in Fig. 3 is called "normal distribution" in statistical terms. In real life, a lot of frequency distributions follow normal distribution, as in the case of delivery times in Pizza Business. Natural variations cause such a distribution or deviation. One of the characteristics of this distribution is that 68% of area (i.e. the data points) falls within the area of -1σ and +1σ on either side of the mean. Similarly, 2σ on either side will cover approximately 95.5% area. 3σ on either side from mean covers almost 99.7% area. A more peaked curve (e.g. more and more deliveries were made on target) indicates lower variation or more mature and capable process. Whereas a flatter bell curve indicates higher variation or less mature or capable process. To summarize, the Sigma performance levels – 0ne to Six Sigma are arrived at in the following way.

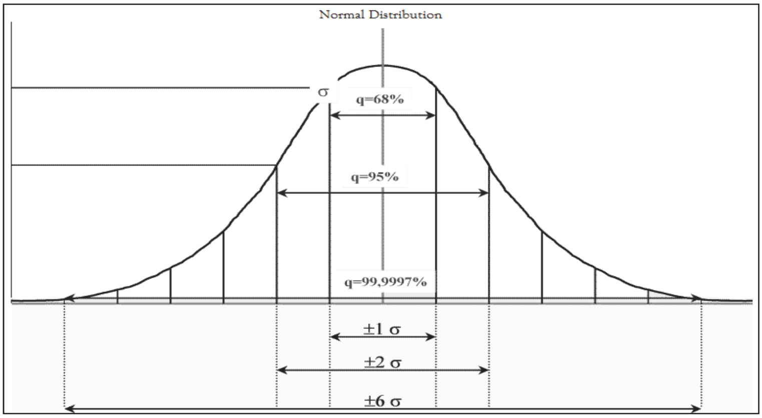

Fig. 3. Normal Distribution

If target is reached:
68% of the time, they are operating at +/- 1 Sigma
95.5% of the time, they are operating at +/-2 Sigma
99.73 % of the time are operating at +/-3 Sigma

Six Sigma: 3.4 ppm = 100-99.99966%

3.4 Six sigma and TQM

Six Sigma is not just a statistical approach to measure variance; it is a process and culture to achieve excellence. Following its success, particularly in Japan, TQM seemed to be popular in organizations which preached quality as fitness for purpose, striving for zero defects with customer focus. Even though TQM was the management tool in the 1980s, by 1990s it was regarded as failure and it was written off as a concept that promised much but failed to deliver.

Research by Turner (1993) has shown that any quality initiative needs to be reinvented at regular intervals to keep the enthusiasm level high. Against this background, Six Sigma emerged to replace the 'overworked' TQM philosophy. The key success factors differentiating Six Sigma from TQM are:

1. Six Sigma emphasizes on Statistical Science and measurement.
2. Six Sigma was implemented with structured training plans at different levels (Champions, Master Belt, Black belt, and Green belt).
3. The project focussed approach with single set of Problem Solving Techniques (DMAIC).
4. The Six Sigma implementation effects are quantified in tangible savings (as opposed to TQM where the benefits cannot be measured). Quantification of tangible savings is a major selling point for Six Sigma.

3.5 Sigma quality level

Sigma Quality Level is a measure used to indicate how often the defects are likely to occur. Sigma is a mathematical term and it is the key measure of variability. It emphasizes need to control both the average and variability of a process. Table 1. shows different Sigma levels and associated defects per million opportunities. For example, Sigma level 1 indicates that it tolerates 690,000 defects per million opportunities with 31% yield. Sigma level 6 allows only 3.4 defects per million opportunities with 99.9997 yield.

Sigma Performance Levels - One to Six Sigma		
Sigma Level	**Defects Per Million Opportunities**	**Percentage Yield**
1	690,000	31
2	308,537	69
3	66,807	93.3
4	6,210	99.38
5	233	99.977
6	3.4	99.99966

Table 1. Sigma performance Levels

Before starting a Six Sigma Project,the important thing to be done first is to find the need for Six Sigma.

It is natural for Organizational processes to operate around 3 to 4 sigma level. In this section, the defect levels for some example scenarios one operating at 3 to 4 sigma level and other operating at Six Sigma level are compared. The comparisons as per Table 2. show that the defects at 3 to 4 Sigma level are found to be too high to be tolerated and organizations have to strive to achieve Six Sigma level as an obvious move. This section elaborates the need for Six Sigma with examples.

4. Why six sigma?

4.1 Does 99.9% yield is good enough for an organization?

With 99.9 % yield, we say the organization operates at 4 to 5 Sigma level. Taking into account some real world examples, with 99.9 % yield, we come across the following example scenarios which are surely unacceptable in customer's point of view :

- Unsafe drinking water almost 15 minutes each day
- 5400 arterial by pass failures each year
- Visas issued to 50 dangerous persons each year

By moving to **Six Sigma level** with 99.9997% yield, significant improvements have taken place resulting in very high quality with almost nil defects and very good customer satisfaction as shown below :

- Unsafe drinking water only few seconds a day
- 18 arterial bypass failures
- No visas issued to dangerous persons

The following real world examples explain the importance and need for achieving six sigma level quality.

Comparison of performace improvement with 99.9% and 99.9997 acceptence		
Scenarios	**99.9% acceptance (Sigma Level : 4 to 5 Sigma)**	**99.9997 % acceptance (Sigma Level : 6 Sigma)**
Arterial bypass failures in an year	5400	18
Commercial aircraft take off aborted each year	31,536	107
Train wrecks a year	180	< 1
Visa issued to dangerous persons	50	none

Table 2. Comparison of performance improvement at different sigma levels

5. Lean

5.1 Lean thinking

Lean Thinking was an another quality and productivity improvement methodology introduced in **Toyota Production Systems (TPS)** which is based on the concept of elimination of waste in processes which had resulted in *productivity gain* and *improvement of speed* and *flow* in the value stream. The principle of Lean can be stated as a relentless pursuit of the perfect process through wastage elimination in the value stream. Lean identifies three different kinds of wastes, using Japanese terminology from the Toyota Production System where lean originated: *muda* (waste of time and materials), *mura* (unevenness/variation), and *muri* (the overburdening of workers or systems).

Every employee in a lean manufacturing environment is expected to think critically about his or her job and make suggestions to eliminate waste and to participate in *kaizen*, a process of continuous improvement involving brainstorming sessions to fix problems.

5.2 Lean in a nutshell

Lean is a business transformation methodology and it is derived from the Toyota Production System (TPS). Within the Lean methodology, there is a relentless focus on increasing customer value by reducing the cycle time of product or service delivery through the elimination of all forms of *muda* (a Japanese term for waste) and *mura* (a Japanese term unevenness in the workflow).

5.3 Six sigma in a nutshell

Six Sigma was a concept developed in 1985 by Bill Smith of Motorola, who is known as " the Father of Six Sigma." This concept contributed directly to Motorola's winning of the U.S. Malcolm Baldrige National Quality Award in 1988. Six Sigma is a business transformation methodology that maximizes profits and delivers value to customers by focusing on the reduction of variation and elimination of defects by using various statistical, data-based tools and techniques.

5.4 Six sigma vs lean

Both methodologies focus on business processes and process metrics while striving to increase customer satisfaction by providing quality, on time products and services. Lean takes a more holistic view. It uses tools such as value-stream mapping, balancing of workflow, or *kanban* pull signaling systems to trigger work, streamline and improve the efficiency of processes, and increase the speed of delivery.

Six Sigma takes a more data-based and analytical approach by using tools to deliver error-free products and services, such as the following examples:

- Voice Of the Customer (VOC)
- Measurement Systems Analysis (MSA)
- Statistical hypothesis testing
- Design of Experiments (DoE)
- Failure Modes and Effects Analysis (FMEA)

Six Sigma uses an iterative five-phase method to improve existing processes. This method is known as *Define, Measure, Analyze, Improve, Control (DMAIC)*, and normally underpins Lean Six Sigma (LSS).

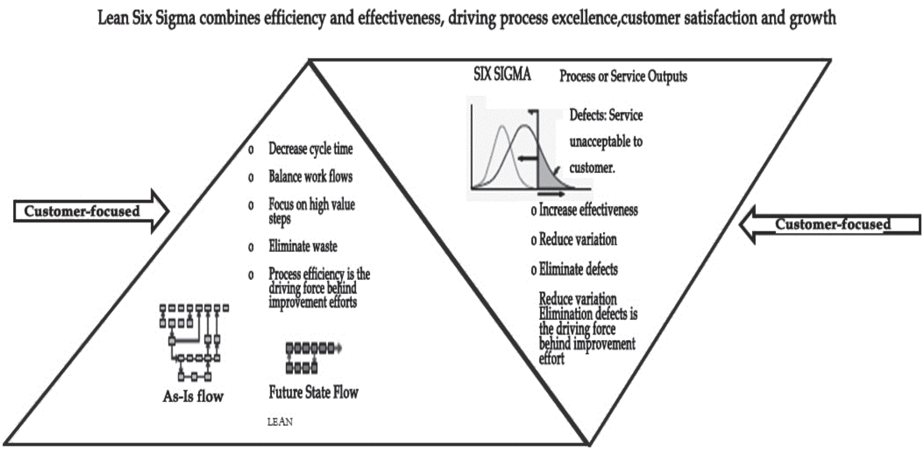

Fig. 4. Lean vs Six Sigma

Over the last 10 to 15 years, an increased need for accelerating the rate of improvement for existing processes, products, and services has led to a combination of these two approaches. As shown in Fig. 4, Lean Six Sigma combines the speed and efficiency of Lean with the effectiveness
of Six Sigma to deliver a much faster transformation of the business.

6. Lean six sigma

Lean Six Sigma came into existence which is the combination of Lean and Six Sigma.
The fusion of Lean and Six Sigma is required because :

- Lean cannot bring process under statistical control, and
- Six Sigma alone cannot dramatically improve process speed or reduce invested capital.

Lean Six Sigma is a disciplined methodlgy which is rigorous, data driven, result-oriented approach to process improvement. It combines two industry recognized methodologies evolved at Motorola, GE, Toyata, and Xerox to name a few. By integrating tools and processes of Lean and Six Sigma, we're creating a powerful engine for improving quality, efficiency, and speed in every aspect of business.
Cindy Jutras,Vice President, Research Fellow and Group Director *Enterprise Applications Aberdeen Group says* ," Lean and Six Sigma are initiatives that were born from the pursuit of operational excellence within manufacturing companies. While Lean serves to eliminate waste, Six Sigma reduces process variability in striving for perfection. When combined, the result is a methodology that serves to improve processes, eliminate product or process defects and to reduce cycle times and accelerate processes".
Embedding a rigourous methodology like lean six sigma into organizational culture is not a short journey, but it is a deep commitment not only to near-term results but also a long-term, continuous, even break-through results.

7. Six sigma DMAIC methodology

Motorola developed a five phase approach called 'DMAIC Model' to achieve the highest level in the Six Sigma, i.e., 3.4 defects per million. The five phases are:

- **Define** process goals in terms of key critical parameters (i.e. critical to quality or critical to production) on the basis of customer requirements or Voice Of Customer (VOC)
- **Measure** the current process performance in context of goals
- **Analyze** the current scenario in terms of causes of variations and defects
- **Improve** the process by systematically reducing variation and eliminating defects
- **Control** future performance of the process

Table 3 lists the important deliverables and tools used in each step of 'DMAIC Model'. The subsequent sections brief the process involved in each phase.

7.1 Define

In the Define phase of the project, the focus is on defining the current state by making the *Problem statement* which specifies what the team wants to improve upon which illustrates the need for the project and potential benefit. The type of things that are determined in this phase include the *Scope of the project*, the *Project Charter*.

7.1.1 Project charter

The problem statement and goal statement are the part of Project Charter. The following deliverables should be part of the project charter :

- Business Case (Financial Impact)
- Problem statement
- Project Scope (Boundaries)
- Goal Statement
- Role of team members
- Mile Stones/deliverables (end products of the project)
- Resources requiered

Strategic Steps	Deliverables	Tools used
Define	Project Charter or Statement of Work(SoW)	Gantt Chart/Time Line Flow Chart/Process Map Quality Function Deployment (QFD)
Measure	Base Line figures	SIPOC (Suppliers, Inputs, Process, Outputs, and Customers) or IPO (Input-Process-Output) diagram
Analyze	Identified Root Causes	Cause-and-Effect Diagram 5-Why Scatter Diagram Regression ANOVA
Improve	Selected root causes and counter measures Improvement Implementation Plan	Affinity Diagram Hypothesis Testing DoE Failure Mode Effect Analysis (FMEA)
Control	Control Plan Charts & Monitor Standard Operating Procedures (SOP) Corrective Actions	Control Charts Poka-Yokes Standardization Documentation Final Report Presentation

Table 3. DMAIC Methodology

The metrics to be used are developed at this phase. The basic metrics are cycle time, cost, value, and labor. Some of the methods used for identifying the metrics are Pareto diagram, SIPOC, voice of the customer, affinity diagram, critical to quality tree.

SIPOC stands for Suppliers, Inputs, Process, Outputs, and Customers. This approach helps us to identify characteristics that are key to the process which in term facilitates identifying appropriate metrics to be used to effect improvement.

To create a SIPOC diagram:

- Identify key process activities
- Identify outputs of the process and known customers
- Identify inputs to the process and likely suppliers

Fig. 5 shows an example SIPOC Diagram of Husband making wife a cup of tea. A SIPOC diagram is a tool that is used to gather a snapshot view of process information. SIPOC diagrams are very useful at the start of a project to provide information to the project team before work commences.
An IPO (Input-Process-Output) diagram is a visual representation of a process or activity as shown in Table 4. It lists input variables and output characteristics. It is useful in defining a process and recognizing the input variables and responses or outputs. It helps us to understand what inputs are needed to achieve each specific output.

Input	Process	Output
Centigrade	Prompt for centigrade value	fahrenheit
	Compute fahrenheit value	

Table. 4 An IPO diagram

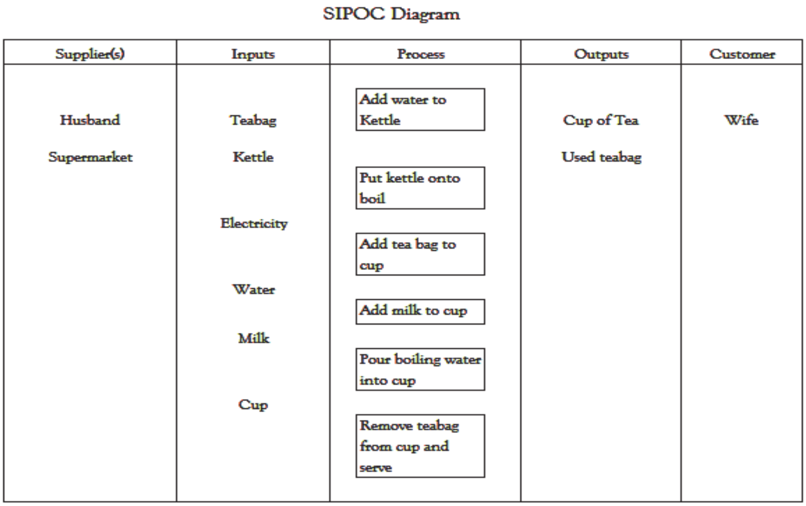

Fig. 5. SIPOC Diagram

7.2 Measure

The Measure is the second step of the Six Sigma methodology. A base line measure is taken using actual data. This measure becomes the origin from which the team can guage improvement.
It is within the Measure phase that a project begin to take shape and much of the hands-on activity is performed. The goal of Measure phase is to establish a clear understanding of the current state of the process you want to improve. For example, a medical practioner prescribes various tests like blood test, ECG test etc for a patient admitted in a hospital. The test reports of various laboratorical tests reflect the current state of health of the patient. Similarly, a Six Sigma practioner, determines current state of health of the system under consideration in this phase.
The deliverables in this phase are refined process map, and refined Project Charter. Some of the tools used in Measure phase are :

- Flow Charts

- Fish bone diagrams
- Descriptive Statistics
- Scatter diagrams
- Stem and Leaf plots
- Histograms

These metrics will establish the base line of the current state. The outcome of applying these tools in the form of charts, graphs or plots helps the Six Sigma Practitioner to understand how the data is distributed. He or she is able to know what the data are doing. The distribution that is associated with data related to a process speaks volumes. The data distribution can be categorized into:

- Normal distribution
- Weibul
- Poison
- Hypergeometric
- Chi Square

The data can be continuous or discrete.

7.3 Analyze

In this step, the team identify several possible causes (X's) of variation or defects that are affecting the outputs (Y's) of the process. One of the most frequently used tools in the analyze phase is the 'Cause and Effect Diagram'. The Cause & Effect Diagram is a technique to graphically identify and organize many possible causes of a problem (effect). They help identify the most likely ROOT CAUSES of a problem. This tool can help focus problem solving and reduce subjective decision making. Fig. 6 illustrates a cause and effect diagram which helps to find out possible causes for software not being reliable. Root cause is the number one team deliverable coming out of the analysis step. Causes can be validated usingnew or existing data and applicable statistical tools such as scatter plots, hypotheses testing, ANOVA, regression or Design of Experiments. Some of the tools used in root cause analysis are shown in Fig. 7.

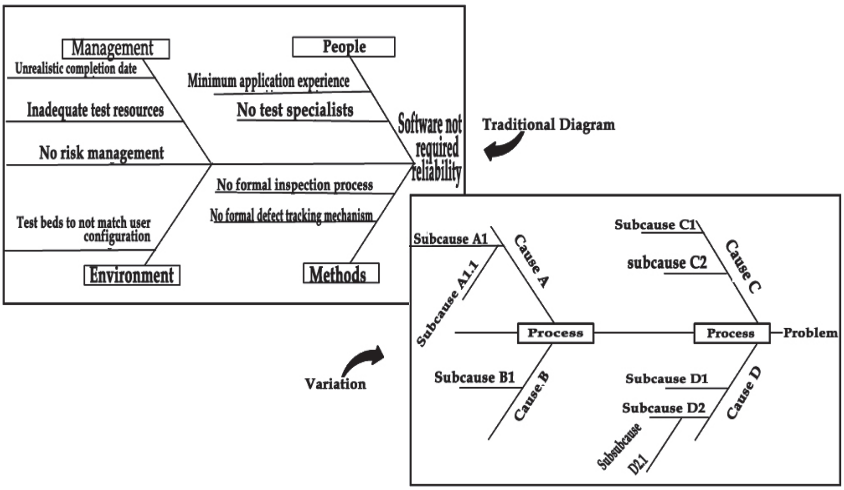

Fig. 6. Cause and Effect Diagram

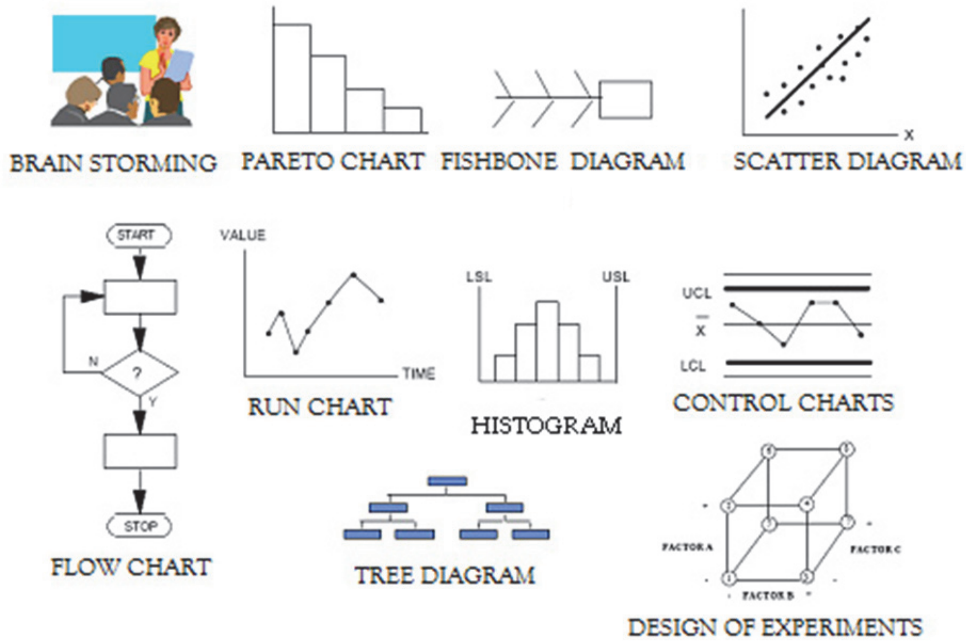

Fig. 7. Tools used in Root cause analysis

7.4 Improve

In this step, the team would brainstorm to come up with counter measures and lasting process improvements that address the validated root causes. The most preferred tool used in this phase is affinity diagram.
We have measured our data and performed some analysis on the data to know where our process is, it is time to improve it.
One of the important methods used for improvement of a process is Design of Experiments (DoE).

7.4.1 Affinity diagram

A pool of ideas, generated from a brainstorming session, needs to be analyzed, prioritized before they can be implemented. A smaller set of ideas are easy to sift through and evaluate without applying any formal technique. Affinity diagramming is an effective technique to handle a large number of ideas. It is typically used when

1. Large data set is to be traversed, like ideas generated from brainstorming and sieve for prioritization.
2. Complexity due to diverse views and opinions.
3. Group involvement and consensus. The process of affinity diagramming requires the team to categorize the ideas based on their subject knowledge thereby making it easy to sift and prioritize ideas. Fig. 8 shows an example affinity diagram with prioritized ideas categorized into different headings.

7.4.2 Design of experiments (DoE)

With DoE, you look at multiple levels of multiple factors simultaneously and make decisions as to what levels of the factor will optimize your output.

- A statistics-based approach to designed experiments
- A methodology to achieve a predictive knowledge of a complex, multi-variable process with the fewest trials possible
- An optimization of the experimental process itself

7.5 Control

In this step, our process has been measured, our data analyzed, and our process improved. The improvement we have made will be sustained. We need to build an appropriate level of control so that it does not enter into an undesirable state. One of the important tool that can be used to achieve this objective is Statistical Process Control (SPC). The purpose of SPC is to provide the practitioner with real-time feedback which indicates whether a process is under control or not.
There are also some lean tools like the 5S's, the Kaizen blitz, kanban, poka-yoke etc.

Fig. 8. Affinity Diagram

Six Sigma Tools	Advanced Tools
Pareto Analysis	Failure Mode Effect Analysis (FMEA)
Flow Process Chart	Design of Experiments (DoE)
Upper Control Limit (UCL) / Lower Control Limit (LCL) Control Chart	Design For Six Sigma (DFSS)
Cause and Effect Diagram	
Input-Process-Output Diagrams	
Brain Storming	
Scatter Diagram	
Histogram	
The Seven Wastes	
The Five Ss	

Table 5. Six Sigma Tools

8. Six sigma and lean tools

Table 5. summarizes some of the important Six Sigma tools used for easy reference. Pareto analysis, Control charts and Failure Mode Effect Analysis are explained in detail with examples.

8.1 Pareto Analysis

Pareto Analysis is a statistical technique in decision making that is used for the selection of a limited number of tasks that produce significant overall effect. It uses the Pareto Principle (also know as the 80/20 rule) the idea that a large majority of problems (80%) are produced by a few key causes (20%). This is also known as the vital few and the trivial many.The 80/20 rule can be applied to almost anything:

- 80% of customer complaints arise from 20% of your products or services.
- 80% of delays in schedule arise from 20% of the possible causes of the delays.
- 20% of your products or services account for 80% of your profit.
- 20% of your sales-force produces 80% of your company revenues.
- 20% of a systems defects cause 80% of its problems.

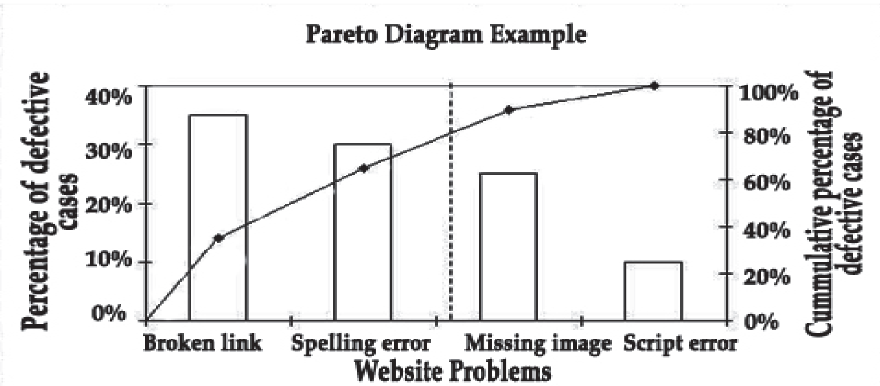

Fig. 9. Pareto diagram

The Pareto Principle has many applications in quality control. It is the basis for the Pareto diagram, one of the key tools used in total quality control and Six Sigma. Seven steps to identifying the important causes using Pareto Analysis :

1. Form a table listing the causes and their frequency as a percentage.
2. Arrange the rows in the decreasing order of importance of the causes, i.e. the most important cause first.
3. Add a cumulative percentage column to the table.
4. Plot with causes on x-axis and cumulative percentage on y-axis.
5. Join the above points to form a curve.
6. Plot (on the same graph) a bar graph with causes on x-axis and percent frequency on y-axis.
7. Draw a line at 80% on y-axis parallel to x-axis. Then drop the line at the point of intersection with the curve on x-axis. This point on the x-axis separates the important causes on the left and less important causes on the right.

8.2 Control charts

A control chart is a statistical tool used to distinguish between variation in a process resulting from common causes and variation resulting from special causes. It presents a graphic display of process stability or instability over time as shown in Fig. 10. Every process has variation. Some variation may be the result of causes which are not normally present in the process. This could be special cause variation. Some variation is simply the result of numerous, ever-present differences in the process. This is common cause variation. Control Charts differentiate between these two types of variation. One goal of using a Control Chart is to achieve and maintain process stability.

Process stability is defined as a state in which a process has displayed a certain degree of consistency in the past and is expected to continue to do so in the future. This consistency is characterized by a stream of data falling within control limits based on plus or minus 3 standard deviations (3 sigma) of the centerline.

A stable process is one that is consistent over time with respect to the center and the spread of the data. Control Charts help you monitor the behavior of your process to determine whether it is stable. Like Run Charts, they display data in the time sequence in which they occurred. However, Control Charts are more efficient that Run Charts in assessing and achieving process stability. Your team will benefit from using a Control Chart when you want to monitor process variation over time.

1. Differentiate between special cause and common cause variation.
2. Assess the effectiveness of changes to improve a process.
3. Communicate how a process performed during a specific period.

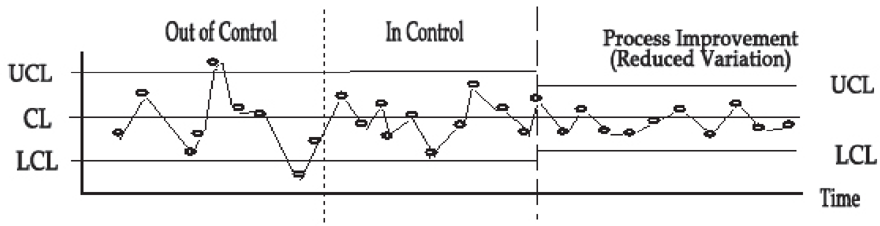

Fig. 10. Control Charts

8.3 Failure mode and effects analysis (FMEA)

Failure Mode and Effects Analysis (FMEA) is a model used to prioritize potential defects based on their severity, expected frequency, and likelihood of detection. An FMEA can be performed on a design or a process, and is used to prompt actions to improve design or process robustness. The FMEA highlights weaknesses in the current design or process in terms of the customer, and is an excellent vehicle to prioritize and organize continuous improvement efforts on areas which offer the greatest return.

The next step is to assign a value on a 1-10 scale for the severity, probability of occurrence, and probability of detection for each of the potential failure modes. After assigning a value, the three numbers for each failure mode are multiplied together to yield a Risk Priority Number (RPN). The RPN becomes a priority value to rank the failure modes, with the highest number demanding the most urgent improvement activity. Error-proofing, or poka-yoke actions are often an effective response to high RPN's.

Following is an example of a simplified FMEA for a seat belt installation process at an automobile assembly plant.

FAILURE MODE & EFFECTS ANALYSIS (FMEA)

Date: 01/01/2011

Revision: 1.3

Process Name: Left Front Seat Belt Install **Process Number: SBT 145**

Failure Mode	A) Severity Rate 1-10 10=Most Severe	B) Probability of Occurance Rate 1-10 10=Highest Probability	C) Probability of Detection Rate 1-10 10=Lowest Probability	Risk Preference Number (RPN) AxBxC
1) Select Wrong Color Seat Belt	5	4	3	60
2) Seat Belt Bolt not tightened	9	2	8	144
3)Trim Cover Clip Misaligned	2	3	4	24

Fig. 11. FMEA

As you can see, three potential failure modes have been identified. Failure mode number two has an RPN of 144, and is therefore the highest priority for process improvement. FMEA's are often completed as part of a new product launch process.

RPN minimum targets may be established to ensure a given level of process capability before shipping product to customers. In that event, it is wise to establish guidelines for assessing the values for Severity, Occurrence, and Detection to make the RPN as objective as possible.

9. Case studies on lean six sigma

Having seen Six Sigma Methodology and Lean Six Sigma tools elaborately, it is appropriate to look into some case studies on Six Sigma implementations. We present two case studies on Six Sigma implementation by two leading companies in this section. These studies reinforce Lean and Six Sigma Concepts as well as demonstrate the the tools used by them for implementing the same. The importance of achieving operational excellence by way of reducing defects and variations in processes as well as eliminations of non value adding steps in processes can be inferred from these case studies . One more case study on “Mumbai Dabba walahs” also presented at the end of the chapter to clearly demonstrate that Six Sigma is a tool not only for coporates but also it is for common man who are capable of achieving Six Sigma level in their services in execution of their daily tasks by fulfilling their customer needs.

9.1 Honeywell aerospace electronics system, singapore – implementing six sigma quality

Honeywell is a US$ 254 billion diversified technology and manufacturing leader, serving customers worldwide with aerospace products and services One of its business units, Aerospace Electronics System in Singapore, uses Six Sigma as a best practice to improve processes in most of its operations. The organisation, which has 150 employees, was set up in Singapore in 1983. It manufactures high quality avionics and navigation equipment and systems. Its principal customers include Cessna, Bell Helicopters, Raytheon, Learjet, Mooney Aircraft, Piper Aircraft, FedEx and Singapore Aerospace.

Six Sigma *Plus* is Honeywell's overall strategy to accelerate improvement in all processes, products and services, and to reduce the cost of poor quality by eliminating waste and reducing defects and variations. Six Sigma is already understood worldwide as a measure of excellence. The "*Plus*" is derived from Honeywell's Quality Value assessment process and expanded former AlliedSignal's Six Sigma strategic tools.
The strategy requires that the organisation approach every improvement project with the same logical method of DMAIC:

- Define the customer critical parameters
- Measure how the process performs
- Analyse causes of problems
- Improve the process to reduce defects and variations
- Control the process to ensure continued, improved performance

9.1.1 Implementing six sigma plus

The tools and skills that help in the implementation of the DMAIC method include:

- Process mapping which helps to identify the order of events in producing a product or service and compares the "ideal" work flow to what actually happens.
- Failure mode and effect analysis which helps to identify likely process failures and minimises their frequency.
- Measurement system evaluation which helps in the assessment of measurement instruments to enable the better separation of important process variations from measurement "noise".
- Statistical tests which assist in the separation of significant effects of variable from random variation.
- Design of experiments which is used to identify and confirm cause and effect relationships.
- Control plans which allow for the monitoring and controlling of processes to maintain the gains that have been made.
- Quality function deployment which is a tool for defining what is important to customers; it enables better anticipation and understanding of customer needs.
- Activity based management to look at product and process costs in a comprehensive and realistic way by examining the activities that create the costs in the first place and hence allowing for better subsequent management.
- Enterprise resource planning which uses special computer software to integrate, accelerate and sustain seamless process improvements throughout an organisation.
- Lean enterprise with skills to enhance the understanding of actions essential to achieving customer satisfaction. These skills simplify and improve work flow, help eliminate unnecessary tasks and reduce waste throughout a process.

9.1.2 Impact of six sigma plus

In the past, generic and low-end competencies such as the manufacture of printed circuit boards were outsourced. With Six Sigma *Plus,* core competencies were redefined and control plans established.
Presently, Aerospace Electronics System, Singapore focuses on core competencies that are unique to itself, such as final assembly and test and final alignment. This helped to stabilise the workforce for the organisation, which once experienced high turnover for its front-end and low-skill jobs. Waste has also been reduced from key business processes. For example,

inspection, which is considered as non-value added, has been eliminated. Instead, Reliance on Operators' Inspection (ROI) is practised and this has helped to increase the value added per employee.
In the past, all Honeywell Singapore's products were 100% inspected by a team from the US. Currently, the Federal Aviation Agency (FAA) certifies its products for manufacturing in Singapore; and 100% of its products are shipped direct to stock to Kansas, US, saving $1 million in inspection cost. In addition, audits by FAA involve only observations and not all processes need to be audited. This is achieved by ensuring that the necessary quality procedures are built into the process. Six Sigma *Plus* in Honeywell has led to the following results:

- Increased Rolled Throughput Yield (RTY)
- Reduced variations in all processes
- Reduced cost of poor quality (COPQ)
- Deployment of skilled resources as change agents.

9.1.3 Key learning points

Some of the key learning points are:

- Strong management commitment and support.
- Well-structured approach and deployment process
- Team-based approach.
- Sharing Six Sigma Plus knowledge.

9.2 Lean six sigma in higher education: applying proven methodologies to improve quality, remove waste, and quantity opportunities in college and universities

9.2.1 Lean flow today

This is another case study which highlights the experiences of Ms Xerox Corporation in implementing Six Sigma in higher education. The case study starts with discussion on the importance of Lean Principles and then elaborately discuss Six Sigma implementation strategies. While Lean Flow began as a manufacturing model, today's definition has been extended to include the process of creating an "optimized flow" anywhere in an organization. The only requirement is that this "flow" challenge current business practices to create a faster, cheaper, less variable, and error prone process. Lean Flow experts have found that the greatest success can be achieved by methodically seeking out inefficiencies and replacing them with "leaner", more streamlined processes. Sources of waste commonly plaguing most business processes include:

- Waste of worker movement (unneeded steps)
- Waste of making defective products
- Waste of over production
- Waste in transportation
- Waste of processing
- Waste of time (idle)
- Waste of stock on hand

9.2.2 Putting lean flow to work

Implementing a Lean Flow requires having the right data and knowing how to use it. There are a number of different approaches taken by organizations, but fundamentally, Lean Flow is achieved by:

- Analyzing the steps of a process and determining which steps add value and which do not.
- Calculating the costs associated with removing non-value-added steps and comparing those costs versus expected benefits.
- Determining the resources required to support

9.2.3 Six sigma today

While the concept of Six Sigma began in the manufacturing arena decades ago, the idea that organizations can improve quality levels and work "defect-free" is currently being incorporated by higher education institutions of all types and sizes. So what is today's definition of Six Sigma? It depends on whom you ask. In his book *Six Sigma: SPC and TQM in Manufacturing and Services,* Geoff Tennant explains that "Six Sigma is many things… a vision; a philosophy; a symbol; a metric; a goal; a methodology." Naturally, as Six Sigma permeates into today's complex, sophisticated higher education landscape, the methodology is "tweaked" to satisfy unique needs of individual schools. But no matter how it is deployed, there is an overall framework that drives Six Sigma toward improving performance. Common Six Sigma traits include:

- A process of improving quality by gathering data, understanding and controlling variation, and improving predictability of a school's business processes.
- A formalized Define, Measure, Analyze, Improve, Control (DMAIC) process that is the blueprint for Six Sigma improvements.
- A strong emphasis on value. Six Sigma projects focus on high return areas where the greatest benefits can be gained.
- Internal cultural change, beginning with support from administrators and champions. value-added steps while eliminating non-value added steps.
- Taking action.

Lean Six Sigma is the application of lean techniques to increase speed and reduce waste, while employing Six Sigma processes to improve quality and focus on the Voice of the Customer. Lean Six Sigma means doing things right the first time, only doing the things that generate value, and doing it all quickly and efficiently.

Xerox Global Services imaging and repository services leverage the Lean Six Sigma-based DMAIC approach:

Define

The Define phase of the DMAIC process is often skipped or short-changed, but is vital to the overall success of any Lean Six Sigma project. This is the phase where the current state, problem statement, and desired future state are determined and documented via the Project Charter. Xerox asks questions like: *What problem are we trying to solve? What are the expected results if we solve the problem? How will we know if the problem is solved? How will success be measured?* In most cases where imaging and repository services are involved, the problem relates to document management and access. Schools look to improve the ways documents are created, stored, accessed, and shared so they may accelerate and enhance work processes, share information more conveniently, and collaborate more effectively. As the project progresses and more information is collected in future phases, the problem statement developed in the Define phase is refined.

Measure

The Measure phase is where Xerox gathers quantitative and qualitative data to get a clear view of the current state. This serves as a baseline to evaluate potential solutions and typically involves interviews with process owners, mapping of key business processes, and gathering data relating to current performance (time, volume, frequency, impact, etc.).

Analyze

In the Analyze phase, Xerox studies the information gathered in the Measure phase, pinpoints bottlenecks, and identifies improvement opportunities where non-value-add tasks can be removed. A business case is conducted, which takes into account not only hard costs but also intangible benefits that can be gained, such as user productivity and satisfaction, to determine if the improvement is cost-effective and worthwhile. Finally, the Analyze phase is when technological recommendations are provided.

Improve

The Improve phase is when recommended solutions are implemented. A project plan is developed and put into action, beginning with a pilot program and culminating in full-scale, enterprise-wide deployment. Where appropriate, new technology is implemented, workflows are streamlined, paper-based processes are eliminated, and consulting services are initiated. Key factors of success during this phase are acceptance by end users and enterprise-wide change without any degradation of current productivity levels.

Control

Once a solution is implemented, the next step is to place the necessary "controls" to assure improvements are maintained long-term. This involves monitoring—and in many cases, publicizing—the key process metrics to promote continuous improvement and to guard against regression. In many cases, Xerox will revisit the implementation after 3-6 months to review key metrics and evaluate if the initial progress has been sustained. A common practice is to put key metrics, including hard cost savings and achievement of pre-defined Service Level Agreements, in full view "on the dashboard" to provide continuous feedback to the organization and so decision-makers can assess the project's level of success as it moves forward.

9.3 Dabbawalas and six sigma

A Six Sigma practioner need not be an educated individual. One interesting case study quoted for Six Sigma application is dabbawalas of Mumbai, India. Dabbawallas (also known as Tiffinwallahs) are persons employed in a service industry in Mumbai whose primary job is collecting the freshly cooked food in lunch boxes from the residences of office workers (mostly in the suburbs), delivering it to their respective work places and returning the empty boxes to the customer's residence by using various modes of transport. Around 5000 dabbawalas in Mumbai transport around 200,000 lunch boxes every day. The reliability of their services meet Six Sigma standard as per study by Forbes Magazine in the year 2002. It has been found that they make less than one mistake in every 6 million deliveries. The tiffin boxes are correctly delivered to their respective destinations as the dabbawalls use an unique identifying coding scheme inscribed on the top of each tiffin box.

10. Conclusion

Six Sigma was a concept developed in 1985 by Bill Smith of Motorola.
Six Sigma is a business transformation methodology that maximizes profits and delivers value to customers by focusing on the reduction of variation and elimination of defects by using various statistical, data-based tools and techniques.

Lean is a business transformation methodology which was derived from the Toyota Production System (TPS) which focusses on increasing customer value by reducing the cycle time of product or service delivery through the elimination of all forms of waste and unevenness in the workflow.
Lean Six Sigma is a disciplined methodlogy which is rigorous, data driven, result-oriented approach to process improvement. It combines two industry recognized methodologies evolved at Motorola, GE, Toyata, and Xerox to name a few. By integrating tools and processes of Lean and Six Sigma, we're creating a powerful engine for improving quality, efficiency, and speed in every aspect of business.
Lean and Six Sigma are initiatives that were born from the pursuit of operational excellence within manufacturing companies. While Lean serves to eliminate waste, Six Sigma reduces process variability in striving for perfection. When combined, the result is a methodology that serves to improve processes, eliminate product or process defects and to reduce cycle times and accelerate processes
Lean and Six Sigma are conceptually sound technically fool proof methodologies and is here to stay and deliver break through results for a long time to come.
This chapter discussed the history of Six Sigma and Lean thinking and important steps in implementing Lean Six Sigma like DMAIC methodology. Some of the important Six Sigma and Lean tools were discussed with examples which will be of help to a Six Sigma practitioner. Three case studies were presented which shares experiences on how Six Sigma implementation had helped them to improve their bottom line by removing variations in the processes and eliminating defects and reducing cycle time.

11. Acknowledgment

We have presented two case studies on Six Sigma implementation by Ms. Honeywell International Inc and Xerox Global Services we sincerely acknowledge for their pioneering work on quality improvement measures by them for improving bottom line of their operations. Some of the illustrations and charts related to Six Sigma and lean tools presented are taken from internet resources available online and the authors acknowledge and thank the contributors.

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2

Definition of the Guide for Implementation Lean

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1. Introduction

Once the company recognizes the need to change to compete, we need to define a way forward in implementing Lean Manufacturing. This guide consists of 5 phases: Plan, Implement, Deploy, Integrate and Excel. The first four stages are usually implemented from 1 year minimum to 10 years depending on the investment of time and resources in the project. Phase 5 has no end, because Lean is a philosophy that you have to work throughout the life in an organization. The purpose of implementation guide is to assist in the understanding of a comprehensive methodology and defined the steps to follow when we know the tools of Lean Manufacturing but not the sequence to implement the process.
The Guide to the Implementation of Lean Manufacturing is divided into 5 phases:

- Phase 1: Plan, the duration is from 1 to 6 months.
- Phase 2: Apply, the duration is from 3 to 6 months.
- Phase 3: Display, the duration is from 2 to 12 months.
- Phase 4: Integration, the duration is from 2 to 6 months.
- Phase 5: Excel, forever and ever.

2. Steps of phase 1: plan

Phase 1: Plan is the most important phase for the Implementation of Lean Manufacturing as it will largely depend on its success or failure. This phase consists of 18 steps, which will be described in the following paragraphs.

2.1 Step 1: assessment of current status

This is the initial step of implementation and it will be done by an initial team of implementation, where each and every one of their members must know the current status of the organization and help to make a deep analysis of the Manufacturing Assessment Lean in which 16 areas of the organization are assessed. They are next listed: 1. Communication, 2. Workplace Organization and Visual Management, 3. Standard Work, 4. Flexibility of Operations, 5. Continuous Improvement, 6. Error Proofing Devices (Poka Yokes), 7. Capacity for Quick Changes (SMED), 8. Total Productive Maintenance (TPM), 9. Material Control, 10. Production Level, 11. Engineering, 12. Lean Accounting Systems, 13. Quality, 14. Customer Chain, 15. Maintenance, 16. Performances indicators.
Each area to be evaluated consists from 6 to 9 items. All items will be graded from 0 to 5; 0 when the practice is not found on the floor, 0% frequency; 1 is observed only in some areas, 25% frequency; 2 it is common but in most cases, 50% frequency; 3 it is very common with

some exceptions, 75% frequency; 4 it is observed throughout the plant, without exception, 100% frequency; 5 it is observed throughout the plant and is the best in the industry. The result obtained in each area is being summarized in a table. The evaluation obtained will be indicative of the current situation of the organization.

Step 1.2: diagnostics corporation

The sum of the column "Results to Evaluate" determines the organization's current diagnosis. The other diagnostic tool is the Value Mapping that is a graphical tool that helps us to see and understand the material and information flows. A product is considered a wall-to-wall unit inside the plant for identifying those activities that add no value, bottlenecks, major problems, etc. In the process of becoming lean, many manufacturing companies omitted a crucial step: the strategic vision of material and information flow. In many cases companies are rushed to apply the concepts of Lean Manufacturing through kaizen events applied to the process level that may lead to some error in the assessment.

All the efforts mentioned above are most effective when applied strategically within the context of the value chain (defined as "all actions required producing a product or family of products from raw material to customer demand.") Participants should learn how to draw the map of current and future value for a hypothetical plant using the basic concepts of mapping, icons and data needed for mapping. Mapping helps us to analyze the entire plant process, observe more than waste. It allows us to identify sources that cause this waste and use a common language for the manufacturing process. Asking a general strategy for improving the area, otherwise there would be separate efforts in each thread, properly implement Lean Manufacturing principles and fixed to the implementation strategy of the 5 stages of a Flexible Production System (FPS), Establish a proper plan, designing the process of a product or family of products from start to finish, not just one area and see the relationship between material flow and information flow.

Mapping Terms Used:

- **Material Flow**: The movement of material through the plant for the manufacture of products.
- **Information Flow**: The means of communication by which each thread tells what to make or do at all times.

Steps to Draw Mapping:

1. Choose a product family or product. Taking into account the needs of customers, production volumes, profits, and the lifetime of the product (not to exert on products coming out of the market). Families are products that have similar processes or produced in the same production lines.
2. Draw the current state map using the symbols or icons and an example of mapping value, using the symbols.
3. Draw a map to future.
4. Develop Implementation Plan.

Now that we should know a diagnosis of current status can start working with an action plan.

Step 1.3: decide to implement lean manufacturing

After learning more objectively the current state of the organization it will decide whether to continue with implementation. At this point all levels of the plant must be fully convinced of the job they are committing to carry out.

Step 1.4: define goals, objectives, measurements and achievements

The team must define the objectives and goals that are written in a table. This aims at the starting point of the diagnosis of the present, (see Step 1.2). Which is a way of establishing who will be responsible and setting the deadlines dates for each of the objectives. Base your management decisions on a long-term philosophy, even achieving short-term financial goals. Have a philosophical determination that supersedes any decision making in the short term. Work, grow, and compose the entire organization towards a common purpose that is bigger than making money. Understand your place in the history of the company and work to take the company to the next level. Your philosophical mission is the foundation for all other principles. Generate value for customers, society and the economy that is our starting point. Evaluate each function in the company as regards its ability to achieve this. Be responsible; strive to decide our own destiny. Act with the same-confidence and trust in their abilities. Accept responsibility for his conduct and maintain and improve the skills that enable you to produce value added.

Step 1.5: policy statement lean manufacturing

The implementation team will draft a policy Lean where guidelines are established or bases of the form in which we work, how we will evaluate the results, how often meetings were held and who designate those responsible for complying the goals or objectives. Establish the vision, approach to the organization, align performance measures and establish high expectations for success and zero fault tolerance.

Step 1.6: lean organization commitment

After developing the Lean policy, this requires that all high levels of organization charts, as well as those responsible for carrying out assigned tasks, a formal commitment to meet the goals and objectives by signing the policy.

Step 1.7: rules for the equipment

In addition to Lean Policy as defined in Step 5, rules will be developed for teams that will be specific enough so that there are no doubts in the proceedings.

- Select Team Members with the following characteristics: technological curiosity, common sense and inner confidence, strong critical thinking and ability to solve problems, multifunctional equipment, manager/supervisor of the pilot area and functional departments (planning, engineering, quality, production control).
- As Home Team to be carried out: training, the reading of literature is required, attend training in Lean Manufacturing and present a summary/progress to staff.
- Recommended Tools: standardized analysis and simulation tools to consider, camcorders, TVs, etc. and computers, printers and projectors.
- As for the facilities we need to have: finding a room for the implementation team and office area and equipped properly.
- Pilot Area Selection, which should be selected with the following criteria: The area should be representative of the main product to contribute to the competitive strength of the business. Innovation is a good chance for success. The solutions must be usable in other parts of the company, status of the current process, cost and volume of the product, rates of outputs, ground work, volume inventory and processing Time.

Step 1.8: Analysis of objectives and targets

Although, the goals and objectives were established from the step 4 at this point should be analyzed again and have been published Lean Policy and Rules for the teams. This review will be more objective because as Phase 1 proceeds will be easier to define the objectives for the understanding of the implementation is clearer by using the following: setting objectives and goals, establish the basic principles of Lean, production with one piece flow, standardized work methods, minimize/eliminate waste, production with zero defects, high productivity, improvement goals, reduced processing time, reduced operating costs, increase the use of labour, increasing the flexibility of labour, flexibility of the team and Kaizen.

Step 1.9: investigate the current conditions

The trained teams begin to work with the Present State Examination that was done in step 1, reviewing each of the grades in the areas evaluated and corroborating these evaluations for team members carry out themselves this point.

Step 1.10: lean assessments

For team members working from corroborated evidence by themselves, must be done again Lean Assessment and Collection of current status information. The first step in this phase was to evaluate the entire organization through an assessment tool. Although there are tools developed by different organizations (Ford, one of them), it was developed in line with the regional situation and the work culture in our business environment. The results of this survey serve to guide the implementation process.

Step 1.11: develop matrix and master plan

They built Lean Policy and the Rules for the equipment. Lean Assessment will be a parent and Master Plan using as a guide the goals that were defined, but now with the sum of all this knowledge. The Matrix and Master Plan should be formal and shall contain the names of high levels of the organization, as well as their commitment to compliance firms.

In the official presentation of the project it must contain comparison of baseline conditions with the projection of lean manufacturing, improve productivity at least 20%, improved labour requirements at least 15% (direct and indirect), workspaces reduced by at least 15%, cell distribution, inventory reduced by at least 50%, total time of the improved process at least 50%, implementation of one piece flow, documentation of implementation costs, capital investment, additional expenses, training costs, introduce improvements to the administration management, include all indicators of decision-making and methodology, let the facts speak for themselves and justifying the cost and duration of implementation.

Step 1.12: publish the policy and the matrix or master plan.

Lean policy and the Matrix or Master plan must be published because in this way the whole organization can learn about them. It will now remove the uncertainty about the implementation.

Step 1.13: visually identify targets

After defining the objectives in the Master Plan, location of each one in the area that corresponds to all employees know the plan and timeline for completion. This should make the Value Mapping the organization to visually identify the activities that add value and which do not add value.

Step 1.14: Plan education and training.

Identify all employees involved in the area where is going to be carried out the implementation to develop an Education and Training Plan, which contains the Lean tools

that are to be implemented and the knowledge needed for the project. Training phase is one of the most important and should be the beginning of every implementation. All staff should understand the purposes of this methodology, objectives, consequences, requirements and most importantly, what is expected of each of them and they benefit. One of the factors of failure in the implementation of such programs is undoubtedly the lack of conviction of the people. When staff do not know, do not understand, was not involved, hardly take a cooperative attitude, and you will feel that the status quo is threatened, their paradigms, and most dangerous, feel it will be replaced by a device, machine, a re-arrangement of the distribution, etc., feel therefore that it will no longer be necessary.
The phenomenon with which we are, which is very common is a resistance to change for fear that our shortcomings, inadequacies and bad habits are brought into the open. These attitudes and feelings are normal in any change process; hence a good training is essential. Training was initiated in parallel with staff of the productive area. For the administrative staff designed courses with durations of 2 hours per day, while operational staff was trained using the technique of the five minutes of quality, also known as a single subject lessons. These lessons of one subject were taught by the same administrative staff (trained on a specific topic before) with the help of the implementation team internally and externally.
The lessons of one subject are a very effective and economical (in terms of training) and is not required of a professional coach, involving all staff and can be given, wherever possible, daily, five to ten minutes before the end of the turn and five to ten minutes before the start of the second shift (the plant had only two shifts). We took lessons from a single topic for each one of the most important concepts. Another method used as training for all staff, was the placing of banners on the concepts and tools of lean manufacturing. After being placed blankets, the staff began to ask about the meaning of them, so when you get to the point of a single subject lessons and training with staff, and had many questions to do and many questions, which was the target. This is what is known as advertising prior to implementation. As one quarter through training, placed pictures of the current situation, referring to the type of waste is concerned and what would be the best way to get rid of that waste, inviting staff to get involved and make proposals to remove and keep areas clean and tidy.

Step 1.15: achieving consensus at all levels

Once you complete the Implementation Plan, will meet all involved to explain the whole system work. The consensus should be reached through hierarchical levels of the organization, starting from high levels to down (catch-the-ball). Make decisions slowly by consensus, considering all options, implement decisions quickly (Nemawashi). Do not choose a single direction and follow a path until you have thoroughly examined the alternatives. When selected, move quickly but cautiously down the road. Nemawashi is the process of discussing problems and possible solutions with all stakeholders, to gather their ideas and reach agreement on a way forward.
This process of consensus, although time consuming, helps broaden the search for solutions, once a decision is made, the stage is set for rapid implementation. Build leaders who fully understand the work, live the philosophy, and teach others. Build leaders, instead of buying outside the organization. The leaders must be models of the company's philosophy and way of doing business. A good leader must understand the daily work in great detail, so that he or she may be the best teacher of philosophy of the company.

Step 1.16: education for awareness

In addition to training, is also initiated an awareness campaign through posters may be showing other companies working with the Lean Manufacturing System, and that conditions are going to see our company in the future we have planned. Develop exceptional people and teams who follow the philosophy of your company. Create a strong and stable culture that values the company, values and beliefs are widely shared and lived through a period of many years. Empowering people with skills of teamwork within the company's philosophy to achieve exceptional results and work hard to strengthen the culture continuously will help to reach awareness.

Use computers to perform various functions to improve quality and productivity and improve the flow of the solution of difficult technical problems. The effort takes place when people use tools to improve business. Make an effort to teach people how to work together as teams toward common goals. Teamwork is something that must be learned for becoming a learning organization through reflection (hansei) and continuous improvement (kaizen). Once you have implemented a stable process, the use of continuous improvement tools to determine the cause of inefficiencies and implementing effective countermeasures. Design processes that require almost no inventory. This will make visible the loss of time and resources for all to see. Once the waste is exposed, have employees who use a process of continuous improvement (kaizen) to remove it. Protect the organization knowledge base by developing stable personnel, slow promotion, and very careful succession systems. Use hansei (reflection) in the main reference points and after you have completed a project, openly identify any shortcomings of the project. Develop countermeasures to avoid the same mistakes again. Learn the best practices standards, rather than reinvent the wheel with each new project and each new director.

Step 1.17: communicate the policy

After months of work in Phase 1, plans have been revised and revised again. The policy also has changed during this process and the plan and is completely finished and defined. It is published again. The policy includes the development and deployment of the mission, vision and values. With the help of equipment implementers, internal and external, developed statements of mission, vision and values for the organization. However, these are not just statements, and actually represent the rudder and sails of the ship in which the entire organization moves, so without this mission and vision is to walk aimlessly.

Step 1.18: start formal

The same day that the policy is issued is the formal start of the Plan of Implementation of Lean Manufacturing in the company and formally notified to all levels, the exact start date according to the Master Plan.

3. Steps of phase 2: apply the Implementation

In phase 2, the plan from Phase 1 is implemented. . Phase 2 has duration of 3 to 6 months and consists of 19 steps.

Step 2.1: Initial application

This is very important that the planting team is made up of personnel with extensive knowledge of lean manufacturing techniques, as will be the example to follow and will also be essential that some members have participated in Phase 1, because it will be a better understanding of the objectives.

Step 2.2: prepare and focus

All work must be done to start based in Phase 1, to do what was planned and not out of schedule.

Step 2.3: working area scrutinizing

Check the area thoroughly where it will be to implement and compare plans, if it is something different, correct the plan, but whenever it is necessary to make any changes should first be changed documents.

- Selection Criteria: The area should be representative of the main product, to contribute to the competitive strength of the business, innovation is a good chance for success and the solutions must be usable in other parts of the company.
- Location of the current process: Cost and volume of the product, rates of outputs, ground work, volume inventory and processing time.

Step 2.4: apply 5S

Apply 5S to work in an organized area. Use visual controls so no problems are hidden. Use simple visual indicators to help people determine immediately whether they are in a normal condition or deviating from it. Avoid using a computer screen where the employees focus outside the workplace. Design simple visual systems at the site where work is done to support flow and pull. Reduce your reports to a single sheet of paper whenever possible, even for their most important financial decisions.

5's technique consists of 5 steps which are:

1. Sort (SEIRI) consists of removing the workstation area or all objects that are not required to perform the task, either in production areas or in administrative areas. An effective way to identify these elements must be eliminated is called red tagging "is a red card expulsion is placed on all items which are considered not necessary for the operation. Then these elements are taken to a holding area. Later, if it was confirmed that they were unnecessary, they are divided into two classes, which are used for another operation and will be discarded useless.
2. Order (SEITON) is to organize the elements we have classified as necessary so they can be found easily. Order maintenance has to do with improving display of items of machinery and industrial installations. Some strategies for this process of "everything in place are: painting floors, clearly defining work areas and locations, with silhouettes of tables and modular shelving and cabinets to have in place things like a trash, a broom, mop, bucket, etc., ie, "A place for everything and everything in its place."
3. Clean (SEISO) means to remove dust and dirt from all elements of a factory. From the point of view of Total Productive Maintenance (TPM) involves inspecting the equipment during the cleaning process. It identifies the problems of leaks, failures, faults or any type of defect. Cleaning includes, in addition to the activity of cleaning work areas and equipment, application design to avoid or at least reduce the dirt and make safer work environment.
4. Standardize (SEIKETSU) aims to maintain the cleanliness and organization achieved through the implementation of the initial 3's. The only standardize work continuously obtained when the three principles above. At this stage or phase (should be made

permanent), the workers who carry out programs and mechanisms designed to enable them to benefit themselves. To build this culture may use different tools, one of which is the location of job site photographs in optimal conditions so that they can be seen by all employees and remind them that this is the state which should remain, one is development of rules in which they specify what should be done every employee with respect to your work area.

5. Discipline (SHITSUKE) means to prevent breaking the established procedures, only if it implements discipline and compliance with rules and procedures already adopted will enjoy the benefits they provide. Discipline is the channel between the 5 S's and continuous improvement. Implies: control periodic surprise visits, employee self, respect for themselves and for others and quality of working lives: Create a culture of sensitivity, respect and care of company resources, Discipline is a rule to change habits and the morale in the workplace increases.

Step 2.5: develop criteria, prepare assessments for the equipment

All team members should work with the same objective and need to develop criteria on can rely on when making assessments.
Project Performance Measurement

- Base: register hour by hour, standardized method, time out, Pareto analysis, collection of quality data, diagram of fish and control of activities.
- Activities for Managers and Supervisors: Identify the basic elements of lean manufacturing, standardized work, the source of quality control, review the performance evaluation of each of these areas and make the necessary adjustment.
- Activities in line / cell of operations: monitor the performance at scheduled intervals of one hour, publish the results daily and monitor statistical trends, rigorously monitor and analyze downtime, develop a list of 10 recurrences and solve major problems identified, conduct a multifunctional training of operators, maintain equipment and tools and maintain at all times the labor organization and cleaning.

Step 2.6: standardize the work and inventory indicators

All methods used in the area should be standardized. Standardized tasks are fundamental to continuous improvement and strengthening of the employee. Use stable, repeatable methods everywhere to maintain predictability, timing, and regular output of your processes. It is the foundation for the method of flow and pull. Capture lessons learned on a process to the point of standardizing best practices today. Allow individual creative expression to enhance the standard practices, and then incorporate it into a new standard so that when a person moves you can train the following people. Start working with inventory on the floor. Standardized work means that all operations are always carried out well and steadily, synchronized with customer requirements. The standard work is created, so that the required levels of quality are achieved and maintained. Within the standard work, labor movements are repetitive and the repeatability released the employee of the need to constantly think about what to do next or adjust their movements. The work is performed in a given sequence, stabilizing, maintaining and controlling quality.

Step 2.7: standardize the worksheets

Worksheets or sheets of process should be standard, contain the same information and the format to everyone involved to find the information in the same location for all processes.

Step 2.8: establish the one-piece flow

Make adjustments if necessary to establish the flow in one piece eliminating the batch system. The following sections present a summary of the changes implemented and the progress with the implementation of programs for Visual Management 5'S, these programs are universal and all organizations and the important fact that they are a important prerequisite. The most important changes deemed necessary to achieve synchronization of flow, reduce inventory and increase value added in the process, fundamental objectives of lean manufacturing.

Pull System called Kanban, is a tool based on the operation of supermarkets, means in Japanese "label statement." The label Kanban contains information that serves as a work order, this is its main function, in other words is an automatic steering device that gives us information about what to produce, how much, by what means, and how to transport. Before implementing Kanban, it is necessary to develop a production level to smooth the current flow of material, it must be practiced in the final assembly line, if there is a large fluctuation in the Kanban process integration will not work and will otherwise disorder, also have to be implanted SMED systems, small batch production, Jidoka, visual control, Poka Yoke, productive maintenance, etc. This is a prerequisite for the introduction of Kanban. Should also be taken into account the following considerations before implementing Kanban:

1. Determine a production scheduling system for final assembly to develop a joint production and labeling.
2. We must set a path that reflects material flow, this implies designate sites for there is no confusion in the handling of materials, making it obvious that the material is out of place.
3. The use of Kanban systems is linked to small batch production.
4. It should be noted that those items of particular value should be treated differently.
5. It must have good communication from the sales department to production for those seasonal items cyclic intensive production, so as to notify you in advance.
6. The Kanban system will be constantly updated and improved continuously.

There are two main functions of Kanban; Production Control and Process Improvement.

Production control is the integration of the different processes and the development of a JIT system, in which the materials will arrive in time and quantity required at different stages of the process and if possible including suppliers.

Process improvement facilitates improvement in the various activities of the company through the use of Kanban, this is done by engineering techniques (waste elimination, organizing the workspace, reducing model changes, use of machinery vs. Use based on demand , multi-process management, device for the prevention of errors (Poka Yoke), error-proof mechanisms, preventive maintenance, Total Productive Maintenance (TPM), reduction of inventory levels).

Step 2.9: standard work manual

Since the flow is established in one piece, it may be necessary to make some changes in the methods and process sheets. Make changes as required and develop the Manual of Standard Work. Toyota's managers recognize that the key is in the details, so ensure that all work is highly specified in terms of content, sequence, time and results. When installing a seat in the car, for example, the screws are tightened in the same order, the time it takes to tighten each screw is specified, and so is the torque which should tighten the screw. This accuracy

applies not only to repetitive movements of the production workers but also the activities of people, regardless of their specialty and their authority.
The requirement that each activity is specified is the first unwritten rule of the system. You put it in raw form, the rule seems simple, something you'd expect everyone to understand and follow easily. But in reality, most managers and their peers outside of Toyota not take this approach to work in the design and implementation, although they think they do. Let's see how the operators in a typical auto assembly plant installed a front seat in the car. They are supposed to take four screws in a cardboard box, take them with a torque wrench in the car, tighten the four screws, and type in a code on the computer to indicate that the work was done without any problem. Then expect the next car arrives.
New entrants are trained by experienced operators, who teach by demonstrating what to do. A senior colleague can be available to assist the operator again when you have difficulty, such as a screw or to enter the code in the computer. This sounds very straightforward, what is wrong with this? The problem is that these specifications actually allow-and even take "considerable variation in the way operators do the work. Without anyone noticing, there is much room for the operator to place the screws back in a different way than does the experienced operator. Some operators can place the front screws then screw back, others to the contrary. Some operators may place each screw, then tighten them all, others can cash them one by one pressing.
All this variation translates into a poorer quality, lower productivity and higher costs. More importantly, it prevents learning and improvement in the organization because it conceals the variations between how the worker does his work and results. In the plants of Toyota, because the operators (new and old, direct and indirect) are a well-defined sequence of steps for a particular job, it is instantly clear when they deviate from the specifications. Although complex and unusual activities, such as: training a work force experienced in a new plant, launching a new model, changing a production line, or changing a part of one plant to another, are designed according to this rule.

Step 2.10: implement specific methods in the area

After standard work, reduced inventories, set the one-piece flow is necessary to formalize the methods that were established in accordance with the requirements of the area where it is working.

Step 2.11: product making quick changes

Make the necessary tests in the areas where you need to make adjustments for changes in product, model, and part number to make the necessary changes. SMED stands for "change model single-digit minutes." These theories and techniques are to make the model change operations in less than 10 minutes. Since the change must take from last good piece to the first good piece less than 10 minutes. The SMED system was born of necessity to achieve JIT production. This system was developed to shorten the preparation time machine, allowing making smaller batches. The exchange procedures were simplified model using common or similar elements commonly used. Facilitate small batch production, reject the formula for economic lot, run each part each day (make), achieve the lot size of 1 pc, making the first piece right every time, changing model in less than 10 minutes.
SMED Three-step approach

1. Remove external time (50%). Much time is wasted thinking about what to do next, or waiting for the machine stops. Tasks reduces planning time (the order of the parts,

when changes occur, what tools and equipment needed, how people speak and materials required inspection.) The aim is to transform a routine event the process, leaving nothing to chance. The idea is to move the external time to external functions.

2. Methods and practice (25%).The study of timing and methods will find the fastest and best way to find the internal time remaining. The nuts and bolts are one of the major causes of delays. The unification of measures and tools can reduce the time. Duplicate common parts for assembly operations will do so this time winning outside of internal operations. For best and effective model changes are required teams of people. Two or more people collaborate in positioning, range of materials and use of tools. The effectiveness is contingent upon the practice of the operation. The time spent is well worth the practice because it will improve the results.
3. Delete settings (15%). Implies that the best adjustments are not needed, so is used to set the positions. It seeks to recreate the same circumstances than last time. How many adjustments can be made as external work is required to fix the tools. The adjustments needed space to accommodate the different types of matrices, dies, punches or tools as required standard spaces.

Step 2.12: quick changes standardized procedure

It is also necessary to validate these changes and so we are gradually reducing waste, and to standardize can be analyzed more quickly when problems arise or when it is possible to make some improvement.

Step 2.13: autonomous maintenance set

Start working on autonomous maintenance, where the operator takes care of your workspace. Total Productive Maintenance (TPM) aims to create a corporate system that maximizes the efficiency of the entire production system, establishing a system to prevent losses in all business operations. This includes "zero accidents, zero defects and zero failures" throughout the life cycle of the production system. It applies in all sectors, including production, development and administrative departments. It relies on the participation of all members of the company from top management to operational levels. Obtaining zero losses is achieved through the work of small teams. The TPM allows differentiating an organization in relation to its competition due to the impact on cost reduction, improved response times, reliability of supplies, knowledge possessed by the people and the quality of end products and services. TPM seeks to:

- Maximize team effectiveness.
- Develop a system of productive maintenance throughout the life of the equipment, involve all departments that plan, design, use, or maintain equipment, in implementing TPM, actively involve all employees, from top management to floor workers.
- Promote TPM through motivational with autonomous small group activities originating: zero accidents, zero defects, zero breakdowns.

The TPM process helps build competitive capabilities from the operations of the company, through its contribution to improving the effectiveness of production systems, flexibility and responsiveness, reduced operating and maintenance costs of "knowledge" industry.

Step 2.14: establish visual control

Start creating a system where only needed to make a point to know if something is working as we want by means of visual control. Visual Controls are a set of tools and visual aids that we facilitate the development of activities necessary to meet an easy and effective way any activity that requires the development of a product. The purpose is to visually identify the resources (tools, parts, work instructions, and performance indicators of the production system) so that everyone involved can understand in the light conditions and needs of the system. Visual controls are designed by the service departments (engineering, quality, materials) which are respected by all plant personnel, and maintenance is responsible for installing them. Visual controls used are:

- Andon System; communication system between modules of production and service departments.
- Poka Yoke Flags; is used to display performance indicators of the production model and the results per hour.
- Module information; assigned place within the production area to place current and relevant information of the area.
- Kanban; a signal to prevent overproduction and ensure that the parties will be pulled from season to season and from cell to cell when required and in the correct amounts.
- Bottlenecks; workstation which is the restriction of the process in the production module.
- Key operations; a signal that indicates the location of transactions recorded by the quality and Features Product Keys.
- Housekeeping 5's; ensures a safe, orderly and pleasant that promotes and facilitates productive work.
- Work instructions; it is a visual description of the method of each operation on workstations.

Step 2.15: controls test set error (poka yoke)

Identify those points in the process where bottlenecks are generated due to errors or inspections, analyze the work and develop error-proof devices (Poka Yoke 2.3.5) that aid to ensure product quality. The term "Poka Yoke" comes from the Japanese words "poka" (inadvertent errors) and "yoke" (prevent). Poka Yoke device is any mechanism that helps prevent errors before they happen, or makes them very obvious for the worker to realize and correct it in time. The purpose of Poka Yoke is to remove as soon as possible defects in a product either preventing or correcting errors that occur.

Poka Yoke systems involve carrying out 100% inspection, as well as feedback and immediate action when defects or errors occur. This approach solves the problems of the old belief that 100% inspection takes time and work, which has a high cost. Poka Yoke system has two functions: one is to make 100% inspection of parts produced, and the second is whether abnormalities occur can give feedback and corrective action. The effects of Poka Yoke method to reduce defects will depend on the type of inspection is being carried out either at the beginning of the line, self-check or continuous checks.

Step 2.16: analyze results

After it has been applied as 5S, Standard Work, Quick Changeover, Total Productive Maintenance TPM, Poka Yokes, it is necessary to analyze the results and compare with the goals and objectives proposed for Phase 1, recorded and always comparing the results with completion dates.

Step 2.17: experiences learned and refocusing of objectives

Implement all the techniques to brainstorm lessons learned through a format that will serve for consultation so we can refocus the objectives of Phase 1. Here you can use the A3 Report (Appendix B) which is a compilation of relevant information.

Step 2.18: reapply 5S

Make an assessment at this point in the 5S's to make the necessary changes.

Step 2.19: Eestablish a safe program status

Analyze the working conditions and put them all in a safe condition program.

4. Steps in phase 3: deploy

After applying Lean Manufacturing Techniques in the Area of Pilot Area Home or applications must be extended to other areas of the plant or organization in Phase 3, extended or folded that it can take 2 to 12 months and consists of 16 steps.

Step 3.1: additional equipment training and education

Team members who worked in Phase 2 can now be the leaders of the new equipment for the remaining areas of the plant. New members must bring to the area where Phase 2 was to see and discuss Labor System Implemented now they are going to implement.

Step 3.2: publish phase 2 activities in whole plant

To summarize the achievements in Phase 2 to publish in all areas of the plant and that employees see the results.

Step 3.3: improving the implementation plan

Based on the experiences gained in Phase 2, improvements are made in the Master Plan of Implementation that the initial team members consider relevant to the new areas.

Step 3.4: repeat the application of phases 1 and 2 in the other areas

With the experience gained in Phases 1 and 2 for area start implementing Lean repeat all the steps in these two phases in the other areas of the plant.

Step 3.5: Establish advanced flow system one piece

Having completed Phase 2 in all areas is a readjustment of the whole plant to implement the Advanced Flow System A part that is to produce a piece and move to the next process, not to accumulate inventory on the floor. A flexible manufacturing system has several definitions because people try to describe it from their perspective. At a higher level, a flexible manufacturing system is a collection of flexible manufacturing cells. A flexible manufacturing cell, in turn, is a group of related machines that perform a particular process or a step in a longer manufacturing process. A cell can be secreted due to noise, chemical hazards, and demand for raw materials or manufacturing cycle time.

It can also be a group of manufacturing machines dedicated to a single purpose that offer flexibility to meet the variable flow of material between stations and different combinations of stations using simple operations. In both cases, the end result is the ability to manufacture parts or assemblies using the same machine group. A production line with variable use and operation of the stations can function as a flexible manufacturing system. Thus, flexible manufacturing describes any group of machines or facilities in order to move material between them. The whole system is run by computers, which collectively can manufacture different parts and products from start to finish.

Although the acronym for flexible manufacturing system is considered in part generic, used by many other terms and acronyms to describe this kind of equipment for manufacturing:

CIMS (Computer Integrated Manufacturing Systems, System Computer Integrated Manufacturing), CMPM (Computer Managed Parts Manufacturing, Manufacturing Management Computer Parts), VMM (Variable Mission Manufacturing, Manufacturing Mission Variable).

The use of flexible manufacturing systems involves the use of other systems, such as: group technology (GT, Group Technology), for classifying manufacturing parts with similar characteristics, the technology just in time (JIT, Just In Time) , which allows raw materials reach the right place at the right time, the MRP (Material Requirements Planning, planning, product demand), where the incoming material is selected to come to the right place at the right time, and finally CAD systems, in order to allow the use of data and design specifications millimeter in the programming of numerical control machines (NC) and automatic inspection.

Step 3.6: achieving multifunctional operators.

Train operators to be multifunctional, they can perform any operation your work cell (see multifunctional operators). Multifunctional operators mean that a single operator performs several processes at once in a cell. To do this you must meet the following points:

- Clearly define the operations performed by each machine and the tasks performed by each operator.
- After organizing the cell manufacturing system, if some processes do not fit into this system to place these machines in remote areas and to bring people there needed according to the production volume required.
- Train operators to be multifunctional.

Step 3.7: applying total productive maintenance additional

Now that the operators are trained to perform any operation on your cell manufacturing, also need training to care for the machinery they are using, applying the Additional Total Productive Maintenance (See Total Productive Maintenance TPM).

Step 3.8: cycle time management

Perform Value Mapping review, which displays the cycle time and analyze the improvements that have been achieved. Compare the different cycle times of products made to define and can be combined in the process.

Step 3.9: implement jidoka

When operators have a domain of work, are allowed to stop the process when problems occur in the raw material, assembly or defects with the aim of not proceeding with off-specification production. The Japanese word "Jidoka" which means testing in the process. When the production process systems are installed Jidoka refers to the integrated quality assurance process. Its philosophy provides the optimal parameters of quality in the production process, the system compares Jidoka production process parameters against established standards and making the comparison, if the process parameters do not correspond to established standards the process stops, warning that there is an unstable situation in the production process, which must be corrected, this in order to avoid the mass production of parts for defective products, processes Jidoka are comparative systems of the "ideal" or "standard" against current results in production.

There are different types of systems Jidoka: vision, strength, length, weight, volume, etc. depending on the type of product or system design Jidoka to be implemented, as any system, information is fed as "ideal" or "standard should be the optimal product quality. Jidoka may refer to equipment that automatically stops under abnormal conditions, also used when a team member finds a problem with your workstation. Team members are responsible for correcting the problem - if they cannot fix it, they can stop the line. The aim of Jidoka can be summarized as:

- Ensure 100% quality time.
- Prevent unexpected failures of equipment.
- Effective use of labor.

Step 3.10: implementing fluid production

The processes are now working with Standard Work, Kanban, SMED, TPM, Jidoka, a single piece flow, several techniques have been applied to achieve a Lean Manufacturing System is implemented as fluid production.

Step 3.11: analyze results

Perform work together teams to analyze results and make necessary adjustments.

Step 3.12: establish kanban system

The Kanban system must already be in widespread use in the plant, formally established and do not allow deviations from the procedures. Use pull systems to avoid overproduction. Give your customers the production they want when they want it, and how much they want. Take material to the production line based on customer usage, is the basic principle of just-in-time. Minimize your work in the processing and storage of inventory, supplying small quantities of each product and replenishing often based on what the customer actually takes. Be sensitive to changes in day-to-day customer demand rather than relying on computer schedules and systems to track inventory unnecessary.

Step 3.13: establish integrated reviews, programming

The work of the entire plant should be interconnected by means of computer programs to create sync operations between departments. Use technology and processes only reliable, thoroughly tested that works for your staff. Use technology to support people, not to replace people. Often, the best thing is to develop a manual process before adding the technology to support the process. The new technology is often unreliable and difficult to standardize and, therefore, threatens the current. Actual tests before adopting new technologies in business processes, manufacturing systems, or products. Reject or modify technologies that conflicts with their culture, or could disturb the stability, reliability and predictability. However, encourage your staff to new technologies to consider when looking for new approaches to the job. Quickly implement fully the technology demonstrated in tests that can improve your processes flow.

Step 3.14: analyze results

Share experiences, analyze results and prepare reports according to the Master Plan.

Step 3.15: interface with material requirement planning (MRP II)

At this point there is control of the plant using lean manufacturing and analyzing the results obtained in each step of implementation is time to make the connection or interface with the System of Material Requirement.

Step 3.16: analyze results

Again the results are analyzed.

5. Steps in phase 4: integrate

Phase 4 , Integration may take 2 to 6 months and the objective of this phase is to establish permanent links between all areas and departments of the plant, as well as linkages with customers and suppliers. This phase consists of 17 steps.

Step 4.1: execution or performance of equipment

Here the teams that developed in the first three phases have combined efforts to integrate the entire plant in the Lean Manufacturing System.

Step 4.2: publish phase 3 activities throughout the plant

Since the beginning of phases 2 and 3 will be posted here all the activities undertaken during Phase 3.

Step 4.3: post lean value chain in the box

Formally publish all commitments have been fulfilled and what is the status of the organization by making a comparison with the initial evaluation, the results have been obtained, to what level is and how it is working.

Step 4.4: link between CIM and FMS

Establishing formal links between Computer Integrated Manufacturing (CIM), and Flexible Manufacturing System (FMS, Flexible Manufacturing System) in order to optimize the processes.

Step 4.5: educate and involve all employees

All employees should know the changes that have been implemented and how they work.

Step 4.6: internal integration

The process for separating the functions to use common technology and information, process information, without explanation, or duplicate functions, and allow different points of view work areas.

Step 4.7: analyze results

Analyze the results to this part of the implementation and make necessary adjustments.

Step 4.8: implement concurrent engineering

Here all the engineering departments will participate with their comments, ideas and commitments in the change that is taking place. Concurrent Engineering is the design methodology of a process or product that includes the simultaneous participation of Engineering, Operations, Accounting, Planning, Customers, Sales and other areas. The goal is to reduce the cycle time of introduction and design, and reduce or eliminate subsequent changes and quality problems involving multifunction devices.

Step 4.9: linking process engineering

All changes must be reflected in the Process Sheet and this department should be linked to the information system of the plant.

Step 4.10: analyze results

Doing analysis for translating the information obtained.

Step 4.11: start supplier development programmer

Since we have all the plant working on lean manufacturing, we also need all our suppliers to work with this system and the first step is to make an assessment, determine your condition and make a commitment.

Step 4.12: link to the supply chain

Go appending suppliers and subcontractors to the Supply Chain of the plant to establish more direct control over them.

Step 4.13: analyze results

Analyzing the results obtained.

Step 4.14: apply extended quality function

Apply Extended Quality Function (QFD, Quality Function Deployment) that will help us understand the requirements of our customers to implement a strategy that allows us to satisfy.

Step 4.15: link to clients

Establish the links that allow us to better communicate with our customers and be better informed on how we are delivering our products and know what we can do to meet your expectations.

Step 4.16: analyze results

Analyze the results.

Step 4.17: study the results and revise strategies

In this last step of phase 4, we need to analyze all the work done and what have been the results to make the necessary changes in the strategies.

6. Steps in phase 5: stand forever and forever

Last of Phases, Phase 5, Excel, is forever and forever, must be carried out throughout the life of the organization since it is continuous improvement. This phase consists of 12 steps.
Kaizen (Continuous Improvement) comes from two Japanese words "Kai" means change and "Zen" meaning improvement. So we can say that "Kaizen" means continuous improvement. The two pillars of Kaizen are the teams and Industrial Engineering, used to improve production processes. In fact, Kaizen focuses on people and process standardization. Its practice requires a team of production personnel, maintenance, quality, engineering, purchasing, and other employees that the team deems necessary. It aims to increase productivity by controlling the manufacturing process by reducing cycle times, standardized quality criteria, and methods of work operation.
In addition, continuous improvement also focuses on eliminating waste, identified as "dumb" (any movement, work or unnecessary inventory in the process), in any form. If a process produces defective items to be scrapped or reworked, labor, materials, time and movement are all wasted, but remember that not only wasted work that adds value to the product are waste operations that are necessary but do not add value to the product, and also useless in the process operations (walking and waiting times), operations that were carried out to produce a paper to be reworked or wasted. The Kaizen strategy begins and

ends with people. With continuous improvement, a direction to guide people to improve their ability to meet expectations of high quality, low cost, and delivery in time, continuously.

Kaizen works as a team and not individually to try to achieve the objectives. If we take the equation of world class in Figure 3.10, we see that this is immersed in an environment called Kaizen. Against the Western perception of Kaizen, which has reduced the whole concept of the simple syllogism of "continuous improvement" is actually more a philosophy than we need to return because of its importance for our purposes. The best writing on this subject is Dr. Masaaki Imai (1989), in his book, “Kaizen: The Japanese competitive advantage", rescues the basic principles of Kaizen:

- Innovation, the real secret of success lies not only in constant improvement; new solutions must be found to old problems. It is easy to cite examples of companies with which to hear their names immediately come to mind expectations of innovation. It is necessary to break with patterns and paradigms and inject large amounts of creativity to our normal lives if we really want to resume our way of doing things.
- Continuous improvement; it is also true that we all remember products or companies that were the great innovation and yet they have disappeared. A simple but representative example is the format and the domestic VCR Beta. Where are they now? How long they stayed on the market? Why did they disappear? Simply because they lacked continuous improvement.
- Process oriented; this is an interesting topic especially if we recall the total employee involvement and commitment that we want to cultivate it. When Kaizen says we should orient more to process the results, means that we must focus our systems to recognize and reward the effort and dedication rather than performance measures. Sadly not even have metric of the effort and much less for the results.
- Humility management; this is a difficult subject, given the excessive political dimensional imbalance. Within many organizations, the political dimension occupies an important than the sound foolishly or human. Let us ask again what it is the Japanese secret for success.
- Creativity; definitely creativity is the basis of innovation and continuous improvement. Policy development work, systems of suggestions and provision of resources, should focus on cultivating the creative thinking of employees. Rigid policies (cows are sacred to Tom Peters, 1988) and rigid systems dramatically hinder creativity in employees.

Step 5.1: Transformation of equipment

In this last phase, and the teams have gained an experience that has led from the formation, regulation of its function to performance or enforcement to genuine transformation.

Step 5.2: publish phase 4 activities throughout the plant

Publish all the activities of phase 4 on the ground. Any person should realize the changes and improvements that have taken place.

Step 5.3: break your paradigms

When it has been made of the existing control is necessary to consider new challenges and try to think about what you never thought to analyze things and getting away from the conventional view that there are ways of doing and thinking totally different paradigms break.

Step 5.4: new ideas for future improvement

Encourage all staff to contribute ideas to improve and create work teams to give them up to ideas.

Step 5.5: establish flexible manufacturing system (FMS)

Having a manufacturing system that allows the flexibility of the process, equipment, machinery, areas do not require staying in the same position, which are movable and can be restructured. The correct process will produce the correct results; create continuous process flow to bring problems to the surface (redesign work processes to achieve high value-added, continuous flow). Strive to reduce to zero the amount of time that any project needs to work instead of sitting idle and waiting for someone, work on it. Click to move material flow and information and to join the process and people together so that problems arise immediately.

Step 5.6: investing in research and development of new methods and technology

To be competitive will also be necessary to devote part of their profits to research and develop new methods and technology to improve products and processes.
Technology Analysis Group

- Assembly line, identify the stages of product assembly, determine the sequence assembly, determine the percentage of sales distribution based on cost and production volume, determine the requirements of the tools, cell manufacturing, sequence the process, material properties (size, type, shape of raw material).
- Phase analysis plan
- Identify the number of possibilities and combinations (Suggestions for improvement).
- Identify common as each product family.
- Vision Cell / Line
- Product flow, locate the production flow of a piece, locate the progressive sequence of construction of the product, the use of material inputs and should be first in first out, operator activity, create an environment that forges standardized methods, put the parts and tools in the correct order the sequence to follow (5S), minimize any activity that does not add value, flexibility, assemble: development of universal tool, Manufacturing: development of SMED / OTED (Single Minute Exchange Die) / (One Touch Exchange Die), Visual Factory, material in point of use / Kankan, production with zero defects, establish quality control source and poka yoke.

Step 5.7: computer integrated manufacturing system

Keep updated and linked all systems.

Step 5.8: operators specializing in automation

Operators are also encouraged to participate in all innovations. The introduction of automated equipment should have personnel with expertise in this type of equipment.

Step 5.9: exchange of experiences.

Always exchange experience helps them gain more knowledge and ideas that can be tested. Lessons learned from past deployments, Lean is not a magic formula, a robust and reliable guidance, short term benefits / immediate and methodology flexible/adaptable

Step 5.10: post results

Publish the results and make sure to publicize any changes to be implemented.

Step 5.11: books and publications productivity.

It is very important that progress be made known outside the plant through leaflets, newspapers, magazines, since it is a way to establish a commitment to Lean.

Step 5.12: celebrate success!

Conclude that it has reached this point is very important because all the people who worked for months or years will feel the satisfaction of having reached a goal that not only crossed a road, but they achieved what they set out from the Master Plan and can continue working on continuous improvement.

7. Important organizational and technical factors for a successful implementation

Below are the most important organizational factors to have a success lean manufacturing implementation:

a. **Training.** The training has other synonyms factor used in the industries that define this term, for example: training, education, cross training, etc. Training is one of the key organizational factors to successfully implement techniques LM.

b. **Employee involvement.** Any work unit cannot supply itself with all aspects needed for optimal operation. To be considered for the organization, department, work area as part of a system, it must consider all members of the same as a unit or a whole. Typically, the organization is divided into three levels of work, which are: managerial, administrative and operational. A cornerstone for the successful implementation of LM is the total involvement of both the production floor personnel, as senior executives. So that it is effective, staff must share the vision and be properly trained in its grounds LM. The involvement of employees is the most important human factor for the category, in most cases refers to the level operator, but in some others, supervisors and department managers. (Wemmerlov & Johnson, 1997), argue that this factor is necessary for the planning and implementation techniques LM.

c. **Teamwork**. Increasingly, companies encourage teamwork training (quality circles, teams consisting of product development, etc.). A task force is a self-directed team that organizes people in a way, be responsible for a certain performance or area. The team takes on many of the responsibilities previously assumed by other people and gives emphasis to the start of the delegation of authority, which is another organizational factor is explained below.

d. **Empowerment**. The English word "empowerment" means strengthening or empowerment, is the fact to delegate power and authority to employees and give them the feeling that they are masters of their own work. The delegation of authority leads to entrust the job to the right person to take you out and to make decisions. It is important that the company delegated authority to its workforce and let them know their limits of authority. To be autonomous, it is important that the workforce possesses various skills, such as the ability of diagnostic, analytical skills, decision making skills, etc. One feature of empowerment is that the maximum benefits from information technology are achieved.

e. **Compensation system**. Systems of compensation, reward or recognition develop pride and self-esteem and workers are vital to achieve the goals of the company. People with authority are an inherent sense of pride in their achievements and contributions to the company. Recognition systems, both psychological and concrete can increase these feelings. Often these systems in an environment of LM should be more oriented teams in their recognition of job performance and specific achievements. In a case study, communication and rewards were affected by lack of mutual respect and trust and thus impeded the progress of the organization during the design and implementation of techniques for LM, and (Steud Yauch, 2002). Various compensation systems such as point systems, systems for production, systems and product quality, etc. The application of them is in accordance with the needs and objectives that the company has.

f. **Management support.** The factor "management support" is an important pillar in the design, development and continuity of the LM techniques. When making a plan to implement the ME in a company, it is necessary that the conception of the idea is approved and encouraged by the highest levels of the company. The origin of the idea of applying the ME, not necessarily arise from the strategic plans of the company, but it must be incorporated into them if they are to implement a change of this magnitude. The facts that simply approve the implementation of the ME without taking the real involvement, participation and support both physically and financially, has a tendency to lead to unsuccessful implementation of the LM. The support and management support with planning and developing a strategic direction of a program I offer reliability and continuity to all employees involved in this deployment.

g. **Communication**. Communication within any organization is essential for good performance and system feedback. If you do not have a clear dissemination of information, it is possible that the changes do not reach all areas involved in the organization or even the plans of activities are covered, as well as the improvements are not approved by all involved. Communication systems play an important role as they should be effective.

h. Resistance to change. He has performed in companies when there are significant changes in number of employees there is a denial, resistance and/or non-acceptance of change to be implemented. It is necessary when performing the program and implementation plan of the LM in the training factor, deepened the concept of advantages and disadvantages of this tool, and so that the employees involved seeing that change being made is for the benefit company and all employees. It is necessary to consider that if a company worked a long time under a production system and now want to switch to another system, there is resistance to this change. It is very common to hear "we've always done it", "so we're fine," "that does not apply in this company", etc. One of the reasons for employee resistance is personal, involving a desire for change, for example, motivation, custom operating systems already defined and training. Another common reason is the culture of the organization, since this is the one that guides the conduct of workers and there may be some fear of not complying with the activities of radical changes in the way I do things in certain transactions, fear that their position is affected (downsizing).

The objective of this manuscript is on technical factors affecting the successful implementation of the LM techniques in order to make a recommendation for a better method of application. The results of this investigation following the meta-analytic methodology identified the following technical factors impacting the successful implementation of the LM techniques:

a. Planning and Analysis / Documentation and Program / Plan Implementation,
b. Methodology for the implementation of techniques,
c. Reducing the time of model change,

d. Distribution of Manufacturing Cells,
e. Using Technology,
f. Evaluation and monitoring,
g. Clear and precise objectives,
h. Adequate systems for measuring and monitoring the implementation,
i. Sustainability.

Each of these significant factors, linked with a percentage improvement in the place where I applied the techniques to determine the success of the technique.

We can conclude that it is very difficult for companies wishing to implement any of these techniques, what organizational factors should be considered for successful implementation, because there are a lot of them, this research has discovered and provided what organizational factors are needed for successful implementation. Based on the information given in the previous chapter, we present the model we recommend for the implementation of Lean Manufacturing and explain how the model was validated.

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3

Quality Function Deployment in Continuous Improvement

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1. Introduction

Six Sigma is a customer focused continuous improvement strategy and discipline that minimizes defects. It is a philosophy to promote excellence in all business processes with aggressive target goals. Six Sigma is a five phase methodology for continuous improvement which uses a metric based on standard deviation. It is also a statistic which describes the amount of variation in a process. Six Sigma is focused on customer satisfaction and cost reduction by reducing variation in processes.

At the core of the method, Six Sigma utilizes a discipline that strives to minimize defects and variation of critical variables towards an achievement of 3.4 defects per million opportunities in product design, production, and administrative processes. Customer satisfaction and cost reduction can be realized by reducing variation in processes that produce products and services which they use. While focused on reducing variation, the Six Sigma methodology uses a well-defined problem solving approach with the application of statistical tools. The methodology uses five phases including Define-Measure-Analyze-Improve-Control (DMAIC). The purpose of the five phases are to define the problem, measure the process performance, analyze the process for root causes, improve the process by eliminating or reducing root causes, and control the improved process to hold the gains.

The goals of Six Sigma include developing a world-class culture, developing leaders, and supporting long-range objectives. There are numerous benefits of Six Sigma including a stronger knowledge of products and processes, a reduction in defects, an increased customer satisfaction level that generates business growth and improves profitability, an increased communication and teamwork, and a common set of tools. Six Sigma is commonly credited to Bill Smith, an engineer at Motorola, who coined the term in 1984. The concept was originally developed as a safety margin of fifty percent in design for product performance specifications. This safety margin was equivalent to a Six Sigma level of capability. Since it's first introduction, Six Sigma has continued to evolve over time and has been adopted throughout the world as a standard business practice.

In order to achieve Six Sigma, an organization must understand the customer's wants and needs, also known as the voice of the customer (VOC). The voice of the customer is defined as the identification, structuring, and prioritization of customer needs. Within the Six Sigma DMAIC methodology, gathering the voice of the customer falls within the define phase. This enables the team to fully understand the customer's expectations at the beginning of the project. Prior to initiating any project or process improvement initiative, the organization or team must determine how the customer defines quality. The customer is typically surveyed or interviewed (among other techniques) to determine their expectations and these are then analyzed using quality function deployment (QFD). A critical aspect of a QFD analysis is gathering the voice of the customer to assess how a product or service measures against what the customer wants or expects.

Customers continually want more reliable, durable products and services in a timely manner. In order to remain competitive, all organizations must become more responsive to customers, strive for Six Sigma capability, and operate at world class level.

Quality function deployment has been widely used to capture the voice of the customer and translate it into technical requirements in the development of products and services. It is a link between product or service development and technical specifications to achieve customer satisfaction. Applications of QFD range from product development, service development, and product re-projecting (Miguel & Carnevalli, 2008).

QFD was developed by Yogi Akao in 1966 and was initially introduced in Japan in the late 1960s and early 1970s. QFD was first implemented in Mitsubishi's Kobe shipyard in 1972. Following QFD's introduction in Japan, it was then implemented primarily in manufacturing settings in the United States. Since then, it has been successfully used in many industries and various functional areas, including product development, quality management, customer needs analysis, product design, planning, engineering decision making, management, teamwork, timing, costing and other areas (Chan and Wu, 2002).

Assessing customer requirements is a complex task. Traditional approaches have focused on present customer needs; however, Wu, Liao, and Wang (2005) have concluded that, since customer needs are dynamic and may vary drastically over time, analyzing future customer needs is critical to an organization's long-term competitiveness. Customer needs may vary depending on various factors, the most important and complex of which is human nature. Other factors may include cultural setting, work environment, age, sex, etc. The most common way to determine customer requirements is through direct customer interaction, but surveyors must consider what a customer means rather than what he or she says.

Quality function deployment is a systematic process to integrate customer requirements into every aspect of the design and delivery of products and services. Understanding the customers wants or needs from a product or service is crucial to the successful design and development of new products and services. QFD is a system that utilizes customer demands to meet client missions by outlining what the customer wants in a service or product. QFD involves the construction of one or more matrices, called quality tables, which ensure customer satisfaction and improved quality services at every level of the service and product development process. QFD is a planning process that translates customer needs into appropriate company requirements at each stage, from research and product/service development to engineering, manufacturing, marketing/sales, and distribution.

It is crucial for any organization to understand their customers' requirements and service expectations as they represent implicit performance standards used by the customers in the assessment of service and product quality. A significant relationship between the relative quality, as perceived by the customers, and the organization's profitability has been shown.

The opportunities to apply QFD in service and business sectors are rapidly expanding. QFD has been used to enhance a wide range of service aspects in healthcare, chemical, and telecommunications industries as well as the typical product design applications. It is vital for companies to identify the exact needs of the customers and to measure their satisfaction toward a Six Sigma level to survive in the current competitive market. QFD focuses on designing in quality rather than inspecting in quality which reduces development times, lowers startup costs, and promotes the use of teams.

QFD maintains the integrity of the VOC and generates innovative strategies to achieve an organization's vision. In addition, it leads directly to policy deployment for implementation and performance management. Overall, QFD is a service planning and development tool, that facilitates service providers with an organized way to assure quality and customer satisfaction while maintaining a sustainable competitive advantage (Akao, 1990). QFD aims at enhanced customer satisfaction, organizational integration of expressed customer wants and needs, and higher profit levels (Griffin and Hauser, 1991).

QFD is a comprehensive quality system aimed specifically at satisfying the customer. It concentrates on maximizing customer satisfaction by seeking out both spoken and unspoken needs (Helper and Mazur, 2006). QFD displays the notation of customer orientation for designing products and services. Its purpose is to listen to the customer and translate their requirements back in any business process so that the end product or service will satisfy their needs and demands (Chan et al., 2006).

Since its introduction, QFD has been used in conjunction with various techniques such as the Kano model (Sauerwein, Bailom, Matzler, & Hinterhuber, 1996), SERVQUAL (Parasuraman, Zeithaml, & Berry, 1988), analytical hierarchy process (AHP), and maximum difference (MaxDiff), among others.

The mission of this chapter is to provide an overview of QFD, the various approaches, goals/purpose of QFD, a step-by-step procedure for performing QFD, and interpreting QFD.

2. Background

The opportunities to apply QFD in service and business sectors are rapidly expanding. QFD has been used to enhance a wide range of service aspects in healthcare, chemical, and telecommunications industries as well as the typical product design applications. It is vital for companies to identify the exact needs of the customers and to measure their satisfaction to survive in the current competitive market. QFD focuses on designing in quality rather than inspecting in quality which reduces development times, lowers startup costs, and promotes the use of teams (Fisher and Schutta, 2003).

Quality Function Deployment:

QFD is a planning process that translates customer needs into appropriate company requirements at each stage, from research and product/service development to engineering, manufacturing, marketing/sales, and distribution (Pawitra and Tan, 2003). The quality function deployment method was first originated in Japan and is used to select the design features of a product to satisfy the expressed needs and preferences of the customer as well as to prioritize those features and select the most important for special attention further down the design process (Fisher and Schutta, 2003). Maritan and Panizzolo (2009) proposed that when used in the strategic planning process, QFD maintains the integrity of the VOC and generates innovative strategies to achieve an organization's vision. They also argue that it leads directly to policy deployment for implementation and performance management. Overall, QFD is a service planning and development tool, that facilitates service providers with an organized way to assure quality and customer satisfaction while maintaining a sustainable competitive advantage (Akao, 1990). QFD aims at enhanced customer satisfaction, organizational integration of expressed customer wants and needs, and higher profit levels (Griffin, 1992).

QFD differs from traditional quality systems that aim to minimize negative quality such as poor service (Mazur, 1993). QFD provides an organized, systematic approach to bringing customer requirements into product and service design (Helper and Mazur, 2006). QFD focuses on delivering "value" by seeking out both spoken and unspoken customer requirements, translating them into actionable service features and communicating them throughout an organization (Mazur, 1993, 1997; Pun et al., 2000). It is driven by the voice of the customer and because of that, it helps service providers to address gaps between specific and holistic components of customer expectations and actual service experience. In addition, it helps managers to adopt a more customer-driven perspective, pointing out the differences between what managers visualize as customer expectations and the actual customer expectations. It provides a way to more objectively address subjective needs yet demonstrates the belief in customer focus and employee involvement for every party involved in the supply chain.

QFD is developed by a cross-functional team and provides an interdepartmental means of communication that creates a common quality focus across all functions/operations in an organization (Stuart and Tax, 1996). The unique approach of QFD is its ability to integrate customer demands with the technical aspects of a service. It helps the cross-functional team make the key tradeoffs between the customers' needs and the technical requirements so as to develop a service of high quality. Hence, QFD is not only a methodological tool but also a concept that provides a means of translating customer requirements in each stage of service development (Chan and Wu, 2002).

Voice of Customer (VOC):

A critical aspect of a QFD analysis is gathering the voice of the customer to assess how a product or service measures against what the customer wants or expects. The voice of the customer is defined as the identification, structuring, and prioritization of customer needs (Griffin and Hauser, 1991). Customer needs are measured in terms of consequences, which are determined by asking customers directly what they are looking for in a product or service. Then, the customer consequences are assessed and technical requirements are developed by knowledgeable professionals associated with the specific field of the product or service being assessed. The technical requirements are design dimensions that are specifically made to meet the customer consequences developed from the VOC. For example, if a customer consequence was better fuel economy (associated with a vehicle), perhaps a technical requirement would be the fuel type or weight of the vehicle that would directly be associated with the customer consequence.

The VOC is obtained primarily by two methods, namely through interviews or focus groups, which are then used to develop a survey questionnaire to distribute to potential and/or existing customers. Griffin and Hauser (1991) suggest that interviews with 20-30 customers should identify 90% or more of the customer needs in a relatively homogeneous customer segment. Multiple analysts (4-6) should review the transcripts of the focus groups to identify group synergies. Once the interviews and/or focus groups are conducted, an affinity diagram can be used to group the similarities in responses from the participants to develop a questionnaire that addresses all the topics important to the participant. The survey then asks the participant to rate an existing product or service on a scale of 1 to 5 on how well they view the product or service performs on each customer consequence. The participant is also asked to weight how important each customer consequence is to them for the product or service. A weighted rating can then be obtained by multiplying the rating and weight assigned to each customer consequence so that prioritization can be assessed. For example, a customer consequence could be discovered to be very important to a participant, but they view the product or service as performing poorly. This consequence would have priority to address over a consequence that the participant viewed as having a high rating on performance yet it was not seen as important.

The next discussion refers to the House of Quality, which is the tool used for organizing the customer consequences and subsequent technical requirements developed to address those consequences.

House of Quality (HOQ):

Olewnik and Lewis (2008) report that the HOQ is a design tool that supports information processing and decision making in the engineering design process. They note that for companies just implementing QFD and the HOQ, there is undoubtedly an improvement in information structure, flow, and direction. Hauser and Clausing (1988) state that the principal benefit of the HOQ is increasing the quality focus of the organization. That is, the HOQ gets people within an organization thinking in the right direction and thinking together.

QFD uses a set of interrelated matrix diagrams. The first matrix is the HOQ, which converts the customer consequences into technical requirements that must be fulfilled throughout the supply chain. The starting point on the left of the house is the identification of basic customer consequences. The next step is the definition of the priority levels that customers assign to these needs. These priorities are translated into numeric values that indicate relative importance, as discussed earlier. Customer ratings, shown on the right side of the house, enable benchmarking with competitors' services. The section just below the roof states the technical requirements used to meet the customer consequences. The relationship between the customer consequences and technical requirements constitutes the main body of the HOQ, called the relationship matrix. This matrix helps identify certain technical requirements that should be given priority if one addresses multiple customer consequences. The correlation matrix defines the relationships among technical requirements, which is represented by the roof of the HOQ. The bottom of the house evaluates the competition in terms of technical requirements in which the target values are defined by the researcher in this matrix (Tan and Pawitra, 2001). The construction of each of the sections in the HOQ is discussed in the following sections. Figure 1 depicts a standard HOQ.

The following section of this paper will outline a standard generic methodology for conducting a QFD analysis, which includes obtaining the VOC and translating it into meaningful data using an HOQ.

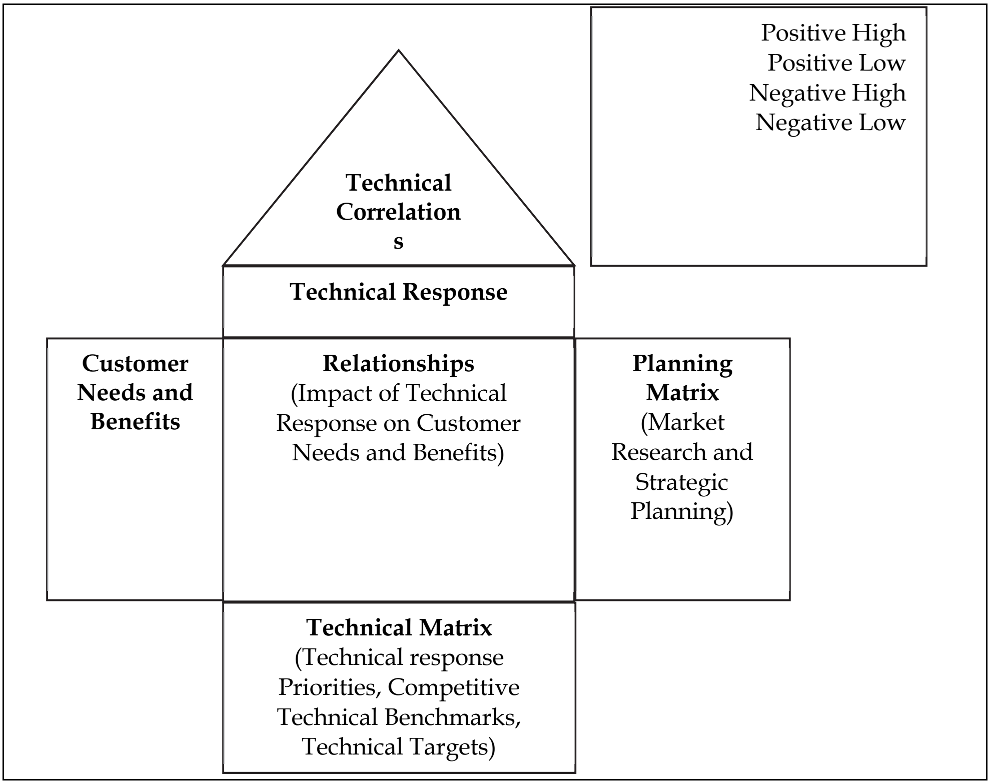


Fig. 1. HOQ Model (Cohen, 2007)

3. Methodology

QFD involves the construction of one or more matrices, called quality tables, which ensure customer satisfaction and improved quality services at every level of the service development process. The House of Quality, one of the most commonly used matrices in the QFD methodology, is a toolbox of decision matrices and the customer requirements and competitive benchmarks are utilized for decision-making (Andronikidis *et al.*, 2009).

The QFD methodology requires the development of a survey to understand the customer consequences for a product's or service's potential, current, or past customers regarding its functions to these demographics, and translates these consequences using quality function deployment into technical requirements to improve service offerings. The final deliverable of the methodology is an HOQ that is constructed by integrating customer consequences gathered via a survey, developing technical requirements to address each customer consequence, benchmarking competitors on similar design structures, and comparing the product or service to its competitors and prioritizing actions based on customer wants and competitors' successes and/or failures. The step-by-step process for the development of the HOQ is discussed in detail in the following sections.

Understanding Customer Choice Decisions: The Voice of the Customer

One of the essential strategies for successful functioning of any organization is delivering superior service or product quality to their customers. Understanding what exactly the customer's needs and wants (voice of the customer) are is a key criterion in total quality management (Griffin and Hauser, 1991). The first step towards understanding customer needs is to identify attributes and customer consequences. Attributes are defined as the physical or abstract characteristics of a service or product. They are objective, measurable, and reflect the provider's perspective. Consequences are a result of using attributes; basically, an end result in what a customer "gets" from using a service or product. Customers judge services and products based on their consequences, not their attributes. In other words, customers judge a service or product on its outcome, or affect of use on them. A service or product has many attributes, and each may have more than one consequence (Fisher and Schutta, 2003).

To gather the VOC, a cross-functional team must conduct focus groups or interviews with a select group of potential, existing, or past customers and ask them what is important to them in the service or product being offered. "Why" is asked numerous times until the respondent responds with the same answer each time. This is the fundamental customer consequence that the customer wants from using the service or product. These responses are grouped using an affinity diagram and used to develop a meaningful survey questionnaire that captures all things important to the customers. To ensure that the appropriate number of responses is gathered (90%), a standard sample size calculation can be performed.

Development of Customer Consequences

During the survey, the respondents are asked to evaluate the particular product or service provider on each customer consequence on a standard 5 point Likert scale. The respondent is also asked to weight each consequence on how important it is to them on a 5 point Likert scale. These ratings and weightings will be multiplied to derive a weighted rating to encompass both the performance rating and the importance for each consequence. With this information, the team can determine which of the consequences are the most important and also the worst in performance and assign priorities.

If respondents for other similar types of products or services are available, the same survey can gather data regarding customer consequences for those competitors. If respondents are not available, the team will use available data (i.e., website published information, annual reports, technical reports, financial statements) to determine which competitor being evaluated is "best" and assign it a value of "5". The team will also identify which competitor is "worst" at each consequence and sign them a value of "1". All competitors will be assigned a value relative to "best" and "worst" using team or industry expertise in the subject area. This information will be used to "benchmark" the product or service being directly evaluated by the team to see how they compare to similar competitors.

Development of Technical Requirements

After the customer consequences are analyzed, the next step in the construction of the HOQ is the development of the technical requirements. The technical requirements are the design specifications that satisfy customer consequences. These technical requirements are on the top of the HOQ and are referred to as the "how" of the HOQ. They describe "how" to meet the customer consequences and improve a product or service. The technical requirements must be within the control of the product or service provider and must be measurable (i.e.,

quantitative measurements, “yes/no”). Each customer consequence can have more than one technical requirement, and each technical requirement may fulfill the need of more than one customer consequence.
The development of technical requirements often requires expertise in the area regarding the service or product and requires creativity to develop. This area of the HOQ is the “thinking outside the box” aspect and there is no definite “right or wrong” answer. Any reasonable technical requirement should be considered. Often times ambiguous research and information collected from many sources (i.e., experts, websites, technical reports) may be used to spark brainstorming and creativity to develop technical requirements.

Relationship Matrix: The Body of the House of Quality

Once the customer consequences are developed, survey results are gathered, and the technical requirements are developed, a matrix to highlight relationships between the customer consequences and the technical requirements is constructed. This matrix is the “body” of the House of Quality. The matrix defines the correlations between the customer consequences and technical requirements as strong, moderate, or weak using a 9-3-1 scale. For this scale the following notations are used Strong (H) = 9, Moderate (M) = 3, and Weak (S) = 1. Each customer consequence is matched with any applicable technical requirement; make note that relationships should not be forced, leaving a blank if no relationship is determined. Here again, this assignment of relationships requires the expertise of the researchers or industry members. Normally only the strongest relationships are specified leaving approximately 60-70% of the matrix blank (Griffin and Hauser, 1991). Although some indicate that ideally in the QFD analysis, no more than 50% of the relationship matrix should be filled, and a random pattern should result (Fisher and Schutta, 2003). This matrix identifies the technical requirements that satisfy most customer consequences. The technical requirements that address the most customer consequences should be a main priority in the design process to ensure a product or service that satisfies the stated customer expectations.

Planning Matrix (Customer Competitive Analysis)

After the completion of the relationship matrix, the focus of the analysis shifts to the construction of the planning matrix. The planning matrix defines how each customer consequence has been addressed by the competition. It provides market data, facilitates strategic goal setting for the new product, and permits comparison of the customer desires and needs. It also compares the service to its key competitors. For the competitive analysis, research should be conducted regarding similar products or services. Researchers may have to assert a level of expertise in drawing meaningful information from the information available, as many competitors will not openly aid their competition by providing market data and design specifications. The researchers will use available data (i.e., website published information, annual reports, technical reports, financial statements) to determine which competitor being evaluated is “best” and assign it a value of “5”. The researchers will also identify which competitor is “worst” at each consequence and sign them a value of “1”. All competitors will be assigned a value relative to “best” and “worst” using researcher or industry expertise in the subject area. This information will be used to “benchmark” the product or service being directly evaluated by the researcher to see how they compare to similar competitors.

Technical Correlations

Following the completion of the relationship and planning matrices, the technical correlations are determined. These correlations are depicted in the roof of the HOQ. The roof maps the relationships and interdependencies among the technical requirements. The analysis of which informs the development process, revealing the existence and nature of service or product design bottlenecks. The relationships among technical requirements are plotted and given a value. Relationships among the technical requirements are important to evaluate, as one technical requirement could either aid or hinder the success of another crucial technical requirement in meeting customer consequences. Past experience and publicly available data (i.e., website information, technical reports, financial reports) can be used to complete the roof of the HOQ. Symbols are used to represent the strength of the relationship between the technical requirements and are assigned by the team.

Technical Matrix

The last step in the formation of the HOQ is the foundation or bottom of the house. This foundation is referred to as the technical matrix. This matrix depicts the values assigned by the team of the direction of improvement and/or standard values of each technical requirement needed to be competitive in the industry. Often times, if a numerical value cannot be absolutely determined, the team and/or industry experts use judgment based on expertise in the subject area to assign "targets." The direction of improvement indicates the type of action needed to ensure that the technical requirements are sufficient to make the product or service competitive for each entity evaluated. For example, if a technical requirement's target value is 5, and a product or service provider's mean for that requirement is 4, the direction of improvement would be up to aim for the higher target value.

Prioritizing Resource Allocations: The Importance/Performance Grid

The collected information from the above methods enables the development of strategic decisions, one of which is the allocation of resources. An importance-performance grid can be developed to prioritize the usage of resources to improve the most critical customer benefits. The mean importance ratings (gathered from the survey) can be plotted on the vertical axis (importance) and the mean customer competitive ratings (gathered from the survey) on the horizontal axis (performance). Using the importance rating values, the mean importance rating (for all consequences) should be calculated. The consequences with an importance rating higher than that of the mean importance rating should be placed above the horizontal line and those lower should be placed below this line. After these values are plotted, the focus can shift to the distribution of consequences on either the left or right side of the vertical line. For this purpose, the mean performance rating is used and labeled for the vertical axis. Each consequence with a lower mean should be plotted to the left of the axis, and each consequence with a performance mean higher than the mean should be plotted to the right of the vertical axis. Using this grid, the level of priority can be assigned to each consequence from the customer's point of view, and subsequently resource allocation decisions can be influenced.

4. QFD tools

There are two main tools utilized in quality function deployment: the Kano model and SERVQUAL. This section describes each of these tools in detail.

The Kano model is a theory of customer satisfaction developed in the 1980s by Noriaki Kano (Kano et al., 1984). During interviews and focus groups, it can be difficult to elicit from customers clear expressions of the consequences that are important to them. Attributes are the physical or abstract characteristics of the product or service where as consequences are the results of using the service. Sometimes customers are not even aware of important consequences (Fisher and Schutta, 2003).

The Kano model is a theory of product development and customer satisfaction. Kano et al. (1984) distinguish three types of product or service requirements that influence customer satisfaction in various ways: ‘‘must be,’’ ‘‘one-dimensional,’’ and ‘‘attractive’’ quality requirements. Must be requirements can be defined as the basic attributes of quality in terms of customer satisfaction. In other words, they are a necessary but insufficient condition for customer satisfaction (Busacca and Padula, 2005).

One-dimensional requirements are related to product or service performance; they create customer satisfaction when present and dissatisfaction when absent (Redfern and Davey, 2003). The higher the perceived product or service quality, the higher the customer’s satisfaction and vice versa. One-dimensional requirements are both a necessary and sufficient condition for customer satisfaction (Busacca and Padula, 2005).

Attractive requirements can be defined as the product or service attributes that satisfy or even excite customers when present but do not dissatisfy when absent (Berger et al., 1993). Such attributes have the greatest influence on customer satisfaction with a given service (Matzler et al., 1996). They are a sufficient, but unnecessary condition for satisfaction (Busacca and Padula, 2005). Attractive attributes can be used as an element of an aggressive marketing strategy to attract competitors’ customers. QFD normally deals with satisfiers not delighters.

Zhao and Dholakia (2009) have reported that although one-dimensional (i.e., linear) relationships are common, other relationships between attribute-level performance and customer satisfaction also exist that change dynamically over time and with user experience. Figure 2 illustrates the three different consequences and indicates the extent to which they can affect customer satisfaction.

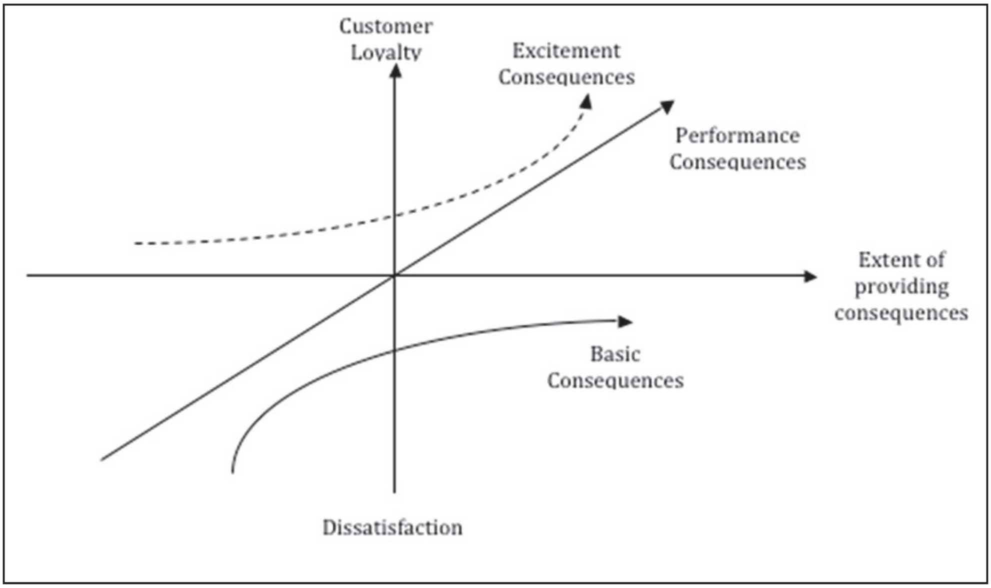


Fig. 2. Kano Model

Berry, Parasuraman, and Zeithaml developed SERVQUAL in 1988. It is a service quality tool based on the customer's perceptions of and expected performance. It is one of the most widely used models for the evolution of service quality (Pawitra & Tan, 2003). Initially, Parasuraman et al. (1985) proposed ten service quality attributes: reliability, responsiveness, competence, access, courtesy, communication, credibility, security, understanding/knowing the customer, and tangibles. However, in the early 1990s, these were condensed into five. The five dimensions of service quality, commonly known as RATER, include (Lim, Tang, & Jackson, 2003):

1. Reliability - ability to perform the promised service dependably and accurately.
2. Assurance - knowledge and courtesy of staff and their ability to convey trust and confidence.
3. Tangibles - physical facilities, equipment, and appearance of staff.
4. Empathy - caring, individualized attention provided to its customers.
5. Responsiveness - willingness to help customers and provide prompt service.

With the help of SERVQUAL, customer satisfaction can be measured in terms of the difference, or gap, between the expected and perceived level of performance. This approach can be applied to any service organization to evaluate the standards of quality for the services provided. "Services are different from goods in many ways: they are intangible, require participation of the customer, simultaneous production and consumption" (Oliveira et al., 2009).

Research conducted by Baki et al. (2008) concluded that the integration of SERVQUAL, the Kano model, and QFD could serve as an effective tool in assessing quality of services provided by an organization. The linearity assumption in SERVQUAL can be eliminated by integrating SERVQUAL with the Kano model and QFD to develop a way to satisfy customer needs, thus leading to increased customer satisfaction and higher profits.

SERVQUAL is a reliable and valid scale used to measure the perceived and expected levels of performance in any service organizations and thus results in improved service offerings. SERVQUAL is most effective when administered periodically to monitor new trends in the service quality. By calculating the average of the differences between the scores on the questions that make up a given dimension, and by calculating an average across all dimensions, an organization's quality standards can be administered (Parasuraman et al., 1988).

SERVQUAL has also been used in the house of quality design process to evaluate customer satisfaction with an organization's services. It can be used to identify and analyze customer requirements and thus forms the first stage in the construction of an HOQ. As noted by Parasuraman et at. (1988), the SERVQUAL dimensions can be modified based on the requirements and needs of an organization to make them more relevant to the context in which they are used (Paryani et al., 2010).

The following sections present two case studies for the Kano model and SERVQUAL methodology.

5. Kano model case study

This case study integrates quality function deployment and the Kano model to examine the application of quality function deployment in the new product development process by using the production of a fuel efficient vehicle. An integrated team of marketers, design engineers, and business experts developed a House of Quality for the fuel efficient vehicle that provided an insight into the customer preferences to be concentrated on and the technical requirements that helped achieve desired results in the prototyping of a Hydrogen Fuel Cell Vehicle (HFCV).

The product that was being developed was a plug-in hybrid. The vehicle's power source consists of a battery and a hydrogen fuel cell. The first step in obtaining the VOC for this case study was to conduct interviews, which was used to derive a customer survey. The interviews were one-on-one conversations conducted with customers to determine their expectations from a vehicle. Only 30 interviews were conducted, as past research has shown that this captures 90% of customer consequences for the general customer base (Griffin and Hauser, 1991).

The interview questions included:

1. What do you look for in purchasing a vehicle?
2. What is your main need in a vehicle?
3. What is your main use for your car now?
4. What is important to you in your current vehicle?
5. What brands of vehicles are you currently familiar with?
6. What brands of environmentally friendly vehicles are you familiar with?
7. Of those vehicles, what do you know about them?
8. What is your opinion of environmentally friendly vehicles?
9. What would be your ideal environmentally friendly vehicle?
10. Name, Age, Occupation?

The purpose of the interview process was not to ask each customer all ten questions, but to promote the customer to talk. When the subject stopped talking, the next question would get the conversation flowing again. To elicit consequences from a customer, the interviewer used a probing technique repeatedly by asking "why" to determine the attributes responsible for making a specific feature appealing to them. Seventeen customer consequences were developed from the interview data.

Affinity Diagram

After the VOC had been gathered via the interview process, the collected data was organized using affinity diagrams. Affinity diagrams group the consequences gathered based on similarity to clarify customer input. The 17 consequences were grouped into six similar categories, and each category was given a title. The left side of the HOQ was completed with customer consequences and attributes. The affinity diagram is shown in Table 1.

Survey

The next step was to obtain the importance rating and rankings of each consequence from the customer base. A survey was conducted of 104 customers regarding the relative importance of the 17 consequences. The reason behind this was to avoid misinterpretation of the customer's overall attitude or satisfaction towards the product that could lead to poor prediction of the customer's purchase behavior. Customers do not place equal importance on all consequences. Three vehicles were chosen for this purpose including a Toyota Prius (Vehicle A), a BMW 335 advanced diesel (Vehicle B), and the HFCV (Vehicle C). In addition, the survey respondent's current car was used to allow comparison. The identities of the three vehicles were not disclosed to the survey respondents. A brief description of each vehicle was provided however, to allow them to make a nonbiased decision on ratings and rankings of each consequence, relative to each vehicle. Each respondent was asked to read the descriptions and provide rating and rankings for each vehicle.

Attributes	**Consequences**
Safety	The vehicle provides accurate safety warnings.
	The vehicle has high safety and standard ratings.
Efficiency	The vehicle gets good mileage.
	The vehicle is energy efficient.
	The vehicle has high horsepower.
Cost	The vehicle is affordable.
	The vehicle has an extensive warranty.
	The vehicle is a hybrid (i.e., it splits power between electric and gas).
Performance	The vehicle has towing capabilities.
	The vehicle does not compromise speed and handling.
	The vehicle can be driven for longer distances (>400 miles).
Comfort	The vehicle provides a comfortable ride.
	The vehicle has a quality audio system.
	The vehicle is climate controlled.
	The vehicle comfortably fits a sufficient number of people.
Eco-friendliness	The vehicle has low emissions.
	The vehicle is environmentally friendly.

Table 1. Affinity Diagram

The survey was conducted in two parts. First, the respondents were asked to identify the most important consequence to them and label it as "10". All other consequences were to be assigned a value (rank) between 1 and 10, relative to the consequence labelled as most important. Therefore, some consequences may be just as important as the first consequence assigned a value of "10", and they too would be assigned a value of "10." Consequences that were almost as important as the first consequence assigned a value of "10" may be assigned values of "9" or below, relative to how important the customer felt they were in relation to the first "10" consequence. The mean of the rankings was calculated for the results of each consequence that constituted the importance column in Table 2.

The second part of the survey involved rating each consequence as it applies to each of the four vehicles on a Likert scale from 1 to 5. The mean of the ratings was calculated for each consequence and noted in the rating column in Table 2. The weighted rating values were obtained by multiplication of the importance (rank) and rating together. The weighted rating is a means of obtaining an optimal solution by evaluating both what is important to a customer and how well the customer thinks each product is doing on what is important to them. This is also used as a means to evaluate resource allocations, as if the customer base feels that a company is lacking on a consequence that they deem very important, more focus can be applied to improving this, which may ultimately improve market share. Conversely, if a customer base feels that a product excels on consequences that are of no importance to them, resources can be directed away from these areas and applied to areas needing improvement. The survey's main purpose was to gather more specific information on potential customer desires and needs. The results of the survey are tabulated in Table 2.

			Vehicle A		Vehicle B		Vehicle C		Current Vehicle	
		Importa-nce	Rating	Wei-ghted Rating	Rating	Weighted Rating	Rating	Wei-ghted Rating	Rating	Wei-ghted Rating
1	This vehicle is climate controlled.	6.6	4.2	27.51	4.2	27.51	3.6	23.58	4.0	26.20
2	This vehicle has a quality audio system.	6.7	3.4	22.64	3.5	23.31	3.3	21.98	3.7	24.64
3	This vehicle provides a comfortab le ride.	7.5	3.3	24.65	3.9	29.13	3.6	26.89	3.7	27.64
4	This vehicle gets good gas mileage.	7.6	4.4	33.44	3.9	29.64	4.4	33.44	3.3	25.08
5	This vehicle has low emissions.	4.7	4.2	19.57	3.5	16.31	4.4	20.50	2.9	13.51
6	This vehicle has low emissions.	5.4	4.2	22.64	3.5	18.87	4.4	23.72	2.9	15.63
7	This vehicle is good for the enviro-nment.	5.1	4.1	20.87	3.6	18.32	4.3	21.89	2.8	14.25
8	This vehicle has a lot of horsepo-wer.	6.5	2.3	15.04	3.8	24.85	2.9	18.97	3.0	19.62
9	This vehicle has towing capabilities.	5.2	1.9	9.79	3.1	15.97	2.5	12.88	2.7	13.91

10	This vehicle does not compromise speed and handling.	7.1	2.9	20.51	3.4	24.42	2.9	20.58	3.5	24.78
11	This vehicle is affordable.	8.0	3.7	29.77	2.5	19.87	2.3	18.03	3.7	29.77
12	This vehicle has an extensive warranty.	6.2	3.2	20.06	3.3	20.49	3.0	18.69	2.9	17.70
13	This vehicle can drive for long distances (>400 miles).	7.1	3.7	26.66	3.6	25.60	3.0	21.68	3.7	26.52
14	This vehicle has a high safety and standard rating.	7.0	3.8	26.63	3.8	26.56	3.7	25.65	3.5	24.12
15	This vehicle provides accurate safety warnings.	5.7	3.6	20.51	3.7	21.13	3.6	20.51	3.5	19.78
16	The vehicle is a hybrid (split powers between electric and gas).	3.2	3.6	11.70	2.1	6.74	3.8	12.21	1.7	5.44
17	This vehicle comfortably fits a family of all sizes.	4.7	2.4	10.95	3.7	17.06	3.3	15.56	2.8	13.23

18	Overall, I am satisfied with this type of vehicle.		3.2		3.6		3.4		3.9	
	Sum	104.07	62.15	362.93	62.74	365.77	62.39	356.76	58.16	341.82
	Average			3.49		3.51		3.43		3.28

Table 2. Importance Rating

Development of Technical Requirements

After the customer consequences were analyzed, the next step in the construction of the HOQ was the development of technical requirements. The technical requirements are the design specifications that satisfy customer needs. This aspect of QFD is directly in the organization's control, and focuses on designing specific, measurable design aspects that ensure the end product meets the customer wants and needs. The technical requirements are called the 'hows' and are placed on the top of the house. Each consequence can have one or more technical requirement. Technical requirements must be within the control of the manufacturer. It must also be measurable to enable designers to determine if the customer's needs are fulfilled. Brainstorming among marketers and product designers was used to develop the technical requirements, along with various Internet sources for references to industry standards. Thirty technical requirements were developed and organized using tree diagrams. One of the seven management tools, the tree diagram is a hierarchical structure of ideas built from the top down using a logic and analytical thought process.

A customer design matrix log was then developed that created a product development log that provided a history of the design process. It contained the design concepts derived from the customer's voice and the corresponding technical requirements that were designed, their measurement units and values. The column 'Measurement units' in Table 3 was placed at the bottom of the HOQ indicating how each technical requirement would be measured. Table 3 shows the customer design matrix log.

Relationship Matrix

Once the customer consequences and the technical requirements were developed, a relationship matrix was constructed. The matrix defines the correlations between customer attributes and technical attributes as weak, moderate, or strong using a standard 9-3-1 scale. For this scale the following notations are used Strong (H) = 9, Moderate (M) = 3, and Weak (S) = 1.

Each customer consequence was matched with each technical requirement. The relationship between them was then determined and placed in the relationship matrix that constitutes the of the HOQ. This matrix identifies the technical requirements that satisfy most customer consequences and determines the appropriate investment of resources for each. The technical requirements that addressed the most customer consequences should be dealt into the design process to ensure a customer-approved product. Ideally in the QFD analysis, no more than 50% of the relationship matrix should be filled, and a random pattern should result (Fisher and Schutta, 2003). Relationships were determined here on the basis of research conducted using resources available on the Internet. Appendix A displays the relationship matrix developed for the HOQ.

No	Customer's Voice	Technical Requirements	Measurement	Measurement Units
1	Climate control	Level of temperature change	Boolean Value	Yes/No
		Time taken to attain the changed temperature	Time	Minutes/Seconds
2	Audio System	Power of speakers	Power	Watts
		No. of operability modes in an audio system	Number	Integer value
3	Comfort	Seating Capacity	Capacity	Integer value
		Distance between front and rear seat	Length	Inches
4	Fuel Efficiency	Engine Power	Power	Horsepower
		Air compression ration	Volume	Cubic cms (cc)
		Size of exhaust pipes	Diameter	Inches
5	Environmental friendly	Lower Emissions (Nitrogen, Carbon-dioxide, Carbon-monoxide)	Weight/Distance	Grams/Km
		Hybrid	Boolean Value	Yes/No
6	Safety	Size of side & rear view mirror	Ratio	Ratio
		Size of damping sheets		
		Suspension/steering stability	Spring frequency	Cycles/minute (cpm)
		No. of airbags	Number	Integer value
		Air bag response time	Time	Seconds
		Alignment of tires	Toe-in (Distance)	Fractions of an inch
		Crash warning system	Boolean Value	Yes/No
7	Long distance travel	Tank capacity	Capacity	Gallons
		Tire quality	UTQG standards	Grades
8	Warranty	No. of parts covered under warranty	Number	Integer value
		Validity of warranty	Time	Years
		Cost of extended warranty	Boolean Value	Yes/No
9	Performance	Torque transmission	Force	Foot-pounds
		Cylinder size	Volume	Liters
		No. of valves/cylinder	Number	Integer value
		Weight of engine	Weight	Grams

Table 3. Customer Design Matrix

Planning Matrix (Customer Competitive Analysis)

After completion of the relationship matrix, the focus of the project shifted to the construction of the planning matrix. This matrix defines how each customer consequence has been addressed by the competition. It provides market data, facilitates strategic goal setting for the new product, and permits prioritization of the customer desires and needs. It also compares the product to its key competitors. A standard 5-point Likert scale was used. Each vehicle was represented by different symbol. A square symbol was used for the Toyota Prius, a circle for the BMW 335d, and a triangle for the HFCV. The ratings were based from the customer survey. Customers rated the three vehicles for each of the 17 customer consequences included in the planning matrix. Appendix A shows the planning matrix in the HOQ.

Technical Correlations

Following completion of the planning matrix, technical correlations were determined. These form the roof of the HOQ. The roof maps the relationships and interdependencies among the technical requirements. The analysis of which informs the development process, revealing the existence and nature of design bottlenecks. The relationships among technical requirements were plotted and given a value. Past experience and test data were used to complete the roof of the HOQ. Symbols are used to represent the level of the relationship between technical requirements. Appendix A shows the completed roof of the HOQ, with all relationships identified between the technical requirements.

Technical Matrix

Next, a technical matrix was constructed to form the foundation of the HOQ. This matrix addresses the direction of improvement, standard values, units of measurement, the relative importance of technical requirements, and technical evaluation.

The customer design provides information regarding consequences, technical requirements, and their units and values. It contains design concepts derived from the VOC and detailed design considerations. The column 'Measurement Units' from Table 3 was placed at the bottom of the HOQ, indicating the units of measurement for each technical requirement.

The relative importance of each technical requirement was calculated by multiplying the value assigned to its relationship with a specific consequence (9, 3, 1) multiplied by the importance of that consequence; the values of all consequences were then added to yield the final weight. These weights were placed in a row at the bottom of the HOQ. A final weight is a comprehensive measure that indicates the degree to which the specific technical requirement relates to the customer consequences.

The technical evaluation of the competition and the product to be developed is carried out by the engineering and technical staff who would design the product. The process establishes strategic goals for the product development process to ensure the satisfaction of the customer. For each technical requirement, the product was compared to its competitors and a technical evaluation was performed. Thus, the construction of the HOQ was completed. Appendix A shows the completed HOQ with the roof.

Prioritizing Resource Allocations

The collected information from the above methods helped in the development of strategic decisions, one of them being the allocation of resources. An importance-performance grid was developed to prioritize the usage of resources for improvement on the most critical customer benefits. The relative importance ratings were plotted on the vertical axis (importance) and the median importance rating on the horizontal axis (performance). Using the values from the column 'Importance' from Table 2, the median importance rating was found out to be 6.5. Consequences with rating higher than that of the median importance rating were placed above the horizontal line and the others below the median. After this decision was made, the focus shifted to the distribution of consequences on either the left or right side of the vertical line. For this purpose, the median was calculated for each consequence and if the mean brand rating was higher than that value it was placed on the right side of the vertical line otherwise on the left side. Using this grid, the level of priority was assigned to each consequence from the customers point of view. Figure 3 shows the Importance-Performance grid for Vehicle C (HFCV).

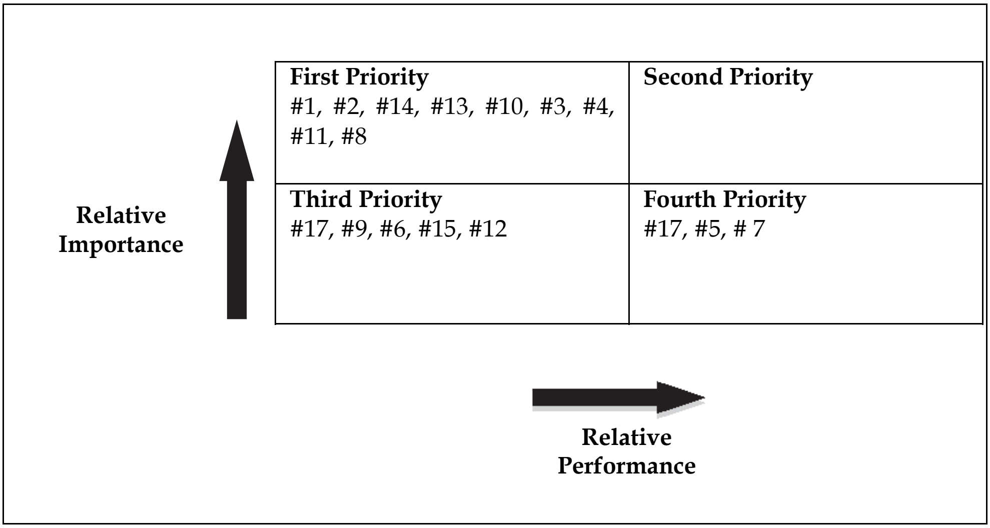


Fig. 3. Importance-Performance Grid

Recommendations and Conclusions

This study has illustrated how QFD can successfully be applied to new product development efforts via the application to the prototyping of a fuel-efficient vehicle. This study was deemed a success, as the results were reasonable per the design team that is currently in progress prototyping the product. For this particular application, the results showed that the first and utmost priority should be given to the following customer benefits/consequences: climate control, quality audio control, high safety and standard rating, long distance travel, high speed and handling, comfortable ride, good gas mileage, substantial horsepower, and affordability. These benefits are ones that must be accomplished in order to appeal to the customers in the market, and thereby give the new product a chance for success as a sellable product. The consequences were identified as priority because they are of high importance to the customer, but have poor performance according to the prototype description given to the respondent group in the study. These are the areas of design that must be addressed so as to create a product that appeals to the consumer. If resources are limited, consideration should be given to shifting resources to these priorities in the design phase. Conversely, the fourth priority benefits include low emissions, environment-friendly, and power split between electric and gas. These benefits are performing well and not of high importance, so no improvement needs to be made with these benefits currently. In fact, resources can actually be shifted away from these aspects and reinvested elsewhere where the design needs improvement to meet customer expectations.

The results presented in this study aided the design team of the HFCV and provided them with an insight into what customers were really looking for in an environmentally friendly vehicle. The application of QFD to the prototyping of a HFCV proved to be beneficial, as the voice of the customer was gathered, analyzed, and factored into the design process to ensure a product that will meet customer expectations.

It has been demonstrated that the QFD methodology can be successfully applied in a new product development process. It also aided the HFCV design team in developing a proprietary knowledge base about their customers' needs and wants which allowed them to make the best design efforts in the early development stages that lowered the development costs and increased profit levels. Although this study focused on the production of HFCV, the QFD methodology presented could serve as a powerful reference to the development of a new product of any kind. The authors hope that this study could attract more new product development teams and organizations to adopt QFD in the NPD process and develop better and successful products and achieve high customer satisfaction with increased profit levels.

6. SERVQUAL case study

This case study integrates quality function deployment and SERVQUAL to evaluate a university career opportunities center (COC) and recommends service standards to increase its benefits to students. A university COC seeks to bridge the gap between students and employers. It equips students with the professional skills they need to find employment. The staff keeps the students regularly informed about various events such as the career fair, and it can help them make major career decisions. A COC should maintain high standards of quality and serve students efficiently. To do so, its staff must understand student needs and constantly monitor feedback to improve their performance.

The mentioned methodology has been applied to a COC at a university. Detailed steps are listed for the construction of the HOQ, with SERVQUAL being incorporated into QFD in this application. A step-by-step procedure for this case is discussed in this section.

SERVQUAL dimensions for a COC

The main goal of applying QFD to a university COC was to identify how the COC could better serve students. This work sought to identify expectations of the students and the measures necessary to meet them. Here, SERVQUAL was applied to identify the key customer needs and requirements. Table 4 presents the SERVQUAL dimensions and their definitions as they relate to their application to the COC case study.

To make the dimensions more relevant to a COC, a few SERVQUAL items were modified or removed based on the responses obtained through student interviews. A total of 15 customer requirements were identified. Table 5 provides the modified SERVQUAL dimensions and customer requirements.

Dimensions	Description
Reliability	The ability of the COC staff to deliver the promised services dependably and precisely.
Assurance	Knowledge and courtesy of the COC staff and their ability to communicate trust and confidence in the students.
Tangibles	Physical aspects of the COC including the appearance of personnel and communication services.
Empathy	Ability to provide individualized attention and care by the COC staff to the students.
Responsiveness	Willingness of the COC staff to serve the students and provide them with prompt services.

Table 4. SERVQUAL: Five Dimensions

Dimensions	Customer Requirements
Empathy	I get a job that fits me
	I have a job that I enjoy
	I know what different jobs are available
	I can work overseas
Reliability	I get job offers
	I get a job that pays well
	I get opportunities with potential employers
	I have my resume easily accessible to companies
Assurance	I stand out to a potential employer
	I am prepared for an interview
	I am comfortable during an interview
Responsiveness	I have interviewing experience
	I get a resume evaluation
Tangibles	I have a professional resume
	I have a professional appearance for an interview

Table 5. SERVQUAL Adjusted Items Description

These SERVQUAL items are the customer consequences that were obtained by conducting interviews with 30 students. The intention behind interviewing these students was to keep the conversation flowing. To elicit the consequences from a customer, the interviewer used a probing technique repeatedly by asking "why" to determine the reason responsible for making a specific aspect appealing to them. When the student stopped talking, the next question would get the conversation flowing again.

Survey conducted for a COC

A survey of 99 students was the primary source of information for this study. The survey asked the students to express their thoughts on various aspects of the COC and to indicate what changes would increase their satisfaction. Customers do not assign equal importance to all requirements. The survey was administered in two sections. First, the students were asked to identify the most important consequence, assigning to each a rank from 1 to 10, with 10 indicating the highest level of importance. The mean rank was calculated for each customer consequence. To determine the quality of COC services, respondents were also asked if they would recommend the service to other students. In the second part of the survey, students were asked to indicate the degree to which each of the consequences was true of an ideal COC and of the specific university COC on a scale from 1 to 5, where 5 indicated strongly agree and 1 indicated strongly disagree. The mean ratings were calculated for each consequence as shown in Table 6. The survey results obtained were analyzed using SERVQUAL by performing a gap analysis that is discussed in the following section. The questionnaire developed for this study is included in Appendix B.

Customer Requirements	Importance Ratings	Current COC Rating	Ideal COC Rating
I have a professional appearance for an interview	6.8	3.6	4.5
I am comfortable during an interview	7.3	3.5	4.6
I stand out to a potential employer	8.1	3.5	4.7
I am prepared for an interview	7.7	3.5	4.5
I have interviewing experience	6.9	3.5	4.5
I get opportunities with potential employers	7.7	3.5	4.6
I can work overseas	3	2.5	3.7
I know what different jobs are available	7.7	3.5	4.6
I have a professional résumé	7.7	3.6	4.6
I get a résumé evaluation	6.6	3.4	4.5
I have my résumé easily accessible to companies	7.5	3.7	4.6
I get a job that fits me	8.4	3.3	4.7
I get a job that pays well	7.8	3.5	4.6
I have a job that I enjoy	8.4	3.3	4.6
I get job offers	8.5	3.3	4.7

Table 6. Survey Results (Averages of all the ratings)

6.3 Prioritizing SERVQUAL dimensions for a COC

The five SERVQUAL dimensions: reliability, assurance, tangibles, empathy, and responsiveness were prioritized based on the gap score calculated for each dimension. There were four items under reliability, three under assurance, two under tangibles, four under empathy, and two under responsiveness for a COC. For each customer requirement, the perceived level (P) and expected level (E) of service were obtained from the survey data. The difference (gap score) between them was calculated, as was the average gap score for each of the five dimensions. The five RATER dimensions for a COC were prioritized based on the value of the average gap scores; i.e. the dimension with the highest average gap score was the one given the highest priority for improvement. Empathy had the highest average gap score (-1.25), making it the highest priority. The dimensions were prioritized in the following order starting with the highest priority: reliability (-1.12), responsiveness (-1.1), and assurance (-1.1), and tangibles (-0.95).

Based on the gap scores calculated for each customer requirement, the importance ratings obtained from the survey data, and the priority level of each SERVQUAL dimension, the customer requirements were prioritized. When two consequences have the same gap score, their mean importance ratings obtained from the survey results could be used to determine their priority level. The results showed that students identified the following requirements, listed in priority order from the highest to lowest:

1. I get a job that fits me
2. I have a job that I enjoy
3. I know what different jobs are available
4. I can work overseas
5. I get job offers
6. I get a job that pays well
7. I get opportunities with potential employers
8. I have my resume easily accessible to companies
9. I stand out to a potential employer
10. I am prepared for an interview
11. I am comfortable during an interview
12. I have interviewing experience
13. I get resume evaluation
14. I have a professional resume
15. I have a professional appearance for an interview

6.4 Development of service characteristics for a COC

After analyzing the survey results using SERVQUAL, the focus shifted to the development of service characteristics that are the design specifications that would satisfy customer needs. Each customer consequence can have one or more service characteristic. Various strategies were developed to reduce or eliminate low customer satisfaction and increase the quality of service. The service characteristics are called the how's. These characteristics appear on top of the HOQ and constitute the technical response matrix. They are the measurable steps to ensure that all customer requirements are met. The service characteristics defined in QFD are within the organization's direct control. These characteristics focus on specific, measurable aspects of service.

Brainstorming was used to develop the service characteristics using various Internet sources which provided references to industry standards. Tree diagrams were used to organize these service characteristics. Tree diagrams are hierarchical structures of ideas built from the top down using logic and analytical thought. A customer design matrix log was then developed to create a service process development log that provided a history of the development process. This log contained the design concepts derived from the VOC, along with the corresponding service characteristics and their values. Twenty service characteristics were developed which are listed in Appendix C.

Dimension	No.	Customer Requirements	Expectation Score (E)	Perception Score (P)	Gap Score (P-E)	Average for Dimension
Tangibles	1	I have a professional appearance for an interview	4.5	3.6	-0.9	-0.95
	2	I have a professional resume	4.6	3.6	-1.0	
Reliability	3	I get opportunities with potential employers	4.6	3.5	-1.1	-1.12
	4	I have my resume easily accessible to companies	4.6	3.7	-0.9	
	5	I get a job that pays well	4.6	3.5	-1.1	
	6	I get job offers	4.7	3.3	-1.4	
Responsiveness	7	I get a resume evaluation	4.5	3.4	-1.1	-1.1
	8	I have interviewing experience	4.6	3.5	-1.1	
Assurance	9	I am comfortable during an interview	4.6	3.5	-1.1	-1.1
	10	I stand out to a potential employer	4.7	3.5	-1.2	
	11	I am prepared for an interview	4.5	3.5	-1.0	
Empathy	12	I can work overseas	3.7	2.5	-1.2	-1.25

Table 7. Calculation of Unweighted SERVQUAL Scores

Dimensions	Priority Level	Customer Requirements	Gap Score	Importance Rating
Empathy	1	I get a job that fits me	-1.4	8.4
	2	I have a job that I enjoy	-1.3	8.4
	3	I know what different jobs are available	-1.1	7.2
	4	I can work overseas	-1.2	3
Reliability	5	I get job offers	-1.4	8.5
	6	I get a job that pays well	-1.1	7.8
	7	I get opportunities with potential employers	-1.1	7.7
	8	I have my resume easily accessible to companies	-0.9	7.5
Assurance	9	I stand out to a potential employer	-1.2	8.1
	10	I am prepared for an interview	-1.0	7.7
	11	I am comfortable during an interview	-1.1	7.3
Responsiveness	12	I have interviewing experience	-1.1	6.9
	13	I get a resume evaluation	-1.1	6.6
Tangibles	14	I have a professional resume	-1.0	7.7
	15	I have a professional appearance for an interview	-0.9	6.8

Table 8. Prioritizing Customer Requirements

6.5 Relationship matrix for a COC

Once the customer consequences and the service characteristics were developed, a relationship matrix was constructed. This matrix defines the correlations between customer attributes and technical attributes/service characteristics as strong, moderate, or weak using a 9-3-1 scale. For this scale the following notations are used: Strong (H) = 9, Moderate (M) = 3, and Weak (S) = 1. Each of the fifteen customer consequences was matched with each of the twenty service characteristics for a COC. The relationship between them was then determined and placed in the relationship matrix that constitutes the center of the HOQ. This matrix identifies the technical requirements that satisfy most customer consequences and determines the appropriate investment of resources for each. The technical requirements that addressed the most customer consequences should be addressed in the design process to ensure a product that satisfies the stated customer expectations. Ideally in the QFD analysis, no more than 50% of the relationship matrix should be filled, and a random pattern should result (Fisher and Schutta, 2003). Relationships were determined here on the basis of research conducted using resources available on the Internet. Appendix C displays the relationship matrix developed as a part of the HOQ for a COC.

6.6 Planning matrix (customer competitive analysis) for a COC

After completion of the relationship matrix, the focus of this study shifted to the construction of the planning matrix, which defines how each customer consequence has been addressed by the competition. This matrix provides market data, facilitates strategic goal setting for the new service, and permits prioritization of customer desires and needs. In this methodology, where we incorporated SERVQUAL into the HOQ, the competitive analysis is done between the current COC and an ideal COC. For the competitive analysis, a survey was conducted to determine the characteristics of an ideal COC, and this ideal COC was compared to a university COC. The survey respondents judged the ideal COC and the current COC against each of the fifteen consequences on a scale of 1 to 5, where '5' indicated strongly agree and '1' indicated strongly disagree. The mean for each consequence was calculated and placed in the columns to the right of the HOQ. A triangle was used for the ideal COC, and a square was used for a university COC. Appendix C shows the planning matrix in the HOQ.

6.7 Technical correlations matrix for a COC

Next, the technical correlations were determined after the completion of the planning matrix. These form the roof of the HOQ. The roof maps the relationships and interdependencies among the service characteristics. The analysis of these characteristics informs the development process, revealing the existence and nature of service design bottlenecks for a COC. The relationships among service characteristics were plotted and given a value. Past experience and test data were used to complete the roof of the HOQ. Appendix C shows the correlations developed for the roof of the HOQ for a COC.

6.8 Technical matrix for a COC

A technical matrix was constructed to form the foundation of the HOQ. This matrix addresses the direction of improvement, target values, the final weights of service and quality characteristics, and the level of difficulty to reach the target values. The direction of improvement indicates the type of action needed to ensure that the service characteristics are sufficient to make the service competitive; this direction is typically indicated below the roof of the HOQ.

Dimension	No.	Customer Requirements	Service Requirements	Measuring Units	Values
Tangibles	1	I have a professional appearance for an interview	No. of workshops conducted on professionalism	Number	Integer value
			No. of formal outfits that could be rented	Number	Integer value
	2	I have a professional resume	No. of workshops conducted on resume and cover letter writing	Number	Integer value
Reliability	3	I get opportunities with potential employers	No. of career fairs held	Number	Integer value
			No. of companies participating in the career fairs	Number	Integer value
			Number of companies invited to hold seminars	Number	Integer value
			Number of alumni invited to be connected to the university	Percentage	Percentage
	4	I have my resume easily accessible to companies	Provide companies with online access to resumes of all students	Boolean value	Yes/No
	5	I get a job that pays well	Expected salary amount	Money	Dollars
	6	I get job offers	No. of interview calls received	Number	Integer value
Responsiveness	7	I get a resume evaluation	No. of staff members appointed for resume evaluation	Number	Integer value
			Waiting time to get an appointment for resume evaluation	Time	Days
	8	I have interviewing experience	No. of mock interviews conducted	Number	Integer value

Table 9. Customer Design Matrix

The quality and service characteristics were analyzed and a standard or limit value was determined for each. These are the industry standard values. These values were established based on well-informed assumptions, and they are believed to be within reach for a university COC. The final weight of each service characteristic was calculated by multiplying the value assigned to its relationship with a specific consequence (9, 3, 1) multiplied by the importance of that consequence (obtained from the survey results); the values of all consequences were then added to yield the final weight, that is a comprehensive measure that indicates the degree to which the specific service characteristic relates to the customer consequences. These final weights are shown in a row along the bottom of the HOQ.

The engineering and technical staff that would design the service process evaluates the level of difficulty involved in achieving each service characteristic. This evaluation becomes the basis for development of strategic goals for the development of the service process to ensure customer satisfaction. The level of difficulty involved in reaching the target values for each service characteristic was determined on a scale of 0 (easy) to 10 (difficult). Thus, the HOQ was completed for a COC; it is shown in Appendix C. Twenty service characteristics were developed that would fulfill customer requirements.

6.9 Results and discussion for a COC

With the help of QFD and SERVQUAL methodologies, the SERVQUAL dimensions, customer consequences/requirements and the service characteristics were prioritized. The priority order of the five RATER dimensions based on their gap scores were determined as: Empathy (-1.25) followed by reliability (-1.12), responsiveness (-1.1), and assurance (-1.1), and tangibles (-0.95). The overall gap score for the five dimensions was -1.1 indicating a scope for improvement for a COC. A few of the customer requirements that ranked higher than the others were: I get a job that fits me, I have a job that I enjoy, I know what different jobs are available, I can work overseas, I get a job that pays well, I get opportunities with potential employers, etc.

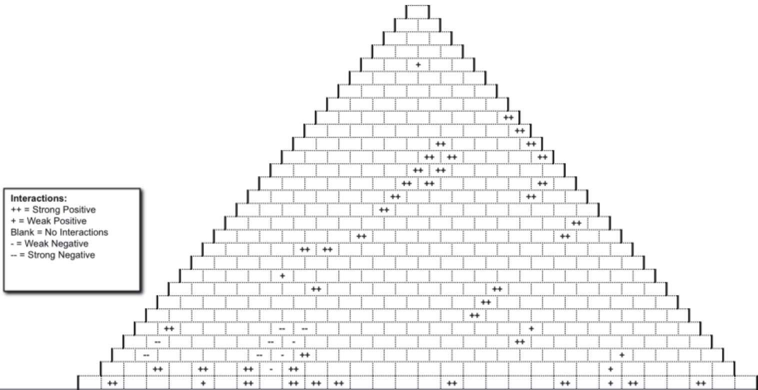
Establishing a team for career guidance and counseling team to provide students with individual attention and care would increase the performance of the COC. Hosting more career fairs with the participation of a large number of companies would provide students with more opportunities to interact with employers and to secure suitable jobs. Establishment of a resume evaluation team with sufficient staff would increase student confidence and help them face interviews. Conducting periodic workshops on writing resumes and cover letters, interviewing, business ethics, and professionalism would increase student knowledge and improve their professional skills. Conducting frequent mock interviews would equip students with practical experience that could help them to perform better in interviews.

The service characteristics were also prioritized that help the design team in development of better services and reduce the service development costs. The number of mock interviews conducted received the highest priority along with number of staff appointed for conducting mock interviews, followed by the number of staff members on the career guidance and counseling team, the number of interview calls received, the number of staff members appointed for resume evaluation, the number of workshops conducted on setting up, and accessing online job accounts. Also important were expected salary amount, employer access to online resumes, number of workshops on interviewing and business ethics, the number of international companies participating in the career fair, and the number of formal outfits that could be rented. A focus on implementing these service characteristics in order of their priority would improve the function of the COC.

Priority Level	Service Characteristics	Weight/Importance
1, 2	Number of mock interviews conducted	179.8
1, 2	Number of staff appointed for conducting mock interviews	179.8
3	Number of staff members in career guidance and counseling team	171.1
4	Number of interview calls received	157.4
5	Number of staff members appointed for resume evaluation	138.5
6, 7	Number of companies participating in the career fairs	133
6, 7	Number of career fairs held	133
8	Number of workshops conducted on resume and cover letter writing	85.4
9	Number of workshops conducted on professionalism	83.9
10	Number of companies invited to hold seminars	87.0
11	Waiting time to get an appointment for resume evaluation	75.3
12	Number of workshops conducted on setting up and accessing online job accounts for students	66
13	Expected salary amount	64.1
14	Provide companies with online access to resumes of all students	61.6
15	Number of job e-mail alerts sent	59.1
16	Number of workshops conducted on interviewing and business ethics	47.3
17	Number of alumni invited to be connected to university	35.8
18	Number of international companies participating in the career fairs	24.6
19	Number of etiquette dinners offered	22.2
20	Number of formal outfits that could be rented	18.6

Table 10. Prioritizing Service Characteristic

7. Appendix A – house of quality for HFCV case study



Relationships:
9 = Strong
3 = Moderate
1 = Weak
0 or Blank = No Relationship

	Importance Rating	Level of temperature change	Time taken to attain the changes in temperature level	Power of the speakers	# of operability modes in audio system	Seating capacity	Distance between front and rear seat	Engine power	Air compression ratio	Size of exhaust pipes	Nitrogen emissions	Carbon monoxide emissions	Carbon dioxide emissions	Size of side and rear view mirrors	Size of damping sheets	Suspension/steering stability	# of airbags	Airbag response time	Alignment of tires	Engine crash warning system	Tank capacity	Tire size	Tire quality	Transmission torque	Cylinder size	Weight of engine parts	# of valves per cylinder	Cost of extended warranty	# of parts covered under warranty	Validity of warranty	Hybrid
The vehicle provides accurate safety warnings	6.55																			9											
The vehicle has high safety and standard ratings	6.97													9		3	3	9	3	9											
The vehicle gets good gas mileage	7.60							9	1													9		9	3	1	9				9
The vehicle is energy efficient	5.39							9	9	3														9							9
The vehicle has high horsepower	6.54							9	9	9													1	3	9	9	9				
The vehicle is affordable	7.98					3																									9
The vehicle has an extensive warranty	6.21																											9	9	9	
The vehicle is hybrid (split power between gas and electric)	3.24										9	9	9																		9
The vehicle has towing capabilities	5.15							9	9															9							
The vehicle does not compromise speed and handling	7.12							9	3							9			9					9							
The vehicle can drive for long distances (>400 miles)	7.13							9	3	1											9		3								
The vehicle provides a comfortable ride	7.47	3	1			9	9								9	9															
The vehicle has a quality audio system	6.66			9	9																								3		
The vehicle is climate controlled	6.55	9	9																												
The vehicle comfortably fits a family of all sizes	4.66					9	9																								
The vehicle has low emissions	4.66	1						9		1	9	9	9																		9
The vehicle is environmentally friendly	5.09										9	9	9																		9
Raw score		86	66	60	60	133	109	392	204	87	117	117	117	63	67	152	21	63	85	122	64	68	28	247	82	66	127	56	76	56	306
Relative %		3%	2%	2%	2%	4%	3%	12%	6%	3%	4%	4%	4%	2%	2%	5%	1%	2%	3%	4%	2%	2%	1%	7%	2%	2%	4%	2%	2%	2%	9%
Importance Rank		2	1	1	1	2	2	5	3	2	2	2	2	1	1	2	1	1	2	2	1	2	1	3	2	1	2	1	2	1	4
Target Value/Specs		Yes/No	29.95 BTU/h/cu. Ft.	125 Watts	4	5	Yes/No	134 HP	13/1 Ratio	2.5 inches	gm/mile	gm/mile	gm/mile	2/30 Ratio	3 inches	1.49 Hz	6	60 miliseconds	0.03 inches	Yes/No	11.9 gallons	inches	1195/65R15 Grade	161 ft lbs	2.2 litres	Yes/No	4	Yes/No	Yes/No	4 years	Yes/No

8. Appendix B – survey questionnaire for COC case study

Part A – Questionnaire

Find the benefit of using the Career Opportunities Center in the list below that is most important to you. Assign it 10 points. Then, assign from 0 to 10 points to the other benefits to indicate how important they are to you in comparison to the most important one. You may assign the same number of points to more than one benefit.

_____ I have a professional appearance for an interview
_____ I am comfortable during an interview
_____ I stand out to a potential employer

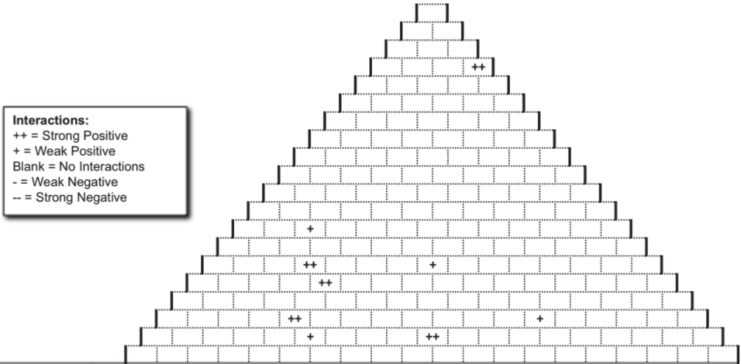
_____ I am prepared for an interview
_____ I have interviewing experience
_____ I get opportunities with potential employers
_____ I can work overseas
_____ I know what different jobs are available
_____ I have a professional résumé
_____ I get a résumé evaluation
_____ I have my résumé easily accessible to companies
_____ I get a job that fits me
_____ I get a job that pays well
_____ I have a job that I enjoy
_____ I get job offers

Part B - Questionnaire

Please rate how well the university's Career Opportunities Center delivers each of these benefits when you use it. Circle the number below that best indicates how well you feel the university's COC satisfies each of the benefits. For comparison purposes, please rate your ideal career center on the same benefits. Use a scale of:
1= Strongly Disagree
2= Disagree
3= Neutral
4= Agree
5= Strongly Agree

	COC	**Ideal COC**
I have a professional appearance for an interview	1 2 3 4 5	1 2 3 4 5
I am comfortable during an interview	1 2 3 4 5	1 2 3 4 5
I stand out to a potential employer	1 2 3 4 5	1 2 3 4 5
I am prepared for an interview	1 2 3 4 5	1 2 3 4 5
I have interviewing experience	1 2 3 4 5	1 2 3 4 5
I get opportunities with potential employers	1 2 3 4 5	1 2 3 4 5
I can work overseas	1 2 3 4 5	1 2 3 4 5
I know what different jobs are available	1 2 3 4 5	1 2 3 4 5
I have a professional résumé	1 2 3 4 5	1 2 3 4 5
I get a résumé evaluation	1 2 3 4 5	1 2 3 4 5
I have my résumé easily accessible to companies	1 2 3 4 5	1 2 3 4 5
I get a job that fits me	1 2 3 4 5	1 2 3 4 5
I get a job that pays well	1 2 3 4 5	1 2 3 4 5
I have a job that I enjoy	1 2 3 4 5	1 2 3 4 5
I get job offers	1 2 3 4 5	1 2 3 4 5
Would you recommend this service to your peers?	1 2 3 4 5	1 2 3 4 5

9. Appendix C - house of quality for COC case study



Relationships:
9 = Strong
3 = Moderate
1 = Weak
0 or Blank = No Relationship

	Importance Rating	# of workshops conducted on professionalism	# of formal outfits that could be rented	# of workshops conducted on resume & cover letter writing	# of mock interviews conducted	# of career fairs held	# of companies participating in the career fairs	Provide companies with online access to resumes of all students	Expected salary amount	# of interview calls received	# of staff members apointed for resume evaluation	Waiting time to get an appointment for resume evaluation	# of workshops conducted on interviewing and business ethics	# of international companies participating in the career fairs	# of workshops conducted on setting up and accessing online job accounts for students	# of staff members in career guidance and counseling team	# of companies invited to hold seminars	# of etiquette dinners offered	# of alumni invited to be connected to university	# of job email alerts sent	# of staff appointed for conducting mock interviews
I have a professional appearance	6.8	9	3										1								
I am comfortable during an interview	7.3				9								3								9
I stand out to a potential employer	8.1			3						9								3	3		
I am prepared for an interview	7.7	3			9						3		3								9
I have interviewing experience	6.9				9																9
I get opportunities with potential employers	7.7					9	9			3							3		1		
I can work overseas	3.0													9		1					
I know what different jobs are available	7.2														9		9		1	9	
I have a professional resume	7.7	1		9							9	3									
I get a resume evaluation	6.6										9	9									
I have my resume easily accessible to companies	7.5							9							1		1				
I get a job that fits me	8.4															9					
I get a job that pays well	7.8								9							1					
I have a job that I enjoy	8.4															9					
I get job offers	8.5					9	9			9						3					
Raw score		92	20	94	197	146	146	68	70	173	152	83	52	27	72	188	95	24	39	65	197
Relative %		5%	1%	5%	10%	7%	7%	3%	4%	9%	8%	4%	3%	1%	4%	9%	5%	1%	2%	3%	10%
Importance Rank		3	1	3	5	4	4	2	2	4	4	2	2	1	2	5	3	1	1	2	5
Target Value/Specs		3 workshops per month	≥35	3 workshops per month	3 sessions per month	2 per year	≥200	Yes	$67,567	≥7	Minimum of 5 people	≤2 days	3 workshops per month	≥30	3 workshops per month	Minimim of 5 people	Minimum 10	5 per semester	100%	2 per semester	Minimim of 5 people
Technical Difficulty (0=Easy, 10=Hard)		3	7	3	6	6	7	2	3	7	4	5	3	5	3	4	5	2	5	3	1

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4

Analysing Portfolios of Lean Six Sigma Projects

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1. Introduction

The widespread acceptance of Six Sigma as a systematic program of process control, planning, and improvement has led to the creation of many databases describing the performance of individual projects, timing, and the techniques used. These databases provide resources for the analysis of quality management practices. Specifically, there are three levels at which analysis can occur in this context:

Micro level – lowest level dealing with individual tools and statistical methods

Meso level – mid level dealing with groups of individual tools and supervisor level decision-making about method selection and timing

Macro level – highest level dealing with organization and institutions and related to overall quality programs and stock performance

Reviewing the literature reveals a large portion concerning macro-level decision-making, particularly the decision whether to implement a Six Sigma program at a company, e.g., Yu and Popplewell (1994), Yacout and Hall (1997), Bisgaard and Freiesleben (2000), Yacout and Gautreau (2000), and Chan and Spedding (2001). Most of this research is based on individual case studies and anecdotal evidence. A second large grouping of studies deals with the micro-level, investigating component tools and techniques for green and black belts (Hoerl 2001a). Little work is published that relates to the meso-level of mid-level managing and operational decision-making (Linderman, Schroeder, Zaheer, and Choo 2003). The uses of these databases for these types of investigation are likely being ignored at most companies for at least two reasons. First, there has traditionally been little assistance from academics in how to make sense of them. Second, the people with the most statistical expertise are involved in the individual projects and not in cross project evaluation. Most managers are not statisticians and need help in making sense of the data now available to them. The growing database of project related quality improvement activities could be useful in the empirical study of some important meso-level research and real-world questions, including determining the health of a given company's quality system, modeling Six Sigma, optimizing the selection and ordering of component methods.

According to Juran and Gryna (1980) the activities that assure quality in companies can be grouped into three processes: quality planning, quality control and quality improvement.

Policies, standard practices, and philosophy make up the quality planning of a system. A good quality system is proactive not reactive. Quality improvement consists of the systematic and proactive pursuit of improvement opportunities in production processes to increase the quality levels. Typically, quality improvement activities are conducted in projects. This proactive and project-based nature distinguishes improvement from quality control, which is an on-line process that is reactive in nature. In Harry (1994) all things are a process. A central belief of Six Sigma is that the product is a function of the design and the manufacturing process which must produce it.

With Juran and Harry in mind, Six Sigma can be viewed as a process and subject to the same controls and improvement objectives of other processes. Determining what methods to use, when to transition to different phases of the project, and under what circumstances to terminate a project could conceivably make the difference between a healthy and profitable program and a failed one. Against this background, the purpose of this study was to look at this growing database in a way that could help management better run improvement projects.

2. Methods

The use of the many databases of project related quality improvement activities could be useful in the empirical study of some important research questions. As stated earlier, potential research topics include: the health of a given company's quality system, modeling Six Sigma, or the optimality of selection and ordering component methods associated with Six Sigma. Researchers focus on what they have data and tools for. Martin (1982) pointed out that the availability of certain types of data might disproportionately influence the problems investigated and the conclusions drawn. Now, new data sources and the associated ability to ask and answer new types of questions are more readily available. For example, "Is my quality system out-of-control?" "Which method would lead to greatest expected profits in my case?" "Under what circumstances does it make business sense to terminate a project?" If these kinds of questions can be systematically explored in the Six Sigma discourse, then important lessons can be learned regarding investment decisions.

This paper discusses two analysis methods designed for meso-level analysis: exponentially weighted moving average (EWMA) statistical process control (SPC) and regression. Since its introduction by Shewhart in the 1930s, the control chart has been one of the primary techniques of Statistical Process Control (Shewhart 1931). Considering how important individual projects can be and that they require months or even years, the logical subgroup size is $n = 1$ project. With only one measurement per subgroup (a project), a subgroup range can not be calculated. The data is comprised of a small number of non-normal observations. The exponentially weighted moving-average (EWMA) control chart is typically used with individual observations Montgomery (2004). The exponentially weighted moving average is defined as:

$$Z_i = \lambda x_i + (1-\lambda)Z_{i-1} \tag{1}$$

The constant λ takes on the values $0 < \lambda \leq 1$. The process target value or the average of the preliminary data can be used as the starting value so that

$$Z_0 = \mu_0 \tag{2}$$

or

$$Z_0 = \overline{x} \tag{3}$$

The EWMA control chart has the following control limits and center line and is constructed by plotting Z_i versus the sample number, i :

$$UCL = \mu_0 + L\sigma\sqrt{\frac{\lambda}{(2-\lambda)}\left[1-(1-\lambda)^{2i}\right]} \tag{4}$$

$$CL = \mu_0 \tag{5}$$

$$LCL = \mu_0 - L\sigma\sqrt{\frac{\lambda}{(2-\lambda)}\left[1-(1-\lambda)^{2i}\right]} \tag{6}$$

According to Montgomery (1997) values of λ in the interval $0.05 \le \lambda \le 0.25$ work well, with $\lambda = 0.05$, $\lambda = 0.10$, and $\lambda = 0.25$ being popular. L values between 2.6 and 3.0 also work reasonably well. Hunter (1989) has suggested values of $\lambda = 0.40$ and $L = 3.054$ to match as closely as possible the performance of a standard Shewhart control chart with Western Electric rules (Hunter 1989).

Regression is another tool that may be employed to model and predict a Six Sigma program. The familiar regression equation is represented by equation 7 below:

$$y_{est}(\beta_{est},\mathbf{x}) = \mathbf{f}(\mathbf{x})'\beta_{est} \tag{7}$$

where $\mathbf{f}(\mathbf{x})$ is a vector of functions only of the system inputs, $\mathbf{x}$. Much of the literature on Six Sigma implementation converges on factors such as the importance of management commitment, employee involvement, teamwork, training and customer expectation. A number of research papers have been published suggesting key Six Sigma elements and ways to improve the management of the total quality of the product, process, corporate and customer supplier chain. Most of the available literature considers different factors as an independent entity affecting the Six Sigma environment. But the extent to which one factor is present may affect the other factor. The estimation of the net effect of these interacting factors is assumed to be partly responsible for the success of the Six Sigma philosophy. Quantification of Six Sigma factors and their interdependencies will lead to estimating the net effect of the Six Sigma environment. The authors are not aware of any publication in this direction.

3. Data base example: midwest manufacturer

The company used for study is a U.S. based Midwestern manufacturing company which manufactures components for the aerospace, industrial, and defense industries. It has approximately 1,000 employees, annual sales of $170 million, with six factories located in five states. The data is all derived from one of its six manufacturing sites. This site has 250 employees with sales of $40 million. Quality improvement and cost reduction are important competitive strategies for this company. The ability to predict project savings and how best to manage project activities would be advantages to future competitiveness of the company.

Field	Description
Expected savings	An estimate of the projects saving over an 18 month period based on the current business forecast.
Expected time	An estimate made at the start of a project as to the time needed to complete the project s-short less than 3 months m-medium between 3 and 9 months l- long over 9 months
M/I management or self initiated	Whether the project was initiated by management or initiated by team members
Assigned or participative	Whether the project was assigned to a team by management or the members actively chose to participate
# people	Number of team members
EC Economic analysis	A formal economic analysis was preformed with the aid of accounting to identify cost and cost brake allocations
CH Charter	Formally define project scope, define goals and obtain management support
PM Process Mapping	Identify the major process steps, process inputs, outputs, end and intermediate customers and requirements; compare the process you think exists to the process that is actually in place
CE Cause & Effect	Fishbone diagram to identify, explore and display possible causes related to a problem
GR Gage R&R	Gage repeatability and reproducibility study
DOE	A multifactor Screening or optimization design of experiment
SPC	Any statistical process control charting and analysis
DC Documentation	Formally documenting the new process and or setting and/or implementing a defined control plan
EA Engineering analysis	Deriving conclusions based solely on calculations or expert opinion
OF one factor experiment	A one factor at a time experiment
Time	Actual time the project took to completion
Profit	A current estimate of the net profit over the next 18 months after implementation based on the actual project cost and actual savings
Actual Savings	A current estimate of the savings over the next 18 months after implementation based on the new operating process and current business forecast
Cost	The actual cost as tracked by the accounting system based on hours charged to the project, material and tooling, equipment
Formal Methods	A composite factor, if multiple formal methods were used in a project this was positive

Table 1. Definition of Variables

Over the course of this study data was collected on 20 variables and two derived variables: Profit (Actual Savings minus cost), and a Boolean variable, Formal Methods (FM) which is "true" if any combination of Charter, Process Mapping, Cause & Effect, Gauge R&R, DOE, or SPC is used and false otherwise (see Table 1). Thirty-nine improvement projects were included in this study, which generated a total of $4,385,099 in net savings (profit).

Data was collected on each project by direct observation and interviews with team members to determine the use of a variable such as DOE or Team Forming. No attempt was made to measure the degree of use or the successfulness of the use of any variable. We only were interested if the variable activity took place during the project. A count was maintained if an activity was used multiple times such as multiple DOE runs (i.e. a screening DOE and an optimization DOE would be recorded as 2 under the variable heading).

Expected Savings and Actual Savings are based on an 18 month period after implementation. The products and processes change fairly rapidly in this industry and it is standard company policy to only look at an 18 month horizon to evaluate projects, based on a monthly production forecast. Costs were tracked with existing company accounting procedures. All projects were assigned a work order for the charging of direct and non-direct time spent on a specific improvement activity. Direct and non-direct labor was charged at the average loaded rate. All direct materials and out side fees (example, laboratory analysis) were charged to the same work order to capture total cost.

One of the main principles of Six Sigma is the emphasis placed on the attention to the bottom line (Harry 2000 and Montgomery 2001). In the literature reviewed, bottom line focus was mentioned by 24% of relevant articles as a critical success factor. Profit, therefore, is used as the dependant variable, with the other 18 variables constituting the dependant variables.

3.1 EWMA

A common first step in deriving the process control chart is to check the assumption of normality. Figure 1 is a normal probability plot of the profits from the projects. The obvious conclusion is that project 5 is an outlier. There is also a possible indication that the other data divide into two populations.

Next, we constructed an EWMA chart of the profit data. We start with plotting the first 25 points to obtain the control limits as shown in Figure 2. One out of limit point was found and discarded after the derivation of this chart, which was the same project as the outlier on the normal probability plot (number 5). This was the sole DFSS project (Design for Six Sigma) in the data base. The others were process improvement projects without design control. A second graph was developed without the DFSS project point to obtain the chart shown in Figure 3. These charts were constructed based on Hunter (1989) with $\lambda = 0.40$ and $L = 3.054$.

Of special interest are the last seven projects. These projects took place after a significant Six Sigma training program. This provides strong statistical evidence that the training improved the bottom line of subsequent projects. Such information definitely supports decisions to invest in training of other divisions. Similar studies with this same technique could be used to verify whether training contributed to a fundamental change in the process.

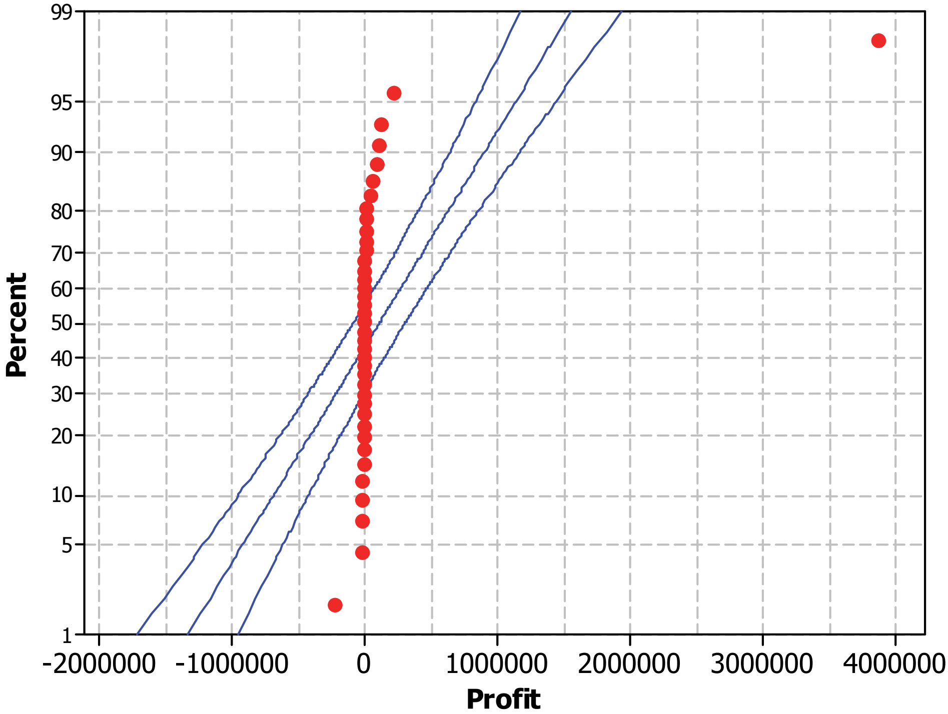

Fig. 1. Normal Probability Chart for Six Sigma Projects.

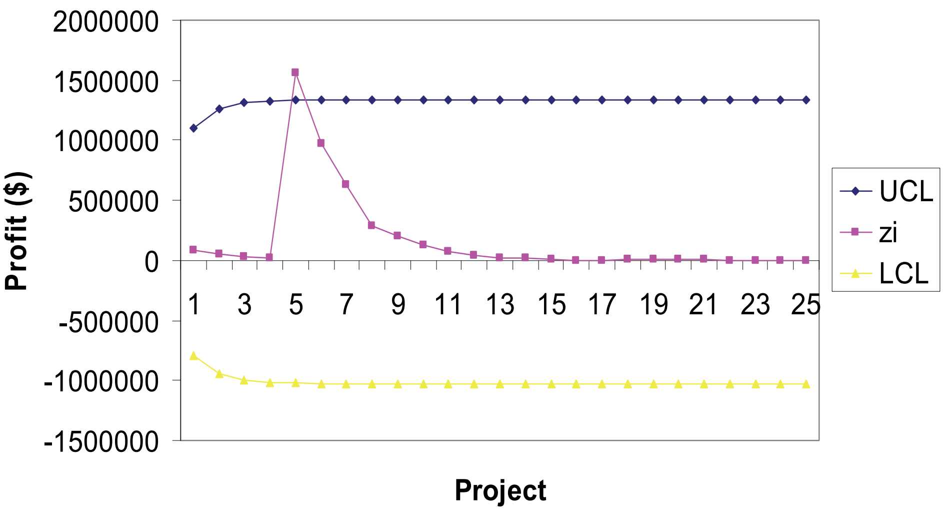

Fig. 2. EWMA Control Chart for first 25 Six Sigma Projects{XE " system"}.

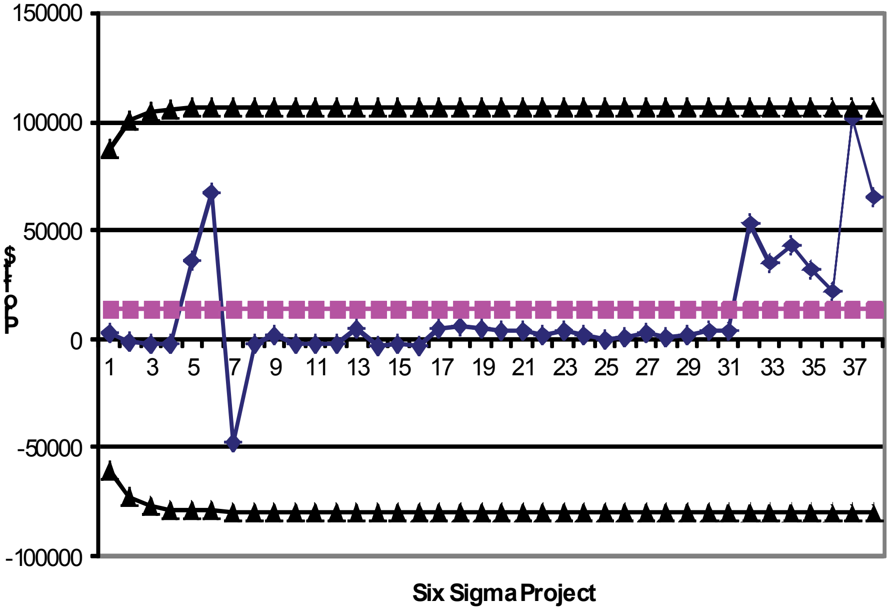

Fig. 3. EWMA Control Chart for Six Sigma Projects {XE “ system“}.

3.2 Regression

Many hypotheses can be investigated using regression. Somewhat arbitrarily, we focus on two types of questions. First, we investigate the appropriateness of applying any type of method as function of the expected savings. Therefore, regressors include the expected savings, the total number of formal methods (FM) applied, and whether engineering analysis (EA) was used. Second, we investigate the effects of training and how projects were selected. In fitting all models, project 5 caused outliers on the residual plots. Therefore, all models in this section are based on fits with that (DFSS) project removed.
The following model resulted in an R-squared adjusted equal to 0.88:

$$\begin{aligned}&\text{Profit }(\$) = -22{,}598.50 + 1.06\text{´Expected Savings} + \\ &2{,}428.13\text{´FM} + 5{,}955.72\text{´EA} + 0.05\text{´Expected Savings´FM} \\ &-0.37\text{´Expected Savings´EA}\end{aligned} \tag{8}$$

Fig. 4. is based on predictions from equation (8). It provides quantitative evidence for the common sense realization that applying many methods when engineers do not predict much savings is a losing proposition.

The model and predictions can be used to set limits on how many methods can be applied for a project with a certain expected savings. For example, unless the project is expected to save $50,000, it likely makes little sense to apply multiple formal methods. Also, the model suggests that relying heavily on engineering analysis for large projects is likely a poor choice. If the expected saving is higher than $100,000 it is likely not advisable to rely solely on engineering analysis.

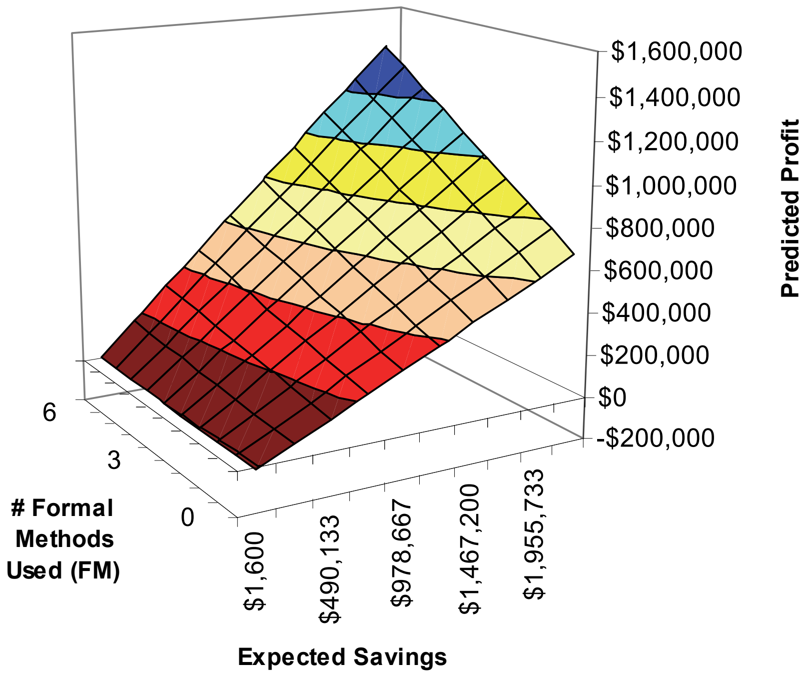

Fig. 4. 3D Surface Plot of the Regression Model in Equation (8)

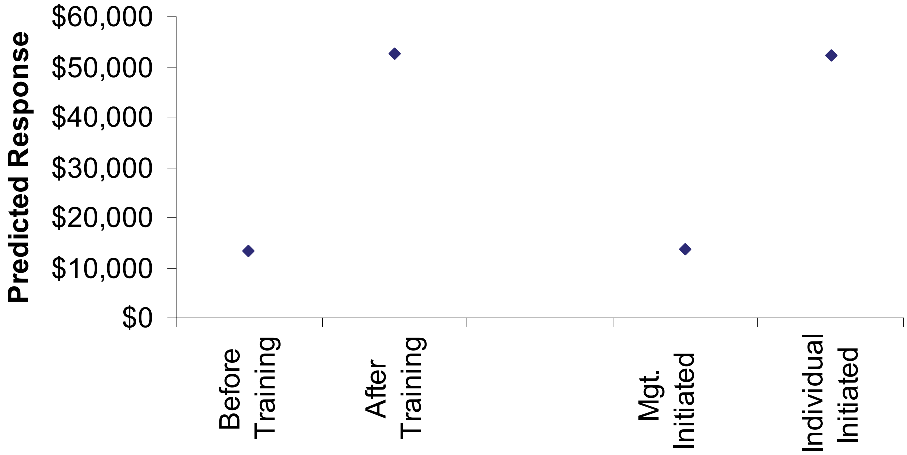

Fig. 5. Main Effects Plot of Predictions of the Simple Regression Model{XE " system"}.

A second regression model was created using the indicator variables: $I = 0$ if the project was not influenced by training and $I = 1$ otherwise and $J = 1$ if the project was management initiate and $J = 0$ otherwise. This model is represented by equation 9, and shows a positive correlation between both independent variables non-management initiated and training with profit:

$$\text{Profit} = 13510 + 38856\, I + 19566\, J \tag{9}$$

This model has an adjusted R-squared of only 0.15 presumably because most of the variation was explained by the variables in equation 8. Note that multicollinearity prevents fitting a single model accurately with the regressors in both equations. The predictions for the model in equation (9) are shown in Figure 5.

4. Discussion

The ability to estimate potential effects of changes on the profitability of projects is valuable information for policymakers in the decision-making process. This study demonstrated that utilizing existing data analysis tools to this new management data source provides useful knowledge that could be applied to help guide in project management. Findings included:

- Design for Sigma Projects (DFSS) can be significantly more profitable than process improvement projects. Therefore, permitting design control can be advisable. In our study, probability plotting, EWMA charting, and regression all established this result independently.
- Training can significantly improve project performance and its improvement can be observed using EWMA charts.
- Regression can create data-driven standards establishing criteria for how many methods should be applied as a function of the expected savings.

Also, in our study we compared results of various sized projects and the use of formal tools. We found that determining the estimate of the economical value to be important to guide the degree of use of formal tools. Based on the results of this study, when predicted impact is small, a rapid implementation based on engineering analysis is best. As projects' predicted impact expands, formal methods can play a larger role.

The simple model also tends to show a strong benefit to training. This model has good variance inflation factors (VIF) values and supports the findings from the SPC findings. Of interest is the negative correlation on management initiation of projects. In this regard, there is still ambiguity in the results. For example, it is not known if people worked harder on projects they initiated or if they picked more promising projects.

The research also suggests several topics for future research. Replication of the value of the methods in the context of other companies and industries could be valuable and lead to different conclusions for different databases. Many other methods could be relevant for meso-analysis and the effects of sites and the nature of the industry can be investigated. Many companies have a portfolio of business units and tailoring how six sigma is applied could be of important interest. In addition, the relationship between meso-analysis and organizational "resilience" could be studied. These concepts are related in part because through applying techniques such as control charting, organization might avoid over-control while reacting promptly and appropriately to large unexpected events, i.e., be more resilient. Finally, it is hypothetically possible that expert systems could be developed for data-driven prescription of specific methods for specific types of problems. Such systems could aid in training and helping organizations develop and maintain a method oriented competitive advantage.

5. Acknowledgment

We thank Clark Mount-Campbell, Joseph Fiksel, Allen Miller, and William Notz for helpful discussions and encouragement. Also, we thank David Woods for many forms of support.

6. Appendix

This appendix contains the data from the 39 case studies shown in Table 2.

Project	Exp. Savings	Exp. Time	M/I	A/P	#people	EC	CH	TF	PM	CE	GR
1	$35000	L	M	A	7	0	1	1	2	1	0
2	$70000	L	M	A	1	1	1	0	0	0	0
3	$81315	M	M	A	2	1	1	1	1	0	0
4	$40000	M	M	A	1	0	0	0	1	0	0
5	$250000	L	I	P	6	1	1	1	0	2	2
6	$150000	L	M	P	4	0	1	1	1	0	0
7	$125000	L	I	P	3	0	1	1	0	0	1
8	$2200000	L	M	P	9	0	1	0	0	3	0
9	$50000	M	M	P	5	1	1	1	1	1	1
10	$39195	M	M	P	1	1	1	0	0	0	0
11	$34500	L	M	A	1	1	0	0	1	1	1
12	$21000	L	M	A	1	0	1	0	0	0	0
13	$25000	M	M	A	1	0	0	0	1	0	0
14	$20000	M	M	A	1	0	0	0	1	0	0
15	$10000	M	M	A	1	0	1	0	0	0	0
16	$20000	S	M	A	1	0	0	0	0	0	0
17	$28000	M	I	P	1	0	0	0	1	0	0
18	$20000	S	M	P	5	0	1	1	0	2	0
19	$20000	S	M	P	1	0	0	0	1	0	0
20	$4350	S	M	A	1	0	1	0	1	0	0
21	$13750	S	M	A	1	0	1	0	1	0	0
22	$8500	S	M	A	1	0	1	0	1	0	0
23	$1600	S	M	A	1	1	0	0	0	0	0
24	$12500	S	M	A	1	0	1	0	1	0	0
25	$4000	S	M	A	1	0	0	0	0	0	0
26	$13000	S	M	A	1	0	0	0	0	0	0
27	$15000	L	I	P	1	1	1	0	0	0	0
28	$6000	M	I	P	1	1	1	0	1	0	0
29	$11500	M	I	P	2	0	1	1	1	0	0
30	$4500	M	I	P	1	1	1	0	1	0	0
31	$11000	S	M	P	5	0	1	1	0	1	0
32	$5400	S	M	P	5	0	1	1	1	1	0
33	$150000	S	I	P	4	0	1	0	1	1	1
34	$8600	S	I	P	2	1	1	0	0	0	0
35	$90000	M	M	A	5	1	1	1	1	1	1
36	$30000	M	M	P	7	1	1	1	0	1	0
37	$45000	S	M	A	3	0	1	0	0	0	1
38	$240000	S	I	P	3	1	0	0	0	0	0
39	$50000	S	I	P	4	1	1	0	1	0	0

Table 2. (Continued).

Project	DOE	SPC	DC	FT	EA	OF	Time	Cost	Act Savings	Profit
1	0	0	1	2	0	1	13	$48700	$36000	$-12700
2	1	0	0	1	1	1	18	$7590	$0	$-7590
3	0	0	1	1	1	0	25	$35300	$31500	$-3800
4	0	0	0	0	1	0	20	$2900	$0	$-2900
5	2	0	1	7	0	1	16	$325500	$4E+06	$3874500
6	0	0	1	1	1	0	9	$76000	$170000	$94000
7	1	0	0	2	1	0	7	$17725	$130500	$112775
8	4	0	0	7	4	0	30	$220000	$0	$-220000
9	2	2	1	7	2	1	5.5	$31125	$97800	$66675
10	0	0	1	1	1	1	14	$12350	$19575	$7225
11	0	0	1	3	2	0	18	$22800	$13500	$-9300
12	0	0	0	0	1	0	18	$2600	$0	$-2600
13	0	0	0	0	1	0	18	$2000	$0	$-2000
14	0	0	0	0	1	0	20	$7500	$21740	$14240
15	0	0	1	1	1	1	8	$30800	$17200	$-13600
16	0	0	0	0	1	0	9	$2000	$0	$-2000
17	0	0	2	2	1	0	4	$12000	$7000	$-5000
18	2	1	1	6	0	0	1.5	$5300	$23220	$17920
19	0	0	1	1	1	0	3	$1900	$8050	$6150
20	0	0	1	1	0	0	3	$1000	$4025	$3025
21	0	0	1	1	0	0	3	$1000	$4025	$3025
22	0	0	1	1	0	0	3	$1000	$4025	$3025
23	0	0	1	1	1	1	3	$3525	$3125	$-400
24	0	0	1	1	0	0	3	$3000	$8400	$5400
25	0	0	0	0	1	0	18	$1900	$0	$-1900
26	0	0	0	0	1	0	8	$1900	$0	$-1900
27	1	0	1	2	1	0	19	$12125	$14985	$2860
28	0	0	1	1	1	0	2.5	$1700	$6500	$4800
29	0	1	0	1	1	1	8	$12880	$11700	$-1180
30	0	0	1	1	1	0	4.5	$3060	$6300	$3240
31	1	2	1	5	0	0	3	$4250	$10900	$6650
32	0	1	1	3	0	0	1.5	$2400	$5375	$2975
33	2	0	1	5	1	0	6	$38900	$165440	$126540
34	0	0	1	1	1	0	1	$1500	$10750	$9250
35	1	1	1	5	1	0	3	$12640	$66100	$53460
36	0	0	1	2	1	1	10	$18780	$34056	$15276
37	1	0	1	3	1	1	13	$38584	$46300	$7716
38	0	1	1	2	1	0	12	$15690	$236280	$220590
39	0	0	1	1	0	0	1.5	$1275	$11927	$10652

Table 2. Data From 39 Case Studies with Expected Times Being Short (S), Medium (M), or Long (L), Management (M) or Individual (I) Initated, Assigned (A) or Participative (P) Team Selection, and The Numbers of Methods Applied Including Economic Analyses (EC), Charter (CH) Creations, Total Formal (TF) Design of Experiments or Statistical Process Control Methods, Process Mapping (PM), Cause & Effect (CE), and Gauge Repeatability and Reproducibility (GR) Analysis.

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5

Successful Projects from the Application of Six Sigma Methodology

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1. Introduction

This chapter describes briefly the Six Sigma Methodology (SSM) phases and Key factors for the effective implementation as well as the important tools. SSM was first introduced by Motorola in the 1980´s to improve product and service quality through the waste and variance reduction (Pyzdek, 2003). The SSM is a systematic way to solve problems with individual projects to attain better profitability. The SSM main objective is to reduce the number of defective parts to as low as 3.4 parts per million. The objective of this chapter is to show that taking into account the key factors and applying the right tools profitable results can be obtained. Three different application cases are used to illustrate the methodology throughout the chapter and were conducted in twin plants in the Juarez area where the authors participated.

The SSM is structured in a five steps or phases in order solve successfully quality problems. These five steps or phases are known as, Define, Measure, Analysis, Improve and Control or DMAIC procedure. This paper describes these steps and illustrates the Key factors and tools that are needed for successful applications. The cases are related to applications that have been published previously (Valles et al., 2009a, 2009b, 2009c) They are design and the Improvement of Binder manufacturing process, Improvement of automotive speakers manufacturing process and the implementation of SSM for the manufacturing of a circuit that is used in inkjet printer cartridges.

The three illustrative applications were successfully implemented by considering the key factors and important tools used throughout the deployment of the SSM. Also, some fundamentals were included such as basic definitions and philosophy, efficient communication, team work, training and management involvement and commitment. Beside the defective part reductions, some other important results were observed in the implementation process, such as culture change, trained employees and better human resources, and better project management skills. In conclusions, there were changes for the better in all the organizations where the SS implementations were conducted.

2. DMAIC procedure

The DMAIC procedure will be briefly describe in this section (Pande et al., 2002). The SSM relies on this procedure for the implementation of improvement projects that requires management commitment and team work. It also involves the use of statistical methods, quality improvement techniques and the scientific method as well.

In the Define step, a team defines the problem objectives and goals, identifies the customers of the process and customers requirements. The project charter, work plan, measurement of the customer requirements and process map documentation are needed.
In the Measure step includes the process performance measure selection, measurement system evaluation and analysis and determination of the process performance level and capability. In this step what to measure must be decided by the team. Sometimes, it is difficult to decide, because data collection is even more difficult and time consuming.
The step of Analysis includes the analysis and determination of potential root causes of variation through the use of statistical tools and the basic quality tools such as Pareto charts, Ishikawa Diagrams, etc. The phases of the root cause analysis are used in this step. They are exploring, generating hypotheses about causes and verifying or eliminating causes. The main input of this step is data generated by the measuring the important variables.
The goal of the Improve step is to find and implement solutions that will eliminate the causes of problems, reduce variation in a process or prevent a problem from recurring. The key factor and important tools for the Improve step are identification, evaluation and verification of potential solutions by the use of basic statistical methods, design of experiments, response surface, Taguchi methods, etc. The identification of potential solutions is often generated by brainstorming.
At last, the Control step has the objective to continue measuring the performance of the process periodically and keeping it under control. The process management control and action plans are made by implementing control charts, control plans and mistake-proof devices. It is important to mention that the first three steps are observational studies, that is, there is not intervention in the process. While in the last two steps are designed experiments, where the researchers take active action into the process in order to achieve the established goals.

3. Reduction of the nonconforming fraction in manufacturing of a circuit

The specific objectives of this project were grouped in three categories; measurement equipment, failure analysis, and process improvement. Regarding the measurement equipment, the objectives were to evaluate the current measurement system and to assess the repeatability and reproducibility of the electric tester. In relation to the method of failure analysis, the objectives were to: evaluate the standardization of criteria for the technical failures; develop a procedure and sampling plan for defective parts; obtain a reliable estimate of the distribution for failures in the total population; propose an alternate method for the analysis of defective parts; and identify and measure the defects, specially the main electrical defect.
About the analysis of problems and process improvement, the objectives were to; identify the factors or processes that affect the quality feature in question (electrical function of the circuit); identify the levels of the parameters in which the effect of the sources of variation will be minimal; develop proposals for improvement; and to implement and monitor the proposed improvements.
Definition: During the years 2006 and 2007 the main product had a low level of performance in electrical test. Historical data shows that on average, 3.12% of the material was defective. The first step was the selection of the Critical Customer Characteristics and the response variable. The critical characteristic, in this case, was the internal electrical defects detected during electrical testing.

Measurement: This phase is to certify the validity of the data through the evaluation of the measurement system. The first step is a normality test of the data and an analysis of the process capacity. This began with the measurement of the percentage of electrical failures. The percentage of electrical failures is obtained after a test is performed to the 100% of electric circuits.

Repetition	Measurement	Moving Range	Repetition	Measurement	Moving Range
1	80.1	0	11	80.0	0.2
2	79.9	0.2	12	80.1	0.1
3	80.1	0.2	13	80.1	0
4	79.8	0.3	14	79.9	0.2
5	80.1	0.3	15	79.9	0
6	80.1	0	16	80.0	0.1
7	79.9	0.2	17	79.8	0.2
8	80.2	0.3	18	79.8	0
9	80.1	0.1	19	80.1	0.3
10	79.8	0.3	20	80.0	0.1

Table 1. Measured by Operator (Reference Value of 73.5 Ohms)

In order to evaluate the accuracy of the equipment, a standard piece was used with a reference value of 75.3 Ω, which was measured 20 times by the same operator. According to the results of the data shown in Table 1, it is concluded that a 0.05% accuracy of the calibration of the instrument is acceptable.
The evaluation of the capability of the measurement process in terms of precision was conducted through a study of repeatability and reproducibility (R&R). The evaluation was conducted with 10 pieces of production taken at different hours, with 3 operators and 3 repetitions. The results of the R&R study was performed with Minitab© shown in Table 2. The total variability introduced by the electrical tester is 3.32%, which is considered excellent.

Source	StdDev	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)	%Process (SV/Proc)
Total Gauge R&R	4.43E-02	0.265832	48.59	3.32	28.90
Repeatability	3.78E-02	0.232379	42.47	2.90	25.26
Reproducibility	2.15E+00	0.129099	23.60	1.61	14.04
Operator	0.00E+00	0.000000	0.00	0.00	0.00
Operator*Part	2.15E-02	0.129099	23.60	1.61	14.04
Part-To-Part	7.97E-02	0.478191	87.40	5.98	51.99
Total Variation	9.12E-02	0.547114	100.00	6.84	59.48

Table 2. Results of the Repeatability and Reproducibility Study

A study of repeatability and reproducibility for attributes was done with purpose of ensuring the consistency of the criteria used by four different inspection areas. Table 3 shows the result.

Evaluation	Shift A Inspector	Shift B Inspector	Shift C Inspector	Shift D Inspector
% Matched	96.67%	96.67%	93.33%	90.00%
%Appraised Vs. known standard	93.33%	93.33%	86.66%	76.67%

Table 3. Study of Repeatability and Reproducibility for Attributes

Analysis: This phase consisted of searching through brainstorming rounds the possible factors that may be affecting the electrical performance of the product. The factors that were considered most important were raised as hypotheses and verified by different statistical tests. The objective was to identify key factors of variation in the process. For the identification of potential causes were prepared Pareto Charts of Defects, in one of them, about 33% of the electrical faults analyzed cannot be identified with the test equipment and 21.58% are attributed to the defect called "Waste of Aluminum Oxide", given that the current equipment does not detect 33% of nonconformities. Samples were sent to an external laboratory, observing that more than 50% of the parts had traces of aluminum oxide so small that they could not be detected with the microscope used in the laboratory of failure analysis. Because this waste may cause several problems, a cause and effect matrix shown in Table 4 was prepared to prioritize areas of focus.

The causes considered important were; the quantity of wash cycles, the thickness of the Procoat layer, Lots circuit, the parameters of grit blast equipment and the operational differences among shifts. With respect to the quantity of wash cycles, to determine if they affect the fraction of electrical defects, an experiment with, one, two and three wash cycles as factor levels with sample sizes of 30 wafers each. Data was tested for normality. The statistical differences among wash cycles are not significant, concluding that Wash Cycle is not an important factor. The results of these tests are not shown. In relation to the thickness of the Procoat finish, it was suspected that the increase of the thickness reduces the percentage of electrical failures. This is to reduce the impact that grains of aluminum oxide has on the semiconductor. An experiment with a single factor was carried out. The factor assessed was the thickness of the layer of Procoat under 4 levels and 30 replications. The 120 runs were conducted completely random. The different thicknesses of Procoat tested were 0, 14, 30, 42 microns. The results of the Anova for this experiment are shown in Figure 1.

The data indicate that there is a difference between the levels, as the p-value is less or equal to 0.0001. Only the level of 0 micron is different from the others and the confidence intervals of the other three levels overlap, then they have the same mean. Figure 2 shows the comparisons of the four levels of procoat in relation to the percentage of electrical failures. The layer of procoat improves electrical performance up to 14 microns (a condition of the current process); however it is not justifiable to increase the thickness of the layer, as it did not represent improvement in the average electric performance or to reduce the variation.

Concerning the Lots of raw material for the Circuit, in order to prove that the condition of the raw material is not a factor that is influencing the electrical performance, it was necessary to verify the following hypotheses: H_0: There is no difference in the fraction of defective units between different batches vs. H_1: There is a difference in the fraction of defective units between different batches. Because the four lots of raw material that were selected randomly contain different amounts of wafers, the experiment was an unbalanced completely random design. Each batch contains between 20 and 24 wafers. In a shift 200 circuits can be assembled. Each circuit is mounted in a cartridge for inkjet printers that are electrically tested on an individual basis. The ANOVA results are summarized in Figure 2, indicating that there is no difference in the percentage of electrical failures of wafers per batch. The P-Value of 0. 864 is a high probability that the lots have equal means. Therefore, the null hypothesis is not rejected. Then it is concluded that the lots of wafers show no difference in electric behavior and the assumption that some batches posses a lower electrical performance is discarded.

Cause and Effect Matrix							
Rating of Importance to Costumers		5.91	2.3	1	0.78		
Y´s		1	2	3	4	5	
X´s		Residual AIO	Scratch	Tester Error	Pad Contamination	Requirement	Total
Process Step	Process Input						
1	Grit Blast	9	9	0	3		75.96
2	Nozzle Attached	6	6	0	6		53.76
3	Lexfilm	0	9	0	9		27.45
4	Electrical Test	0	0	9	0		9.36
5	Dicing	0	3	0	0		6.81
6	Tab Bond	0	0	0	0		0
	Total	89	61	9	14		

Table 4. Cause-Effect Matrix

```
One-way ANOVA: Evaluation Layer Thickness Procoat

Analysis of Variance
Source     DF        SS        MS       F      P
Factor      3 0.0046162 0.0015387   23.28  0.000
Error     116 0.0076688 0.0000661
Total     119 0.0122850
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
0 micron   30  0.026520  0.011065                          (----*----)
14micron   30  0.011585  0.005927  (----*----)
30 micro   30  0.013405  0.007448     (----*----)
42 micro   30  0.011868  0.007169   (----*----)
                                   ------+---------+---------+---------+
Pooled StDev = 0.008131               0.0120    0.0180    0.0240    0.0300
```

Fig. 1. Results of the ANOVA for the Procoat Layer Thickness

Additionally, the test of equal variances (for the four lots) concluded that there is no hard evidence to suggest that the variability in the percentage of electrical failures depends on the lot or semiconductor wafers. Figure 3 shows the results of Bartlett test, where the p-value of 0.926 (P> 0.05). Data was tested for normality before the test the hypothesis of equality of the averages of the batches with an ANOVA. There was no evidence to say that the data was not normally distributed.

```
One-way ANOVA:

Analysis of Variance
Source      DF        SS          MS          F        P
Factor       3    0.000294    0.000098      0.25    0.864
Error       86    0.034350    0.000399
Total       89    0.034645
                                          Individual 95% CIs For Mean
                                          Based on Pooled StDev
Level        N      Mean       StDev      -------+---------+---------+---------
Lot  1      24    0.96930    0.01974              (------------*-------------)
Lot  2      24    0.96445    0.02165       (------------*-------------)
Lot  3      21    0.96655    0.01896         (--------------*-------------)
Lot  4      21    0.96596    0.01926        (--------------*-------------)
                                          -------+---------+---------+---------
Pooled StDev =   0.01999                        0.9600    0.9660    0.9720
```

Fig. 2. ANOVA for Different Lots of Wafers

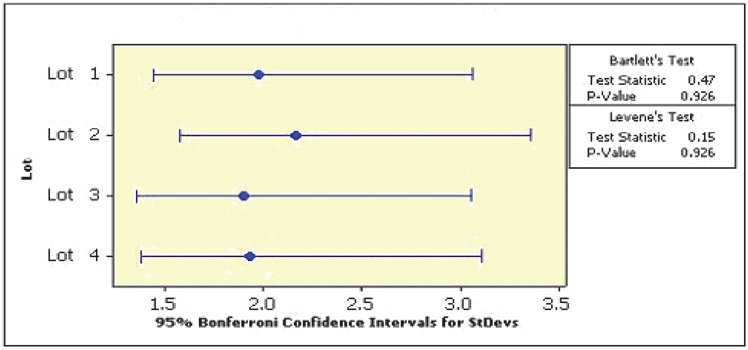

Fig. 3. Variance Test for Lots of Wafers

Factor	Levels		
Pressure (psi)	95	100	110
Tooling Height (inches)	0.060	0.070	0.080
Cycle Time (milliseconds)	6000	7000	8000
Machine	1	2	3

Table 5. Factors Evaluated in Equipment Grit Blast

The analysis for the data from Table 6 was run with a main effect full model. This model is saturated; therefore the two main effects with the smallest Sum of Squares were left out from the model. This is that Machine and Cycle time do not affect the electrical Performance. The analysis for the reduced model is presented in Figure 4. It can be observed that the Pressure and the Tooling Height are significant with p-values of 0.001, and 0.020, respectively.

Pressure (psi)	Tooling Height (in)	Cycle Time (milliseconds)	Machine	% Acceptable
95	0.060	6000	1	0.9951
95	0.070	7000	2	0.9838
95	0.080	8000	3	0.9908
100	0.060	7000	3	0.9852
100	0.070	8000	1	0.9713
100	0.080	6000	2	0.986
110	0.060	8000	2	0.9639
110	0.070	6000	3	0.9585
110	0.080	7000	1	0.9658

Table 6. Results of Runs in Grit Blast

General Linear Model: % Acceptable versus Pressure (ps, Tooling Heig

```
Factor               Type   Levels  Values
Pressure (psi)       fixed       3  95, 100, 110
Tooling Height (in)  fixed       3  0.06, 0.07, 0.08


Analysis of Variance for % Acceptable, using Adjusted SS for Tests

Source               DF     Seq SS     Adj SS     Adj MS      F      P
Pressure (psi)        2  0.0011478  0.0011478  0.0005739  70.37  0.001
Tooling Height (in)   2  0.0001978  0.0001978  0.0000989  12.12  0.020
Error                 4  0.0000326  0.0000326  0.0000082
Total                 8  0.0013782


S = 0.00285589   R-Sq = 97.63%   R-Sq(adj) = 95.27%
```

Fig. 4. ANOVA for the Reduced Model for the Grit Blast Parameters

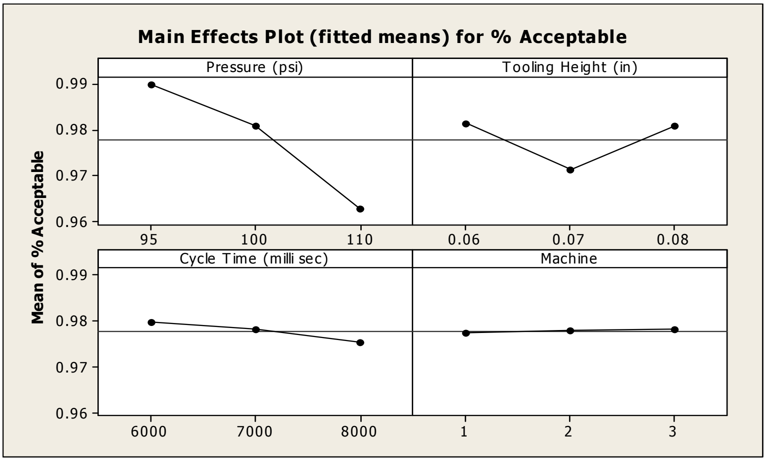

Fig. 5. Chart in Benchmarks Main Effects of Grit Blast

The Figure 5 shows the main effects plot for all four factors, which confirm that only Pressure, Tooling Height and Cycle Time are affecting the quality characteristic. Figure 6 shows that normality and constant variance are satisfied.

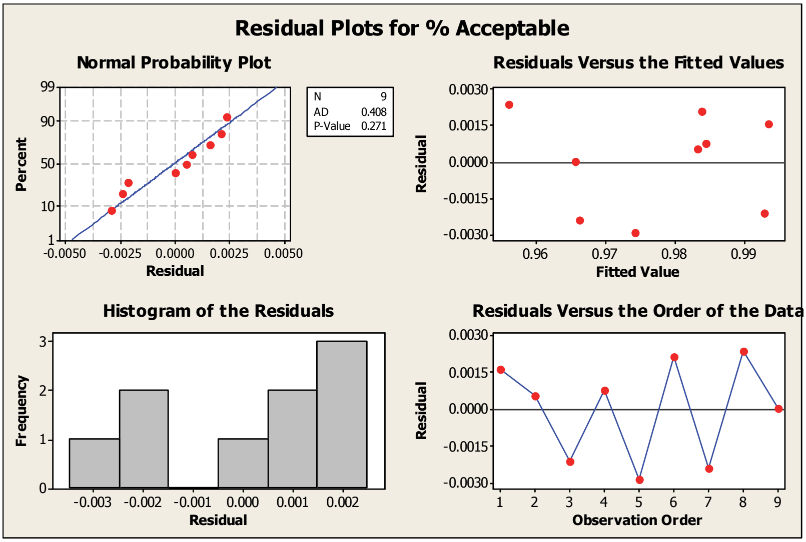

Fig. 6. Residual Plots for the Acceptable Fraction.

Finally, with the intention of determining whether there is a difference in performance of four shifts, a test analysis of variance and equality of means was performed. The Table 7 shows that there is a difference between at least one of the shifts, since the p-value is less or equal to 0.0001. The above analysis indicates that all four shifts are not working with the same average efficiency. For some reason shift A presents a better performance in electrical test. Also it can be observed that shift D has the lowest performance. With the intention of confirm this behaviour; a test of equal variances was conducted. It was observed that the shift A shows less variation than the rest of the shifts, see Figure 7. This helps to analyze best practices and standardized shift A in the other three shifts.

Once it was identified the factors that significantly affect the response variable being analyzed, the next step was to identify possible solutions, implement them and verify that the improvement is similar to the expected by the experimental designs. According to the results obtained, corrective measures were applied for the improvement of the significant variables.

With regard to the inefficient identification of flaws in the failure analysis, and given that 33% of electrical faults analyzed in the laboratory could not be identified with the test equipment that was used. Then, a micromanipulator was purchased. It allows the test of circuits from its initial stage. Furthermore, it is planned the purchase of another equipment different than the currently used in the laboratory of the matrix plant at Lexington. This equipment decomposes the different layers of semiconductor and determines the other particles that are mixed in them. These two equipments will allow the determination of the particles mixed in the semiconductor and clarify if they are actually causing the electrical fault, the type of particle and the amount of energy needed to disintegrate.

One-way ANOVA: Shifts A, B, C y D						
Source		DF	SS	MS	F	P
Factor		3	13.672	4.557	9.23	0.000
Error		124	61.221	0.494		
Total		127	74.894			
S = 0.7027 R-Sq = 18.26% R-Sq(adj) = 16.28%						
Individual 95% CIs For Mean Based on Pooled StDev						
Level	N	Mean	StDev	+---------+---------+---------+---------		
A	32	3.0283	0.4350	(----*----)		
B	32	3.6078	0.6289	(----*----)		
C	32	3.5256	0.8261	(----*----)		
D	32	3.9418	0.8412	(----*----)		
				+---------+---------+---------+---------		
				2.80 3.20 3.60 4.00		
Pooled StDev = 0.7027						

Table 7. ANOVA Difference between Shifts

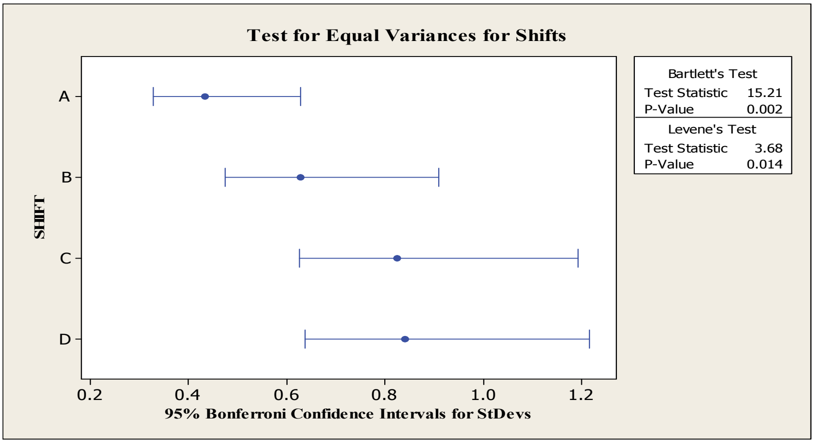

Fig. 7. Equality of Variance Test for the Shifts

About the percentage of defective electrical switches with different thicknesses of Procoat (0, 14, 30 and 42 microns). The use of Procoat will continue because the layer has a positive effect on the electrical performance of the circuit. However, because the results also showed that increasing the thickness of the layer from 14 to 42 microns, does not reduce the level of electrical defects. The thickness will be maintained at 14 microns.

For the drilling pressure in the equipment, lower levels are better and for the improvement of the electrical performance without affecting other quality characteristics, such as the dimensions of width and length of the track. It was determined that the best level for the

pressure would be 95 psi. With respect to the height of the drill, since it significantly affects the electrical performance and this is better when the tool is kept at 0.60 or 0.80 inches on the semiconductor. For purposes of standardization, the tool will remain fixed at a height of 0.60 inches.
In relation to the cycle time, it showed to be a source of conflict between two quality characteristics (size of the track and percentage of electrical failures). Although it is a factor with a relatively low contribution to the variation of the variable analyzed. Several experiments were run with the parameters that would meet the other characteristic of quality. Figure 5 shows the main effect. For the variable electrical performance, a factor behavior of the type smaller is better was introduced. While for the other variable output capacity of the process, a higher is better behavior was selected and for that reason, it was determined that this factor would be in a range from 7,000 to 8,000 milliseconds.
Finally, with respect to the difference between the four-shift operations and electrical performance, results indicate that the "A" shift had better electrical performance, with the intention of standardization and reduction of the differences, a list of best practices was developed and a training program for all shifts was implemented. In this stage is recommended an assessment of the benefits of the project (Impact Assessment of Improvement). Once implemented the proposed solutions, a random sample size 200 was taken from one week work inventory product and for all shifts. This sample was compared to a sample size 200 processed in previous weeks. Noticeable advantages were found in the average level of defects, as well as the dispersion of the data. Additionally, the results of the tested hypotheses to determine if the proposed changes reduced the percentage defective. Electrical test indicate that if there is a difference between the two populations.

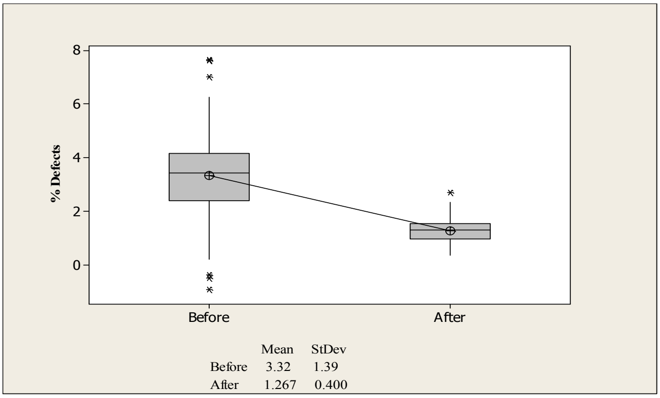

Fig. 8. Box Plots for the Nonconforming Fractions of Before and After

In Figure 8, Box diagrams are shown for the percentage of defects in the two populations. It is noted that the percentages of defects tend to be lower while maintaining the parameters of the equipment within the tolerances previously established as the mean before implementation is 3.20%, against 1.32% after implementation. The test for equality of variances shows that in addition to a mean difference there is a reduction in the variation of the data as shown in see Figure 9. Figure 10 shows a comparison of the distribution of defects before and after implementation. It can be seen that the defect called "Aluminum oxide residue" was considerably reduced by over 50%.

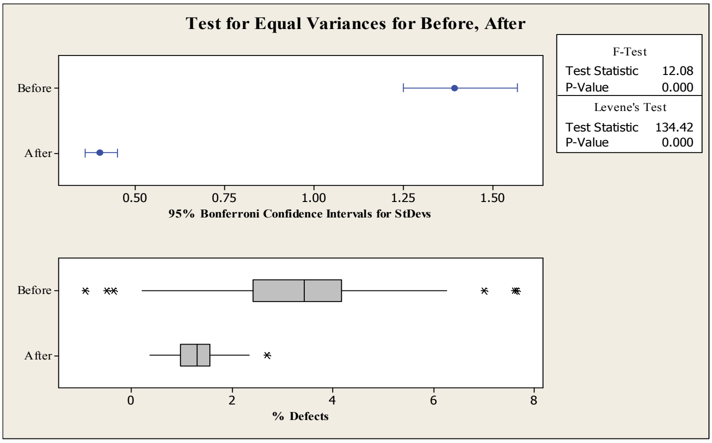

Fig. 9. Test of Equality of Variances for the Nonconforming Fractions of Before and After

Control: In order to achieve stable maintain the process, identified the controls to maintain the pressure, height of the tool and cycle time within the limits set on the computer Grit Blast and test electrical equipment. Identification of Controls for KPIV's: Because these three parameters had been covered by the machine operator to offset some equipment failures such as leaks or increasing the cycle time. It was necessary to place devices that will facilitate the process control in preventing any possible change in the parameters.

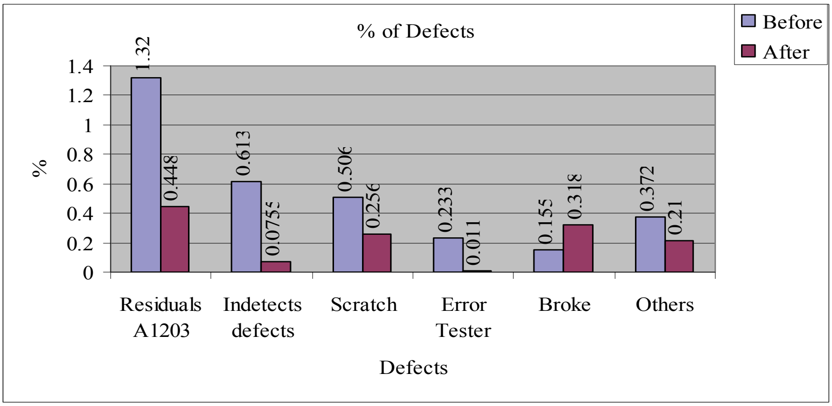

Fig. 10. Distribution of Defects Before and After

Additionally, to help keep the machine operating within the parameters established without difficulty, it was essential to modify the plan of preventative maintenance of equipment. Due to the current control mechanisms are easily accessible to the operator; it was determined to improve those controls to ensure the stability of the equipment and process. All of this coupled with an improvement in preventative maintenance of the equipment. Based on the information generated with the assessment of the assumptions above, it generated an action plan which resulted in a reduction in the percentage of electrical failures in general. As well as a reduction in the defect called "Short but residue of aluminum oxide". Table 8 shows a comparison of the nonconforming fraction, PPM's and Sigma levels of before and after implementation.

	% Defects	Sigma Level	PPM's
Base Line	3.20	3.35	31982
Goal	1.60	3.64	16000
Evaluation	1.32	3.72	13194

Table 8. Comparison of Before and After

Conclusion: The implementation of this project has been considered to be a success. Since, the critical factor for the process were found and controlled to prevent defects. Therefore the control plan was updated and new operating conditions for the production process. The based line of the project was 3.35 sigma level and the gain 0.37 of sigma. Which represent the elimination of 1.88% of nonconforming units or 18,788 PPMs. Also, the maintenance preventive program was modified to achieve the goal stated at the beginning of the project. It is important to mention that the organization management was very supportive and encouraging with the project team. The Six sigma implementation can be helpful in reducing the nonconforming units or improving the organization quality and personal development.

4. Capability improvement for a speaker assembly process

A Six Sigma study that was applied in a company which produces car speakers is presented. The company received many frequent customer complaints in relation to the subassembly of the pair coil-diaphragm shown in Figure 11. This subassembly is critical to the speaker quality because the height of the pair coil-diaphragm must be controlled to assure adequate functioning of the product. Production and quality personnel considered the height was not being properly controlled. This variable constitutes a high potential risk of producing inadequate speakers with friction on the bottom of the plate and/or distortion in the sound. Workers also felt there had been a lack of quality control in the design and manufacture of the tooling used in the production of this subassembly. The Production Department as well as top management decided to solve the problems given the cost of rework overtime pay and scrap which added up to $38,811 U.S. dollars in the last twelve months. Improvement of the coil-diaphragm subassembly process is presented here, explaining how the height between such components is a critical factor for customers. This indicates a lack of quality control.

Define: For deployment of the Project, a cross functional project team was integrated with Quality, Maintenance, Engineering, and Production personnel. The person in charge of the project trained the team. In the first phase, the multifunctional 6σ team made a precise description of the problem. This involved collecting the subassemblies with problems such as drawings, specifications, and failure modes analyses. Figure 11 shows the speaker parts and the coil-diaphragm subassembly. The subassembly was made in an indexer machine of six stations. The purpose of this project was to reduce quality defects; specifically, to produce adequate subassemblies of the coil-diaphragm. Besides, the output pieces must be delivered within the specifications established by the customer. The objective was to reduce process variation with the Six Sigma methodology and thus attain a Cpk ≥1.67 to control the tooling.

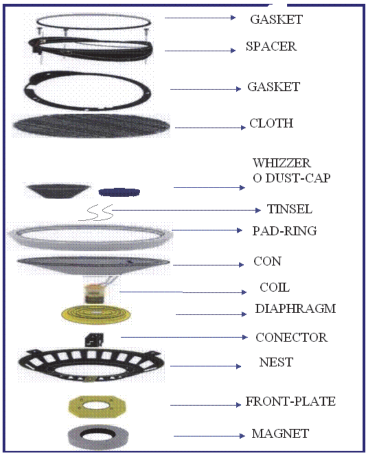

Fig. 11. Speaker Explosion Drawing

Then, the critical characteristics were established and documented based on their frequency of occurrence. Figure 12 shows the five critical defects found during a nine month period. It can be seen that height of the coil-diaphragm out of specifications is the most critical characteristics of the speaker, since it contributes 64.3% of the total of the nonconforming units. The second highest contributing defect is the distortion with 22.4%. These two types of nonconforming speakers accumulate a total of 86.8%. By examining Figure 10, the Pareto chart, it was determined that the critical characteristic is the height coil-diaphragm. The project began with the purpose of implementing an initial control system for the pair coil-diaphragm. Then, the Process Mapping was made and indicated that only 33.2% of the activities add value to parts.

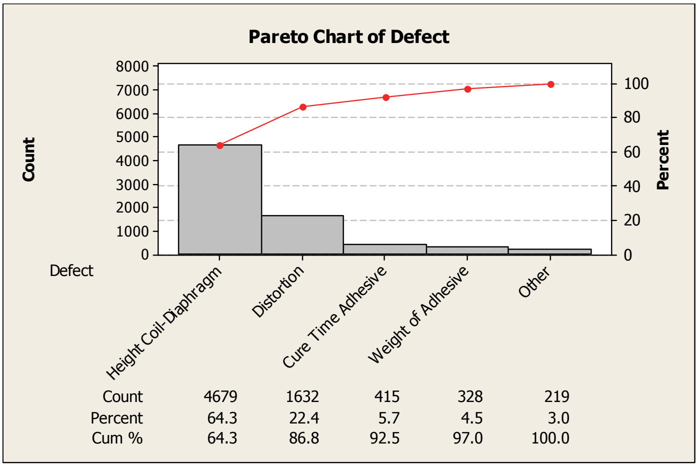

Fig. 12. Pareto Diagram for Types of Defects

Also the cause and effect Matrix was developed and is shown in Table 9. It indicates that tooling is the main factor that explains the dispersion in the distance that separates coil and diaphragm. At this point, there was sufficient evidence that points out the main problem was that the tooling caused variation of the height of the coil diaphragm.

Measurement: Gauge R&R and process capability index Cpk studies were made to evaluate the capability of the measuring system and the production process. Simultaneously, samples of the response variables were taken and measured. Several causes of error found in the measurements were: the measuring instrument, the operator of the instrument and the inspection method.

Step Number	Level of Effect 1.- NO EFFECT 4.- MODERATE EFFECT 9.- STRONG EFFECT	Present	Functionality	Appearance	Adhesion	Total
	Factor in Process					
1	Tooling	9	9	9	9	342
2	Diaphragm dimension	9	9	4	9	302
3	Weight of adhesive	9	9	4	9	302
4	Weight of accelerator	9	9	4	9	302
5	Diameter of coil	9	9	9	4	292
6	Cure time	9	9	4	4	252
7	Injection devise	9	9	4	4	252
8	Air pressure	9	9	4	4	252
9	Wrong material	9	9	4	4	252
10	Broken material	9	4	4	4	202
11	Personal training	9	9	1	1	198
12	Manual adjustment	1	4	4	4	122
13	Production Standard	1	9	1	1	118
14	Air	1	1	1	1	38

Table 9. Cause and Effect Matrix for the Height of Coil-Diaphragm

To correct and eliminate errors in the measurement system, the supervisor issued a directive procedure stating that the equipment had to be calibrated to make it suitable for use and for making measurements. Appraisers were trained in the correct use and readings of the measurement equipment. The first topic covered was measurement of the dimension from

the coil to the diaphragm, observing the specifications. The next task was evaluation of the measurement system, which was done through an R&R study as indicated in (AIAG, 2002). The study was performed with three appraisers, a size-ten sample and three readings by appraiser. An optical comparative measuring device was used. In data analysis, the measurement error is calculated and expressed as a percentage with respect to the amplitude of total variation and tolerance. Calculation of the combined variation (Repeatability and reproducibility) or error of measurement (EM): P/T = Precision/Tolerance, where 10% or less = Excellent Process, 11% to 20% = Acceptable, 21% to 30% = Marginally Acceptable. More than 30% = Unacceptable Measurement Process and must be corrected.
Since the result of the Total Gage R&R variation study was 9.47%, the process was considered acceptable. The measuring system was deemed suitable for this measurement. Likewise, the measuring device and the appraiser ability were considered adequate given that the results for repeatability and reproducibility variation were 8.9% and 3.25%, respectively. Table 10 shows the Minitab© output.
The next step was to estimate the Process capability index Cpk. Table 11 shows the observations that were made as to the heights of the coil-diaphragm. The result of the index Cpk study was 0.35. Since the recommended value must be greater than 1, 1.33 is acceptable and 1.67 or greater is ideal. The process then was not acceptable. Figure 13 shows the output of the Minitab© Cpk study. One can see there was a shift to the LSL and a large dispersion. Clearly, the process was not adequate because of the variation in heights and the shift to the LSL. A 22.72% of the production is expected to be nonconforming parts.

Source	StdDev(SD)	Study Var (5.15*SD)	%Study Var(%SV)
Total Gage R&R	0.022129	0.11397	9.47
Repeatability	0.020787	0.10705	8.90
Reproducibility	0.007589	0.03908	3.25
C2	0.007589	0.03908	3.25
Part-To-Part	0.232557	1.19767	99.55
Total Variation	0.233608	1.20308	100.00
Number of Distinct Categories = 15			

Table 10. Calculations of R&R with Minitab©

Height/ Measurement	Sample/Hour										
	1	2	3	4	5	6	7	8	9	10	11
1	4.72	4.88	5.15	4.75	4.42	4.76	5.14	5	4.88	4.66	4.75
2	4.67	4.9	5	4.4	4.81	4.81	4.78	4.8	5	4.58	4.88

Table 11. Heights of Coil-Diaphragm before the Six Sigma Project

Verification of the data normality is important in estimating the Cpk, which was done in Minitab with the Anderson-Darling (AD) statistic. Stephens (1974) found the AD test to be one of the best Empirical distribution function statistics for detecting most departures from normality, and can be use for n greater or equal to 5. Figure 14 shows the Anderson-Darling test with a p-value of 0.51. Since the p-value was greater than 0.05 (α=0.05), the null hypothesis was not rejected. Therefore, the data did not provide enough evidence to say that the process variable was not normally distributed. As a result, the capability study was valid since the response variable was normally distributed.

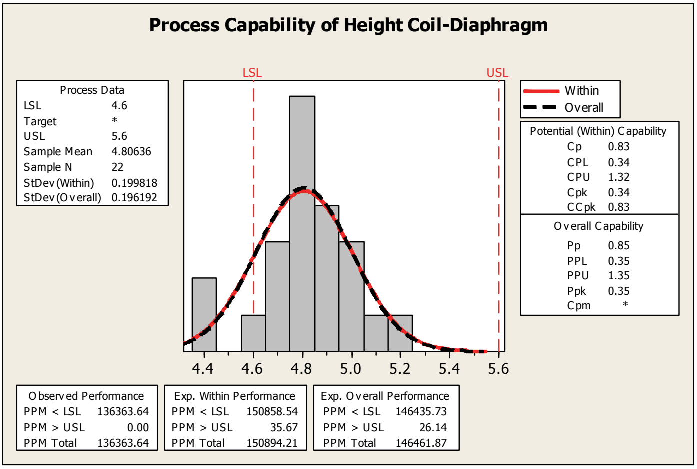

Fig. 13. Estimation of the Cpk Index for a Sample of Coil-Diaphragm Subassemblies

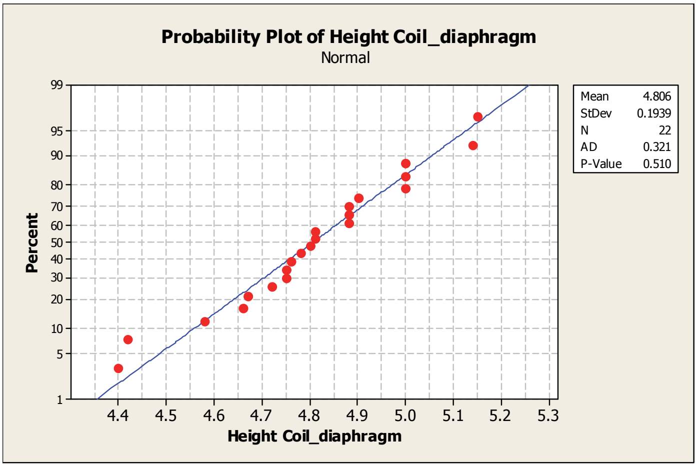

Fig. 14. Normality Test of the Coil-Diaphragm Heights

Analysis: The main purpose of this phase was to identify and evaluate the causes of variation. With the Cause and Effect Matrix, the possible causes were identified. Afterward, the Six Sigma Team selected those which, according to the team's consensus, criteria and experience, constituted the most important factors. With the aim of determining the main root-causes that affected the response variable, a diagram of cause and effect (Ishikawa diagram) was prepared in a brainstorm session where the factors that influenced the height between the coil and the diaphragm were selected. The causes were statistically analyzed, and the tooling was found to have had a moderate effect in the critical dimensions. The tooling effect had the largest component of variation. Several causes were found: first, the tools did not fulfill the requirements, and their design and manufacture were left to the supplier; also, the plant had no participation in designing the tools; second, the weight of

the adhesives and the accelerator were not properly controlled. Since the tools were not adequate given that some variation was discovered in the amounts delivered, this had an impact on the height.
The tooling was analyzed to check whether the dimensions had affected the height between the coil and the diaphragm. The regression analysis was made to verify the hypothesis that the dimensions of the tooling do not affect the height between the coil and the diaphragm. The First two test procedures used to verify the above hypothesis were the regression analysis and the one-way ANOVA. The results of both procedures were discarded because the basic assumptions about normality and homogeneity in the variances were not satisfied. Then the Kruskal-Wallis test was carried out to verify the hypothesis. The response variable was the Height of the Coil-Diaphragm and the factor was the Tooling height. Table 12 illustrates the results
Figure 15 shows the results of Kruskal Wallis analysis with a p-value less than 0.001. Then the decision is to reject the null hypothesis. Consequently, it is concluded that the data provide sufficient evidence to say that the height of the tooling affects the height of subassembly coil- diaphragm.

		Coil-Diaphragm Height (in mm)						
Levels	Tooling Height	1	2	3	4	5	6	Mean
1	4.78	4.70	4.75	4.70	4.75	4.78	4.76	4.74
2	4.88	4.81	4.83	4.85	4.87	4.81	4.81	4.83
3	4.90	4.88	4.91	4.95	4.94	4.92	4.93	4.92
4	5.00	5.10	5.20	4.98	4.98	5.31	4.97	5.09
5	5.10	5.12	5.14	5.23	5.20	5.19	5.31	5.19
6	5.30	5.40	5.55	5.38	4.97	4.99	5.39	5.28

Table 12. Results of Tooling Height vs. Coil-Diaphragm Height

Kruskal-Wallis Test: Height of Coil-Diaphragm versus Tool Height

```
Kruskal-Wallis Test on Height of Coil-Diaphragm

Tool Height   N  Median  Ave Rank      Z
4.78          6   4.750       3.5  -3.82
4.88          6   4.820       9.5  -2.29
4.90          6   4.925      15.5  -0.76
5.00          6   5.040      24.4   1.51
5.10          6   5.195      28.0   2.42
5.30          6   5.385      30.1   2.95
Overall      36              18.5

H = 31.05  DF = 5  P = 0.000
H = 31.09  DF = 5  P = 0.000  (adjusted for ties)
```

Fig. 15. Result of Kruskal Wallis Test

In addition, the thickness of the diaphragm was analyzed. A short term sample of pieces of diaphragms were randomly selected from an incoming lot, and measured to check the capability of the material used in the manufacturing. This analysis was conducted because

when the thickness of the diaphragm could be out of specification and the height coil-diaphragm could be influenced. The diaphragm specifications must have a thickness between 0.28 ± 0.03 mm for a certain part number. The material used in the subassembly is capable because the measurements were within specifications and had a Cpk of 1.48. Which is acceptable because was greater than 1.33. Also, the weight of adhesive was analyzed, thus, another short term sample of 36 deliveries were weighted. The weight of the glue must be within 0.08 and 0.12 grams. The operation of delivering the adhesives in the subassembly is capable because the Cpk was equal to 3.87, which greater than 1.67 and acceptable. The weights of the adhesive appear to be normal. Regarding the accelerator weight, 36 measurements were made on this operation, whose specifications are from 0.0009 to 0.0013 grams. Also, the data about weights of the accelerator indicates a Cpk of 1.67. Therefore, this process was complying with the specifications of the customer.
Finally, the Multi-Vari analysis allowed the determination of possible causes involved in the height variation. To do the Multi-Vari chart, a long term random sample of size 48 was selected, stratifying by diaphragm batch, speaker type and shift. The main causes of variation seem to be the batch raw material (diaphragm and coil) used, and the second work shift in which the operators had not been properly trained. See Figure 16. Two different lots of coil and the two shifts were included in the statistical analysis to verify whether raw material and shifts were affecting the quality characteristic. The results of multivariate analysis indicated that these factors did not influence significantly the subassembly height.

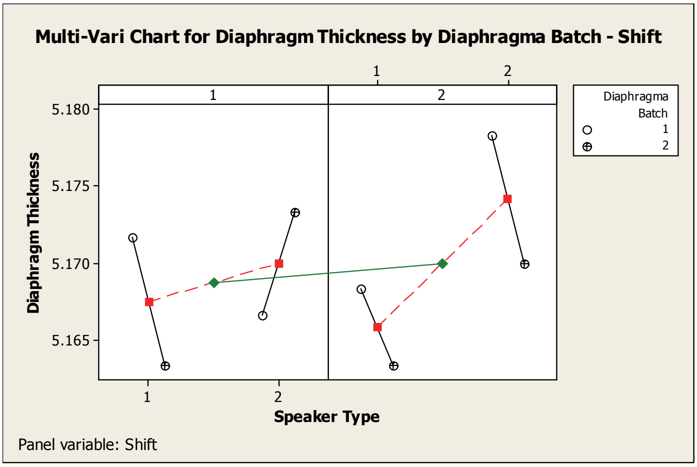

Fig. 16. Multi-Vari chart for Height by Batch, Speaker Type and Shift.

Improvement: In the previous phase, one of the causes of variation on the Height of Coil-Diaphragm was found to be the Tooling height. The tooling height decreases due to the usage and wearing out. The phase began with new drawings of the tooling subassembly coil and diaphragm, and the verification and classification of drawings and tooling, respectively. The required high-store tools (maximum and minimum) supplemented this as well. Tooling drawings were developed for the production of the subassemblies coil-diaphragm, the coil-diaphragm subassemblies, controlling the dimensions carefully according to work instructions. No importance had been previously given to the tools design, drawings and production.

After all the improvements were carried out, a sample of thirty-six pieces was drawn to validate the tooling correction actions by estimating the Cpk. The normality test was performed and the conclusion was that the data is not normally distributed. Then, Box-Cox transformation was applied to the reading to estimate the process capability. Figure 17 shows the substantial improvement made in the control of the heights variation. The study gave a Cpk of 2.69; which is greater than 1.67. This is recommended for the release of equipment and tooling.

Control: This investigation in addition to the support of management and the team all strengthened the engineering section and led to very good results. A supervisor currently performs quality measurements of the tooling for control. Such a tooling appraisal was not carried out as part of a system in the past, but now it is part of the manufacturing process. This change allowed an improvement through the control of drawings and tooling as well as by measuring the tooling before use in the manufacture of samples and their release.

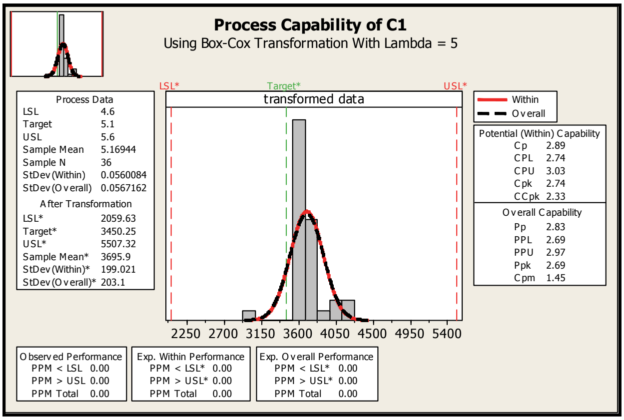

Fig. 17. Estimation of Cpk for Height Coil-Diaphragm with Control in the Tooling

A management work instruction was mandatory to control the production of manufacturing tooling for subassemblies. The requirement was fulfilled through the high-quality system ISO / TS 16949 under the name of "Design Tools". Furthermore, management began to standardize work for all devices used in the company. The work instruction "Inspection of Critical Tooling for the Assembly of Horns" was issued and applies to all the tooling mentioned in the instruction. Design of the tooling was documented in required format that contains the evidence for the revision of the tooling. Confirmatory tests were conducted to validate the findings in this project, and follow-up runs to be monitored with a control chart were established.

Conclusion: At the beginning of this project, the production process was found to be inadequate because of the large variation: Cpk´s within 0.35, as can be seen in Figure 13. Implementing the Six Sigma methodology has resulted in significant benefits, such as no more re-tooling or rework, no more scrap, and valuable time saving, which illustrates part of the positive impact attained, the process gave a Cpk of 2.69, as shown in Figure 17.

Furthermore, this project solved the problem of clearance between the coil and the diaphragm through the successful implementation of Six Sigma. The estimated savings per year with the subassembly is $31,048 U.S. dollars. The conclusion of this initial project has helped establish the objective to go forward with another Six Sigma implantation, in this case to reduce distortion in the sound of the horn.

5. Improvement of binder manufacturing process

In process of folders, a family of framed presentation folders is manufactured. The design has a bag for placing business cards. The first thing that took place in this project was to define the customer requirements:

1. Critical to Quality: Folders without damage and without Flash.
2. Critical for Fill Rate: Orders delivered on time to the distribution centers and orders delivered on time to customers.
3. Critical for Cost: Less waste of materials and scrap.

Define: The problem is that the flash resulting in the sealing operation of business cards, damages the subsequent folders rivet operation, reducing the quality and increasing the levels of scrap. Figure 18 shows the sample of the location and the business card bag. The Figure 19 shows the distribution of plant where the problem appears.

Fig. 18. Folder and Business Card Holder

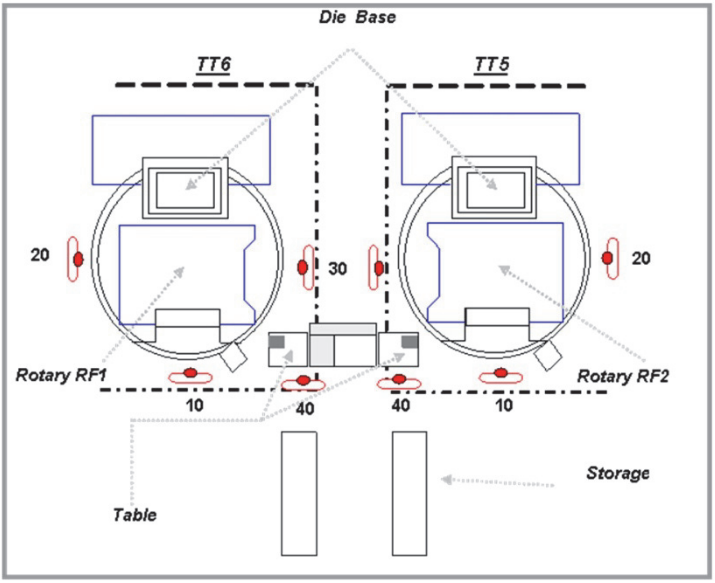

Fig. 19. Layout of the machines Rotary Table 5& 6

Measure: The record sheet is a simple, graphical method for collection of the occurrences of events. Each mark represents an occurrence and the operator can quickly tabulate the count of the occurrences. Table 14 shows the record sheet for the defects of the binder.

Defect	Count															Subtotal
Feeder	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	14
Maintenance	x	x														2
Vinyl Problem	x															1
RF Problem	x															1
Load and unload problem	x	x	x	x	x	x	x	x								8
Total																26

Table 13. Record Sheet for the location of problem appearance

The Pareto Chart helps focus the most important causes; Figure 20 shows the main flaws in the area of folders and the damage, The most common defect is the damage in the BC holder, that is the major contributor with 60% of the problems of the BC.

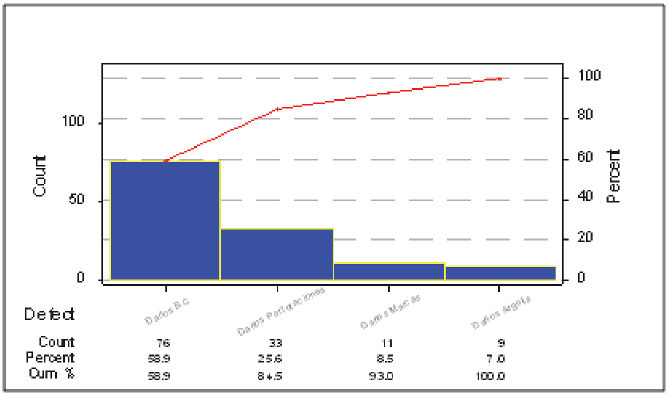

Fig. 20. Pareto Chart for the Type of Damage

Analysis: To illustrate where the damage occurs see Figure 21, that shows an overview of the “Hang”machine, as the station is loaded with subassemblies that will rivet the ring (the operator decides what amount to place), station load and the movement of the conveyor.
Rotary Table 4 (R4) machine is similar to the rotaries 5 & 6, except that here the BC is sealed to the bag. The R4 makes a good seal with the appropriate parameters, but it has the disadvantage of producing an average 20 pieces of scrap per shift. This is where our problem lies, because if the surplus is not cut or partially cut. This can damage other subsequent subassemblies in the riveting process. A Cause and Effect diagram shows the supposed relationship between a problem and their potential causes. Figure 22 shows the possible causes of variation in the cutting of vinyl for BC, the machine where it is cut like a giant guillotine, caused flash after the sealing operation around the vinyl bag.

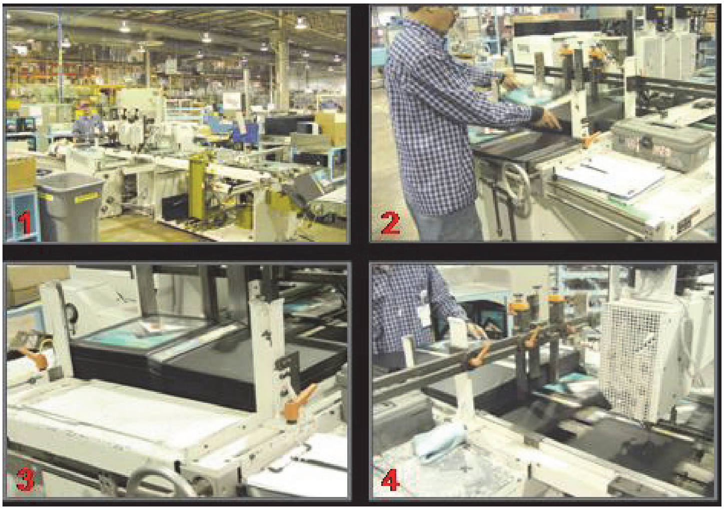

Fig. 21. Hang Machine where the Loadingand Unloading problem Ocurrs

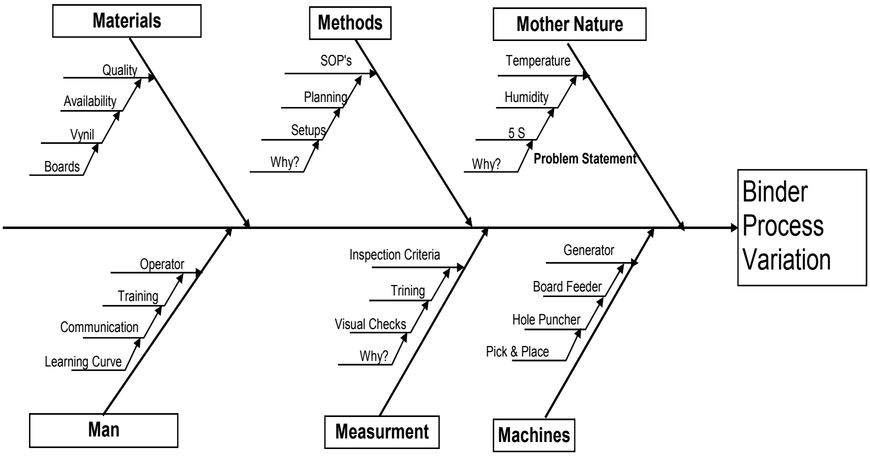

Fig. 22. Cause and Effect Diagram for the Assembly Binder Process

Improvement: A possible solution was changing the design of the BC, shown in Figure 23. This modification was to replace the vinyl bag with 4 cuts at 45 degrees (this design is used in another model of folders). This option would reduce the cost by not using clear vinyl for BC, by eliminating the cutting and sealing operations; by doing so, additionally, completely eliminates the damage caused by the flash of BC.

Marketing rejected this proposed BC bag, arguing that the folder was submitted and that the update of the catalogs on the Internet had been just published. Therefore it can be able to modify it until next year. This option was rejected, and then team decided to build a die cut (36 holes), with exact measurements of the size of BC bag in order to avoid the variation in the BC gap (see Figure 24 and 25).

Fig. 23. BC Bags Actual and Proposed for Reducing the Scrap

Fig. 24. Press Machine that cuts the BC Bags

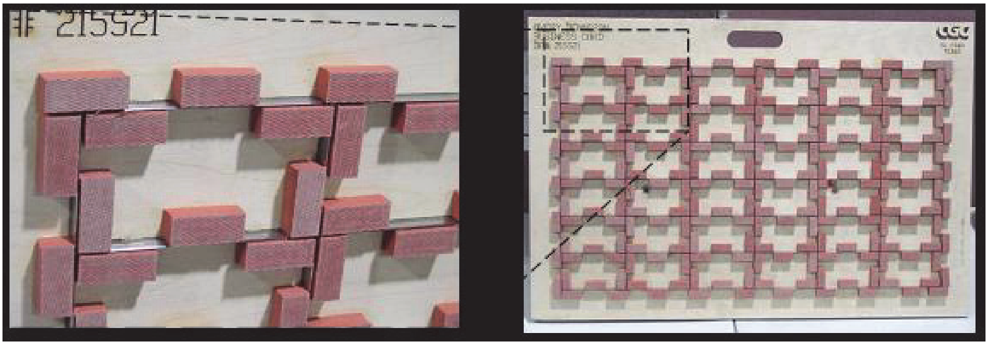

Fig. 25. New Die Design with Smaller Tolerance in the BC Bag Dimensions

Another improvement was to change the dishes where the BC is placed to be sealed with the bag; a frame of Delrin was used with the exact size of BC, to serve as a protector. Consequently, the BC does not move until it passes the sealing operation. The results of the changes made were remarkable. BC cutting was accurate and there was not any flash (see Figure 26).

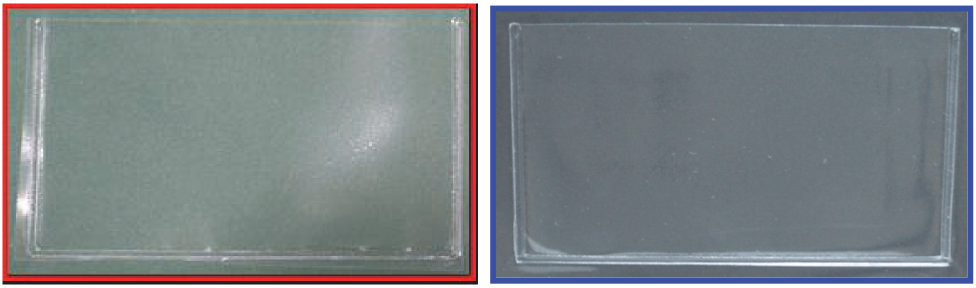

Fig. 26. Product before and after the Improvement

Control: The use of the fixture was supervised being mandatory its use, it was used to comply with the exact dimensions and assure that the measure of the BC is correct (see Figure 27). The reduction of defects was from 90 pieces to 3. These 3 defects occurred because the vinyl was misaligned.

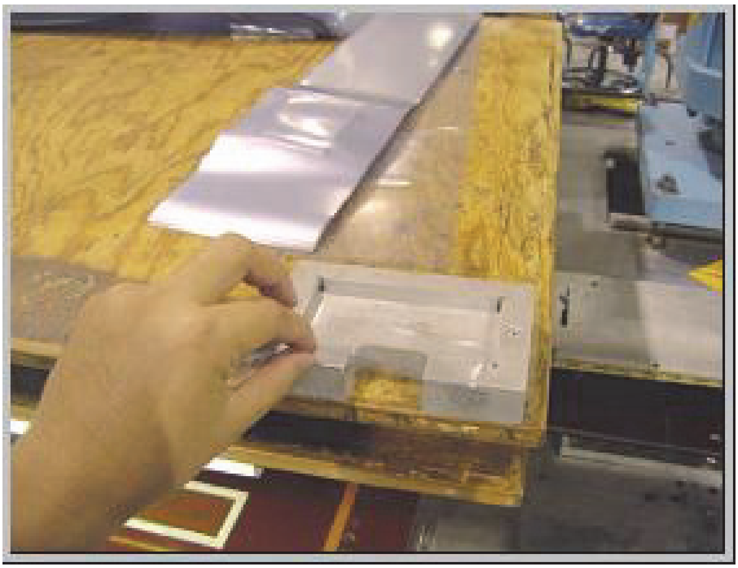

Fig. 27. Fixture to check the correct dimension of BC

6. Conclusions

The implementation of these projects has been considered to be a success, since in the project of manufacture of circuits the based line of the project was 3.35 sigma level and the gain 0.37 of sigma. Which represent the elimination of 1.88% of nonconforming units or 18,788 PPM´s. The second project speaker manufacturing, the initial Cpk was .35 and after the project implementation the resulting Cpk is 2.69. The binder manufacturing process was improved from 90 to 3 defects in a shift.

The key factors in these implementations were; team work, multidisciplinary of the team, management commitment, team training and knowledge, communication and project management (Antony & Banuelas, 2002; Byrne, 2003; Henderson & Evans, 2000). Also, the maintenance preventive program was modified to achieve the goal stated at the beginning of the project 2. It is important to mention that organizations management was very supportive and encouraging with the project teams. The Six sigma implementation can be helpful in reducing the nonconforming units or improving the organization quality and personal development. The conclusion of these projects has helped establish the objective to go forward with others Six Sigma implementations. This results show that DMAIC methodology is a systematic tool that ensures the success out of a project. In addition to the statistical tools that factual information is easier to understand and to show evidence about the veracity of the results, because many of them are very familiar.

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6

Applying Six Sigma Concepts, Techniques and Method for Service Management: Business and IT Service Management (BSM & ITSM)

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1. Introduction

Six Sigma methods and techniques are applied in business & IT projects for product (Goods and Services) & process design (Define, Measure, Analyze, Design and Verify or DMADV) and improvements (Define, Measure, Analyze, Improve and Control or DMAIC). Six sigma methodologies have been applied within the IT Service Management disciplines primarily for Service and Process Improvement and Optimization.

Six Sigma methods and techniques have a relatively rich history with the manufacturing industry and tangible products vis-à-vis intangible and perishable services. As the services industries look forward to the advent of productization of services or service products, there is an attempt to minimize variations in service quality via service design and service improvement projects. The focus of these projects range from service definition to service systems to service automation (i.e. making service less labour intensive). As such, six sigma methods and techniques have a major role to play in both design and improvement of services and service management processes.

Even though Six Sigma concepts & techniques can be applied for most if not all IT Service management processes (see ITIL v3 for taxonomy of Service Management processes mapped to the Service Life Cycle), they will primarily relate to Service Quality Management processes such as:

- Service Availability Management
- Service Capacity Management
- Service Performance Management
- Service Continuity Management
- Service Security Management
- (Service) Event Management
- (Service) Incident Management and
- (Service) Problem Management

This paper discusses six sigma methods (both DMAIDV and DMAIC) and techniques as they apply to the fives stages of Process Maturity (or Service Management Maturity)

- Ad hoc
- Defined
- Measured

- Matured &
- Optimized

Note: Some of the techniques discussed here are generally used within the Six Sigma and Quality Control and Management context and projects, but are also used in several non six sigma projects and context.

Note: Design for Six Sigma (DFSS) has not only been applied to Service Management processes but also for sub-processes such as Root Cause Analysis (RCA) as a sub-process within problem management or Incident Reporting (IR) as a sub-process within incident management.

IT Service Management Process Improvement relates to IT Service Management Maturity and the Continuous Process Improvement or CPI program. Service Quality is a function of (or depends on) People, Processes, Information and Technology and the maturity level of Service Quality Management as an IT process domain. Service Quality Management processes as IT processes play a critical role in understanding and achieving service quality objectives and targets.

Service Management as a practice has five maturity levels and each service management domain or IT process can be at different levels of maturity at a given time (see figure 1 below for the five different maturity levels and the corresponding process capabilities / features). Process maturity (and higher ratings of process maturity level) is attained via incremental process improvement projects. It is important to note that processes can only be improved from one maturity level to another sequentially. It is extremely difficult to skip maturity levels.

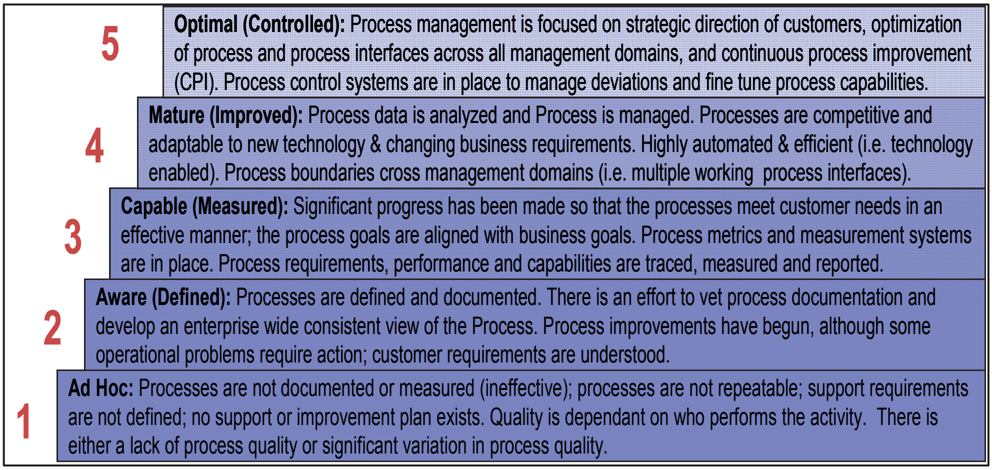

Fig. 1. IT Service Management (ITSM) Process Maturity Levels

Six Sigma DMADV – Define (Process), Measure, Analyze, Design and Verify methodology is relevant for moving from level 1 to level 2 i.e. essentially developing an enterprise wide definition of an IT process and gathering requirements as part of the process design work.

Six Sigma DMAIC – Define (Process Improvement Problem), Measure, Analyze, Improve and Control as a methodology is relevant for growing the process from maturity level 2 to maturity level 3, 4 and 5.

See figure 2 below.

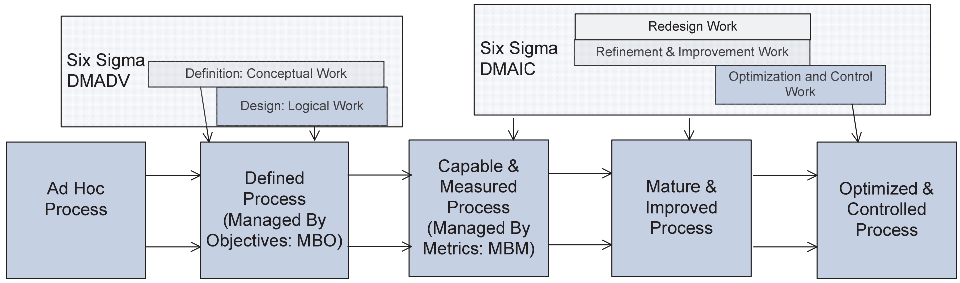

Fig. 2. Six Sigma and IT Service Management (ITSM) Process Maturity Levels

2. Process maturity levels

- Ad Hoc (Level 1)

A process is at maturity level 1, when the enterprise does NOT have an enterprise wide consistent view of the process i.e. the process is NOT defined via documentation and published to spread process awareness within the extended enterprise. It is likely that certain process activities are defined and implemented in certain silos in the enterprise such as a business unit or a domain team (e.g. an enterprise network team).

Application of six sigma example: several lean six sigma concepts such as reducing or eliminating process waste can be applied during this stage of process maturity.

- Defined and Aware (Level 2)

Level 2 maturity implies the process has been well defined; the process definition documents have been vetted among the process community and approved by key process stakeholders as well as published enterprise wide. This implies that the enterprise has a consistent view of the process and the different organizations are aware of the process, current process capabilities (activities, interfaces, tools, organization, among others). Process interfaces are also defined. There can be several qualitative process improvement projects (type 1 process improvement projects – see section below for a discussion on Type 1 and Type 2 projects) at this level of maturity as the process metrics (critical success factors, key goal indicators, key performance indicators, among others) are understood and documented. At this stage of process maturity, the process management team should be focused on managing the process with Management by Objective (MBO) principle.

Application of six sigma example: development of smart process metrics that align with the process principles, policies and guidelines. A process principle can map to multiple process policies and a process policy can map to multiple process guidelines (detailed guidelines) and rules. SMART metrics can directly map to guidelines. The principles to policies to guidelines (rules) heirarchy can provide guidance to automate the process and certain process activities.

Fishbone or Ishikawa diagrams can be used help define process and process scope. As an example: Faulty components impacting service availability is a service availability management process issue while a denial of service attack impacting service availability is a security management process issue.

DMADV method directly related to process maturity level 2.

- Capable and Measured (Level 3)

Level 3 maturity implies that the qualitative process improvement projects initiated and completed at Level 2 have improved the process capabilities. The process management team has the capability to implement all relevant process activities, process interfaces and process related projects. More importantly, the process management is now focused on managing the process with Management by Metrics (MbM) principles. This implies that there is a robust and reliable measurement system in place to collect data on the SMART (Specific, Measurable, Attainable, Relevant and Time bound) process metrics. At this stage, the process management can initiate type 2 process improvement projects for those process metrics which already have an appropriate measurement system. The six sigma DMAIC method directly relates to process maturity levels 3, 4 and 5.
Application of six sigma example: development of a measurement system to gather data on specific SMART process metrics that align with the process principles, policies and guidelines.

- Improved and Mature (Level 4)

At this level of maturity, the process management team is actively engaged in analyzing the process data and managing the process based on the results of the analysis. The process should be performing relatively well on most relevant process Key Performance Indicators (KPIs) based on the results of the improvement projects initiated at Level 2 and Level 3. The process and process capabilities are competitive as several of them have been technology enabled. Process is significantly technology enabled and as such is adaptable to changing business needs and requirements. Process Interfaces are not only defined, but also implemented and relatively mature. Process interfaces with other Business and IT Processes and Services are implemented, mature and efficient. Most process improvement projects are type 2 projects.
Note: Very few IT organizations reach maturity level 4 and 5.
Application of six sigma example: six sigma process improvement projects focused on a specific quantifiable process improvement problem that improves the process along one or more key process metric (SMART metric). Optimized and Controlled (Level 5)
Very few organizations in the world have reached this level of maturity for process management. At this level of maturity, process management is focused on process efficiency, optimization and control as well as the strategic direction of the customer (business), and improving alignment with business, optimization of the process, process activities and process interfaces via a set of Type 2 process improvement projects. The process management team has also established a process control system to manage process deviations (outliers, drift, among others) i.e. a process exception handling system and sustain the process performance at the improved level.
Application of six sigma example: six sigma process improvement project focused on the development of one or more control systems focused on specific Process related KPIs. ITSM Process specific control systems are being developed by leading IT companies, as a case in point, an intelligent scaling engine or ISE (patented by author) can use real time service and resource data to make analytics based decisions to scale up or down specific services, service components and infrastructure resources that enable the service. ISE is specifically applicable to the performance and capacity management as an IT process.

3. Type 1 process improvement projects i.e. quantitative improvement projects

These projects occur when the process has reached level 3 or higher levels of maturity (i.e. Process measurement systems are in place with process metrics and data for those metrics) and the improvement projects are focused on improving the process performance with regard to specific process metric or process related metrics (SMART objectives – Specific, Measurable, Attainable, Relevant and Time-Bound Objectives). Six Sigma as a process improvement method which leverages the define (define a process improvement problem / opportunity) , measure, analyze, improve and control or DMAIC method, is very relevant for these types of process improvement projects.

The process and process related metrics can be metrics associated with the process inputs, actual processing (process activities), process outputs as well as process outcomes. In general, it is a good practice to focus Type 1 process improvement projects on metrics associated with the process outcomes (which are, generally, of more interest to business & process stakeholders). The process could focus on improving a measure of central tendency (such as mean – example mean time to recover/restore service) or a measure of variation (such as standard deviation – variation associated with the time to recover/restore service by service incident).

An example would be a six sigma project to improve average and variation (standard deviation) associated with the time to restore service via service recovery plans (which focus on fast recovery and restore technologies and updated service and component recovery plans and procedures for a set of services). The average time to restore service after a service incident can be measured before and after the project was implemented to study the impact of the six sigma project.

4. Type 2 process improvement projects i.e. qualitative improvement projects

These projects can occur at any level of process maturity and do NOT have quantitative process or process related metrics associated with them.

An example would be a documentation project to define the process conceptually and logically and bring about a consistent enterprise wide view of the process and process objectives, scope, activities, among others. This would typically be done when a process is at level 1 in a process maturity scale.

Another example would be designing and building measurement systems to collect data around process metrics. This would typically be done when a process is at level 3 in a process maturity scale and aims to achieve the next level of process maturity.

In a purely technical sense, type 1 process improvement projects are the true process improvement projects and relate to the technical definition of improvement (shown below).

Definition of Improvement:

Improvements are Outcomes that when compared to the 'before' state, show a measurable increase in a desirable metric or decrease in an undesirable metric

5. Salient characteristics of six sigma for service management

Some of the key characteristics of six sigma methods and tools that are relevant for Business and IT service management and service quality management are discussed below:

- Customer Centered (Customer or End User Centricity)

Several six sigma concepts such as Voice of the Customer (VOC) and Critical Customer Requirements are relevant for the service quality or non functional requirements gathering and documentation process.

- Process Focused

Extraordinary Process for Ordinary People

ITIL v3 and other IT operating models focus on multiple IT process domains. Service Quality Management itself is a set of processes in the service design phase of the service life cycle but has implications for the entire service life cycle. Six sigma takes a process approach to quality management & quality improvement (both product/service as well as process quality) and as such can be applied to

1. IT enabled Business Service Quality & IT Service Quality as well as
2. Quality Management as a process domain in Business Service Management and IT Service Management models.

- Data Driven

Six sigma projects are data driven and depend on data and analysis of data for quality improvements. Service and process quality data is generated from multiple tools, including monitoring and management tools. IT organizations can and do maintain historical and current service and process quality data which are relevant for applying six sigma projects.

- Follows a structured method & roadmap

DMAIC and DMAIDV are two methods applied for
Product (such as Hardware) and Service (such as messaging) design
Product / Service Improvements
Process Design (such as Service Incident Management) and
Process Improvements

- Oriented toward Business results.

The primary objectives of Business Service Management (BSM) and IT Service Management (ITSM) focus on business outcomes and aligning business and IT, as such six sigma's focus on business results maps to service management focus on business objectives.

6. Six sigma tools for service management

In general the tools and techniques discussed here can be used for both process design and process improvement projects, however, few of them are more applicable for process definition and design while others are more applicable for process improvement and control projects.

7. QFD and NFR Framework

Quality Function Deployment and the House of Quality are critical tools for identifying, gathering, prioritizing, implementing and tracing service quality or non-functional requirements (both IT service and IT process requirements). IT processes are generally automated and implemented with a set of ITSM tools and technologies – hence QFD and HOQ can be applied to these tooling requirements also.

In my Non Functional (or Service Quality) Requirements (NFR) framework paper (The Open Group White Papers 2009 – see references), I discuss how service quality objectives such as service availability, or service continuity or service usability objectives can be documented as funded requirements (business, customer and end user centric), which then can be translated to design specifications and configuration parameters for service run time environment. I have also argued that we can develop enterprise specific and enterprise level service quality models, that document these objectives, requirements, specifications, parameters and metrics (measurable) to allow for reuse (do not have to reinvent the wheel with every service and every business unit) and traceability of service quality requirements.

8. DPMO for ITSM processes and services

Defects Per Million Opportunities (DPMO) is a relatively simple concept and is applied using a simple approach for the manufacturing industry engaged in producing tangible products. However, DPMO can be applied in the service industries engaged in producing intangible, inseparable (production & consumption), perishable and more variable services using a different approach.

Specifically for the IT services and IT enabled business services, we can take two simultaneous approaches toward DPMO, i.e. a) DPMO associated with the service systems or systems that enable the service and b) DPMO associated with the customer experience or parts of the customer experience. Here we elaborate DPMO associated with the customer experience.

DPMO can be applied to each instance of customer interaction (example: Browsing an ecommerce site dedicated for the travel industry – hotels, rental cars, flights among others) i.e. treating each interaction as an opportunity.

DPMO can be applied to each instance of customer transaction (example: request and purchase of an online e-ticket) i.e. treating each customer transaction (or request for a transaction) as an opportunity.

DPMO can be applied to each instance of customer consumption (service provider production) – (example: The acts of checking in & choosing seat, boarding, taking an airline seat, experiencing air travel and off-boarding an airplane) i.e. treating each act of consumption as an opportunity.

DPMO can be applied to each instance of the customer experience (example: all of the three above, plus post sales service etc) i.e. treating the individual customer experience as an opportunity.

There fore, TCI, TCT, TCC and TCE (Total Customer Interaction, Transactions, Consumption and Experience can all be related to total opportunities (TO) and are relevant for determining defects per million opportunities.

The CRM, CIM and CEM (Customer Relationship Management, Customer Interaction Management and Customer Experience Management) software suites as well as Interactive Intelligence (Customer Interactive Intelligence) software and tools help service providers collect data to support objectives and metrics around defects per million opportunities (DPMO). In other words, these tools provide data for these measurements related to service DPMOs. This is true for IT enabled business services and IT services as well as IT enabled business processes and IT processes.

9. Critical to Quality (CTQ) and Vital Business Functions (VBFs)

CTQ tree maps Customer Key Goal Indicators or Broad Customer / End User related Objectives to more specific customer related performance indicators or KPIs using such approaches as VOC or Voice of the Customer. When CTQ is applied in the context of IT enabled Business Services we get vital business functions (within a Business Service), which is an ITSM term. Therefore CTQ provides a means to arrive at VBFs.

Note: Key Goal Indicators (KGIs) and Key Performance Indicators (KPIs) are commonly used by CIO Offices and IT management and are also part of such IT frameworks as COBIT (Control Objectives for Information and related Technologies) and ITIL (IT Information Library). However, CTQs focus on broad customer objectives (KGI) and translating the same to more specific customer requirements (and metrics or KPIs associated with them).

10. Objectives (KGI) and SMART metrics (KPI)

Process KGI or Process Objectives are critical for Management by Objectives or MBO particularly at process maturity levels of 1 and 2. As the process measurement system is designed and implemented at the maturity level 3, MBM or Management by Metrics can be initiated to reach maturity level 4 and above. SMART (Specific, Measurable, Achievable, Relevant and Time Bound) Process Metrics and Process Analytics play a key role for MBM.

11. Process analytics

Both statistical and non-statistical analytical techniques propagated via the six sigma methods, particularly during the analyze phase of six sigma project have great relevance for service management process analytics. As an example: Event Tree Analysis, Fault Tree Analysis and Decision Tree Analysis, a set of related non-statistical analytical techniques (used in six sigma projects) have direct relevance for event, incident and problem management (three operational processes in service management) and indirect relevance for availability, continuity, performance & capacity, and security management (four design processes in service management). Most, if not all, analytical techniques covered by the six sigma methods are either directly relevant or indirectly relevant for one or more of service management processes.

12. Fishbone or ishikawa analysis

Fishbone diagrams can be useful to identify and analyze potential causes for Service Quality issues. In this case we are using fishbone diagrams to better understand service availability issues. Fishbone analysis and diagrams can be useful tools to identify and analyze potential causes for Service Unavailability. Overall service availability and service unavailability are a function of multiple capabilities (see Fishbone One):

- Technology Capabilities (see Fishbone Two)
- Process Capabilities (see Fishbone Three)
- Organizational Capabilities and
- Information Capabilities

The fishbone diagrams are generic diagrams and can be used to for multiple purposes including conceptualizing service availability models. The diagrams below depict the Y is Fn of x (x1, x2, x3 ….) model. You can further decompose these models by making each of the x (or independent variable) a Y or dependent variable. These models can and need to be customized for each service. The x or independent variables impact overall service availability can also change with time. Fishbone diagrams can also be used as input for problem management.

Fishbone Diagrams for Understanding Service Availability:

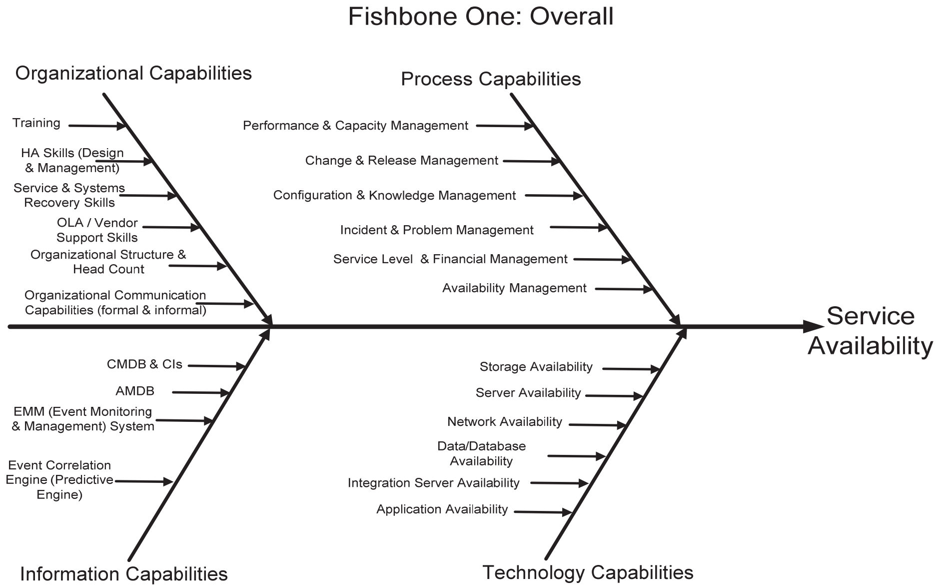

Fig. 3. Fishbone One for Overall Service Availability

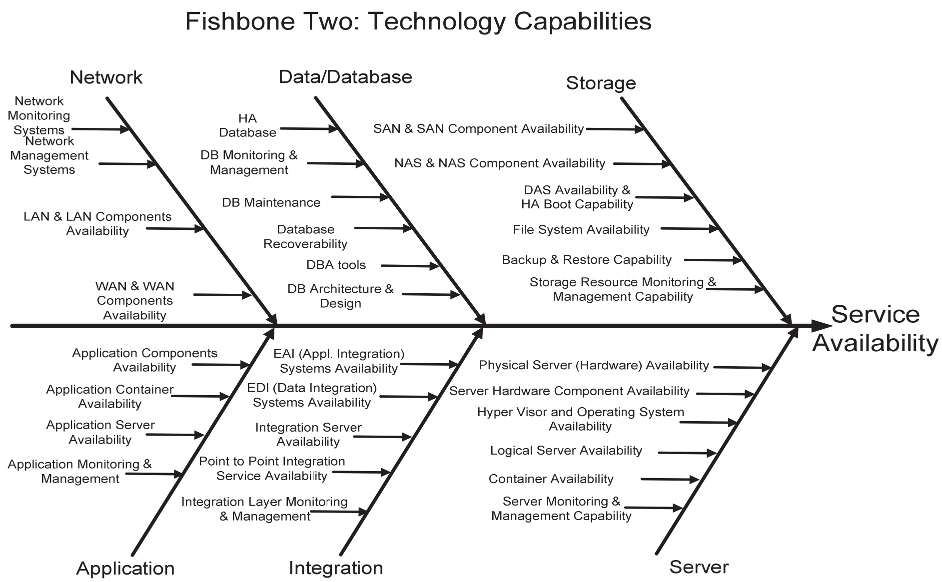

Fig. 4. Fishbone Two for Technology Factors

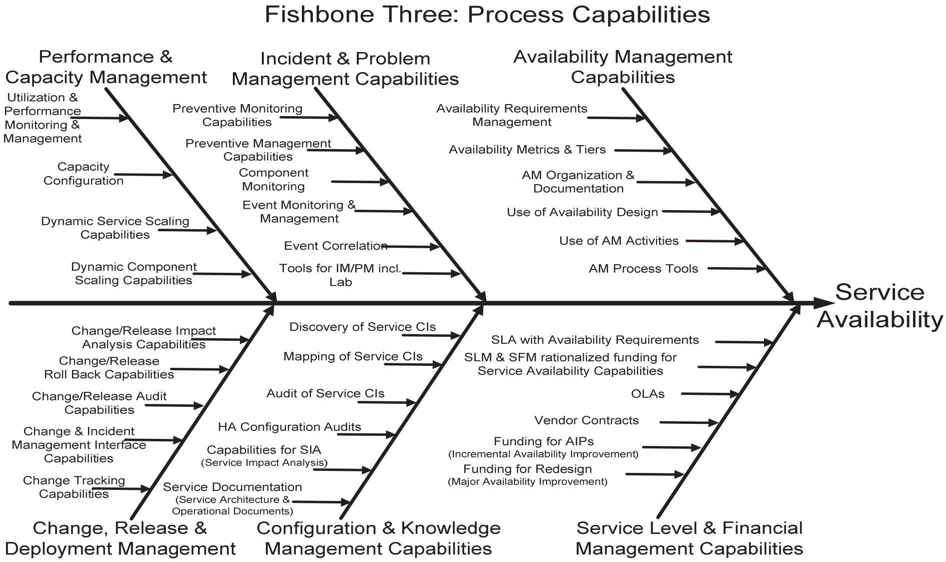

Fig. 5. Fishbone Three for Process Factors

We have only discussed a few key examples of Six Sigma tools and techniques and their application to business and IT service management. Therefore, this is not an exhaustive list of relevant six sigma tools applicable for service management.

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7

Demystifying Six Sigma Metrics in Software

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1. Introduction

Design for Six Sigma (DFSS) principles have been proved to be very successful in reducing defects and attaining very high quality standards in every field be it new product development or service delivery. These Six sigma concepts are very tightly coupled with the branch of mathematics i.e. statistics. The primary metric of success in Six sigma techniques is the Z-score and is based on the extent of "variation" or in other words the standard deviation. Many a times, statistics induces lot of fear and this becomes a hurdle for deploying the six sigma concepts especially in case of software development. One because the digital nature of software does not lend itself to have "inherent variation" i.e. the same software would have exactly the same behavior under the same environmental conditions and inputs. The other difficult endeavor is the paradigm of samples. When it comes to software, the sample size is almost always 1 as it is the same software code that transitions from development phase to maturity phase. With all this, the very concept of "statistics" and correspondingly the various fundamental DFSS metrics like the Z-score, etc start to become fuzzy in case of software.

It is difficult to imagine a product or service these days that does not have software at its core. The flexibility and differentiation made possible by software makes it the most essential element in any product or service offering. The base product or features of most of the manufactures/service providers is essentially the same. The differentiation is in the unique delighters, such as intuitive user interface, reliability, responsiveness etc i.e. the non-functional requirements and software is at the heart of such differentiation. Putting a mechanism to set up metrics for these non-functional requirements itself poses a lot of challenge. Even if one is able to define certain measurements for such requirements, the paradigm of defects itself changes. For e.g. just because a particular use case takes an additional second to perform than defined by the upper specification limit does not necessarily make the product defective.

Compared to other fields such as civil, electrical, mechanical etc, software industry is still in its infancy when it comes to concepts such as "process control". Breaking down a software process into controlled parameters (Xs) and setting targets for these parameters using "Transfer function" techniques is not a naturally occurring phenomenon in software development processes.

This raises fundamental questions like –

- How does one approach the definition of software Critical To Quality (CTQs) parameters from metrics perspective?
- Are all software related CTQs only discrete or are continuous CTQs also possible?
- What kind of statistical concepts/tools fit into the Six Sigma scheme of things?
- How does one apply the same concepts for process control?
- What does it mean to say a product / service process is six sigma? And so on …

This chapter is an attempt to answer these questions by re-iterating the fundamental statistical concepts in the purview of DFSS methodology. Sharing few examples of using these statistical tools can be guide to set up six sigma metrics mechanisms in software projects.

This chapter is divided into 4 parts --

1. Part-1 briefly introduces the DFSS metrics starting from type of data, the concept of variation, calculation of Z-score, DPMO (defects per million opportunities) etc
2. Part-2 gives the general set up for using "inferential statistics" – concepts of confidence intervals, setting up hypothesis, converting practical problems into statistical problems, use of transfer function techniques such as Regression analysis to drill down top level CTQ into lower level Xs, Design of experiments, Gage R&R analysis. Some cases from actual software projects are also mentioned as examples
3. Part-3 ties in all the concepts to conceptualize the big picture and gives a small case study for few non-functional elements e.g.Usability, Reliability, Responsiveness etc
4. The chapter concludes by mapping the DFSS concepts with the higher maturity practices of the SEI-CMMI^R model

The Statistical tool Minitab^R is used for demonstrating the examples, analysis etc

2. DfSS metrics

2.1 The data types and sample size

The primary consideration in the analysis of any metric is the "*type of data*". The entire data world can be placed into two broad types - qualitative and quantitative which can be further classified into "*Continuous*" or "*Discrete*" as shown in the figure-1 below.

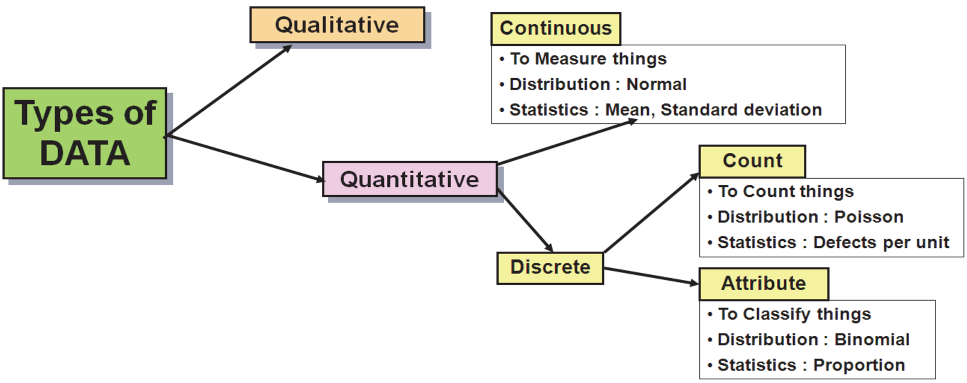

Fig. 1. The Different Data Types

The Continuous data type as the name suggests can take on any values in the spectrum and typically requires some kind of gage to measure. The Discrete data type is to do with counting/classifying something. It is essential to understand the type of data before getting into further steps because the kind of distribution and statistics associated vary based on the type of data as summarized in figure-1 above. Furthermore it has implications on the type of analysis, tools, statistical tests etc that would be used to make inferences/conclusions based on that data.

The next important consideration then relating to data is *"how much data is good enough"*. Typically higher the number of samples, the better is the confidence on the inference based on that data, but at the same time it is costly and time consuming to gather large number of data points.

One of the thumb rule used for Minimum Sample size (MSS) is as follows :-

- For Continuous data: *MSS = (2*Standard Deviation/ Required Precision)*^{2}. The obvious issue at this stage is that the data itself is not available to compute the standard deviation. Hence an estimated value can be used based on historical range and dividing it by 5. Normally there are six standard deviations in the range of data for a typical normal distribution, so using 5 is a pessimistic over estimation.
- For Discrete-Attribute data : *MSS = (2/Required Precision)*^{2} **Proportion * (1-proportion)* . Again here the proportion is an estimated number based on historical data or domain knowledge. The sample size required in case of Attribute data is significantly higher than in case of Continuous data because of the lower resolution associated with that type of data.

In any case if the minimum sample size required exceeds the population then every data point needs to be measured.

2.2 The six sigma metrics

The word "Six-sigma" in itself indicates the concept of variation as *"Sigma"* is a measure of standard deviation in Statistics. The entire philosophy of Six Sigma metrics is based on the premise that *"Variation is an enemy of Quality"*. Too often we are worried only about "average" or mean however every human activity has variability. The figure-2 below shows the typical normal distribution and % of points that would lie between 1 sigma, 2 sigma and 3-sigma limits. Understanding variability with respect to *"Customer Specification"* is an essence of statistical thinking. The figure-3 below depicts the nature of variation in relation to the customer specification. Anything outside the customer specification limit is the ***"Defect"*** as per Six Sigma philosophy.

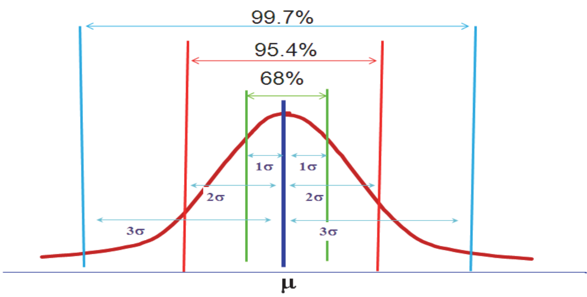

Fig. 2. Typical Normal Distribution

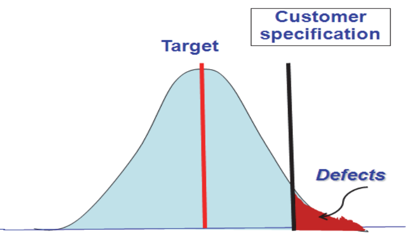

Fig. 3. Concept of Variation and Defects

2.2.1 The Z-score

Z-score is the most popular metric that is used in Six sigma projects and is defined as the *"number of standard deviations that can be fit between the mean and the customer specification limits"*. This is depicted pictorially in figure-4 below. Mathematically that can be computed as

$$Z = \frac{|CustomerSpecLimit - \mu|}{\sigma}$$

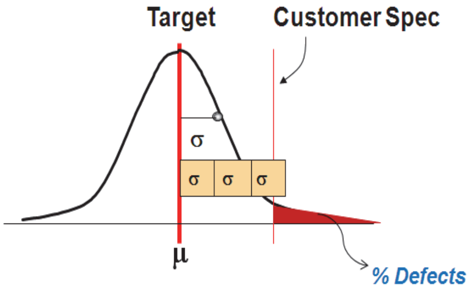

Fig. 4. The Z-score

So a *"3-Sigma"* process indicates 3 standard deviations can fit between mean and Specification limit. In other words if the process is centered (i.e. target and mean are equal) then a 3-sigma process has 6 standard deviations that can fit between the Upper Specification limit (USL) and Lower specification limit (LSL). This is important because anything outside the customer specification limit is considered a defect/defective. Correspondingly the Z-score indicates the area under the curve that lies outside Specification limits – in other words *"% of defects"*. Extrapolating the sample space to a million, the Z-score then illustrates the % of defects/defectives that can occur when a sample of million opportunities is taken. This number is called **DPMO** (Defects per million opportunities). Higher Z-value indicates lower standard deviation and corresponding lower probability of anything lying outside the specification limits and hence lower defects and vice-versa. This concept is represented by figure-5 below:

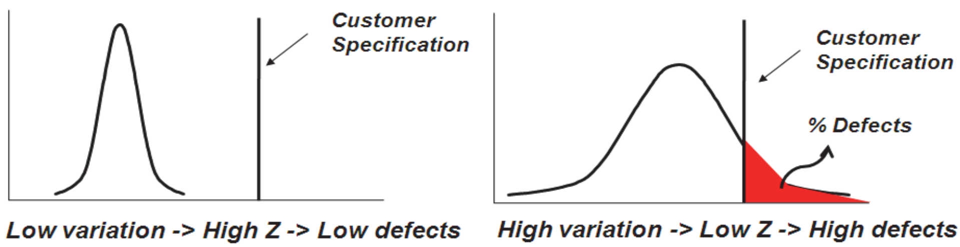

Fig. 5. Z-score and its relation to defects

By reducing variability, a robust product/process can be designed – the idea being with lower variation, even if the process shifts for whatever reasons, it would be still within the customer specification and the defects would be as minimum as possible. The table-1 below depicts the different sigma level i.e. the Z scores and the corresponding DPMO with remarks indicating typical industry level benchmarks.

Z_{ST}	DPMO	Remarks
6	3.4	World-class
5	233	Significantly above average
4.2	3470	Above industry average
4	6210	Industry average
3	66800	Industry average
2	308500	Below industry average
1	691500	Not competitive

Table 1. The DPMO at various Z-values

Z-score can be a good indicator for business parameters and a consistent measurement for performance. The advantage of such a measure is that it can be abstracted to any industry, any discipline and any kind of operations. For e.g. on one hand it can be used to indicate performance of an "Order booking service" and at the same time it can represent the "Image quality" in a complex Medical imaging modality. It manifests itself well to indicate the quality level for a process parameter as well as for a product parameter, and can scale conveniently to represent a lower level Critical to Quality (CTQ) parameter or a higher level CTQ. The only catch is that the scale is not linear but an exponential one i.e. a 4-sigma process/product is not twice as better as 2-sigma process/product. In a software development case, the Kilo Lines of code developed (KLOC) is a typical base that is taken to represent most of the quality indicators. Although not precise and can be manipulated, for want of better measure, each Line of code can be considered an opportunity to make a defect. So if a project defect density value is 6 defects/KLOC, then it can be translated as 6000 DPMO and the development process quality can be said to operate at 4-sigma level.
Practical problem: "*Content feedback time*" is an important performance related CTQ for the DVD Recorder product measured from the time of insertion of DVD to the start of playback. The Upper limit for this is 15 seconds as per one study done on human irritation thresholds. The figure-6 below shows the Minitab menu options with sample data as input along with USL-LSL and the computed Z-score.

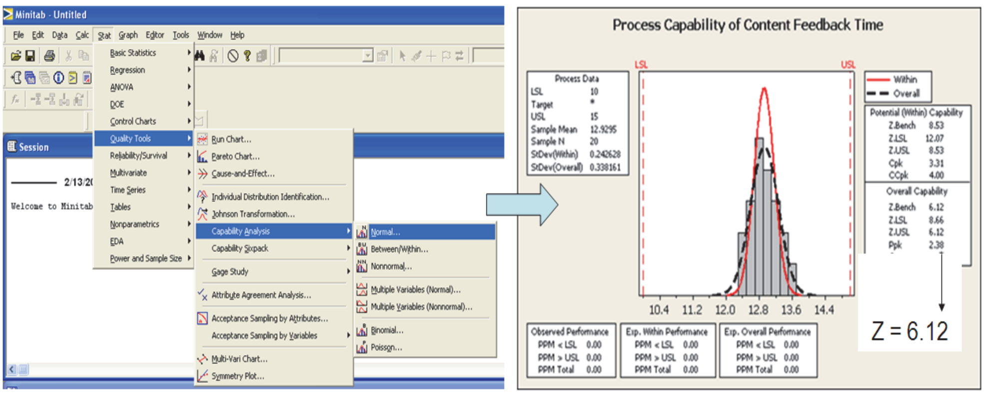

Fig. 6. Capability Analysis : Minitab menu options and Sample data

2.2.2 The capability index (Cp)

Capability index (Cp) is another popular indicator that is used in Six sigma projects to denote the relation between *"Voice of customer" to "Voice of process"*. Voice of customer (VOC) is what the process/product must do and Voice of process (VOP) is what the process/product can do i.e. the spread of the process.

$$Cp = VOC/VOP = (USL\text{-}LSL)/6\sigma$$

This relation is expressed pictorially by the figure-7 below

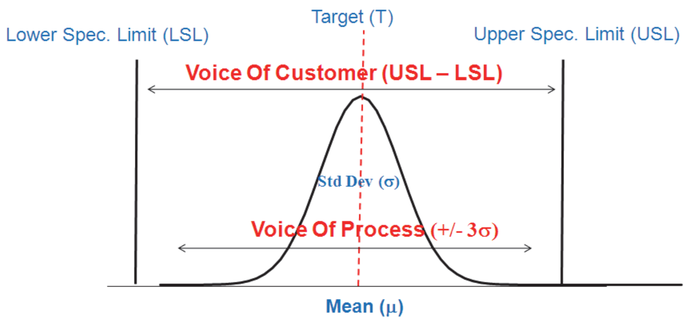

Fig. 7. Capability Index Definition

There is striking similarity between the definitions of Cp and the Z-score and for a centered normally distributed process the Z-score is 3 times that of Cp value. The table-2 below shows the mapping of the Z-score and Cp values with DPMO and the corresponding Yield.

Z_{ST}	DPMO	Cp	Yield
6	3.4	2	99.9997 %
5	233	1.67	99.977 %
4.2	3470	1.4	99.653 %
4	6210	1.33	99.38 %
3	66800	1	93.2 %
2	308500	0.67	69.1 %
1	691500	0.33	30.85 %

Table 2. Cp and its relation to Z-score

3. Inferential statistics

The *"statistics"* are valuable when the entire population is not available at our disposal and we take a sample from population to infer about the population. These set of mechanisms wherein we use data from a sample to conclude about the entire population are referred to as *"Inferential statistics"*.

3.1 Population and samples

"Population" is the entire group of objects under study and a *"Sample"* is a representative subset of the population. The various elements such as average/standard deviation

calculated using entire population are referred to as *"parameters"* and those calculated from sample are called *"statistics"* as depicted in figure-8 below.

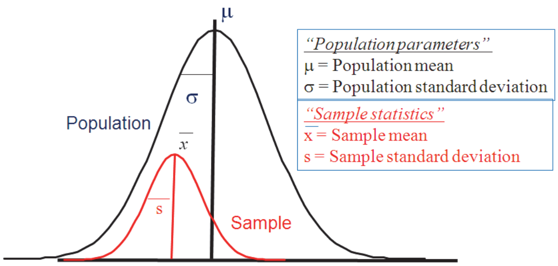

Fig. 8. Population and Samples

3.2 The confidence intervals

When a population parameter is being estimated from samples, it is possible that any of the sample A, B, C etc as shown in figure-9 below could have been chosen in the sampling process.

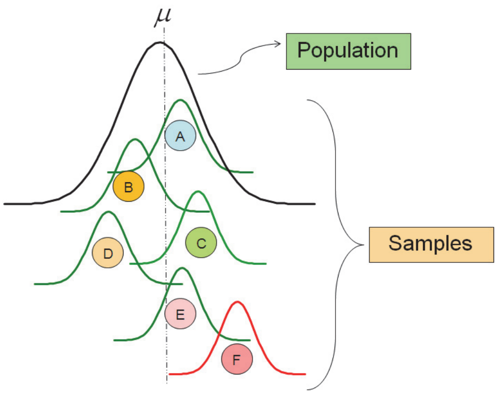

Fig. 9. Sampling impact on Population parameters

If the sample-A in figure-9 above was chosen then the estimate of population mean would be same as mean of sample-A, if sample B was chosen then it would have been the same as sample B and so on. This means depending on the sample chosen, our estimate of population mean would be varying and is left to chance based on the sample chosen. This is not an acceptable proposition.

From *"Central Limit theorem"* it has been found that for sufficiently large number of samples **n**, the *"means"* of the samples itself is normally distributed with mean at **μ** and standard deviation of **σ/sqrt (n)**.

Hence mathematically :

$$\mu = \bar{x} \pm z_{\alpha} s / \sqrt{n}$$

Where x is the sample mean, s is the sample standard deviation; α is the area under the normal curve outside the confidence interval area and z-value corresponding to α. This means that instead of a single number, the population mean is likely to be in a range with known level of confidence. Instead of assuming a statistics as absolutely accurate, *"Confidence Intervals"* can be used to provide a range within which the true process statistic is likely to be (with known level of confidence).

- All confidence intervals use samples to estimate a population parameter, such as the population mean, standard deviation, variance, proportion
- Typically the 95% confidence interval is used as an industry standard
- As the confidence is increased (i.e. 95% to 99%), the width of our upper and lower confidence limits will increase because to increase certainty, a wider region needs to be covered to be certain the population parameter lies within this region
- As we increase our sample size, the width of the confidence interval decreases based on the square root of the sample size: Increasing the sample size is like increasing magnification on a microscope.

Practical Problem: *"Integration & Testing"* is one of the Software development life cycle phases. Adequate effort needs to be planned for this phase, so for the project manager the 95% interval on the mean of % effort for this phase from historical data serves as a sound basis for estimating for future projects. The figure-10 below demonstrates the menu options in Minitab and the corresponding graphical summary for *"% Integration & Testing"* effort. Note that the confidence level can be configured in the tool to required value.

For the Project manager, the 95% confidence interval on the mean is of interest for planning for the current project. For the Quality engineer of this business, the 95% interval of standard deviation would be of interest to drill down into the data, stratify further if necessary and analyse the causes for the variation to make the process more predictable.

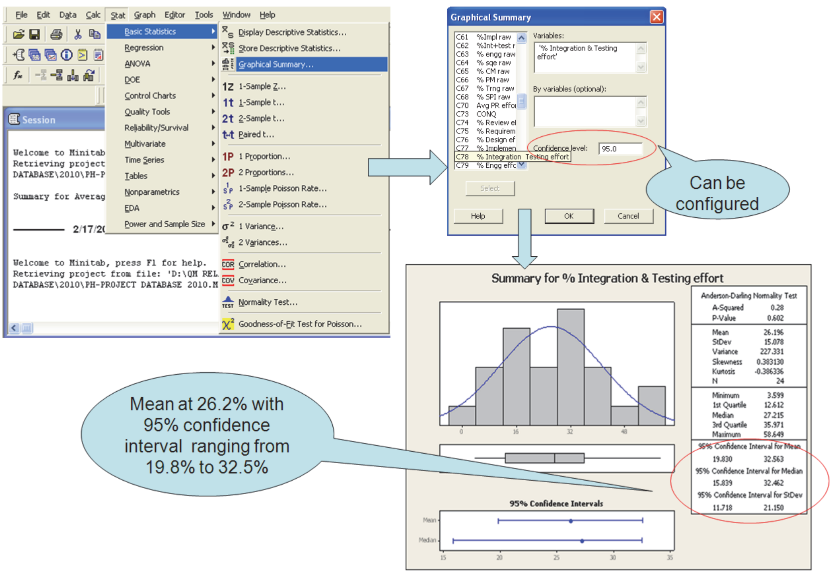

Fig. 10. Confidence Intervals : Minitab menu options and Sample Data

3.3 Hypothesis tests

From the undertsanding of Confidence Intervals, it follows that there always will be some error possible whenever we take any statistic. This means we cannot prove or disprove anything with 100% certainity on that statistic. We can be 99.99% certain but not 100%. *"Hypothesis tests"* is a mechanism that can help to set a level of certainity on the observations or a specific statement. By quantifying the certainity (or uncertainity) of the data, hypothesis testing can help to eliminate the subjectivity of the inference based on that data. In other words, this will indicate the *"confidence"* of our decision or the quantify risk of being wrong. The utility of hypothesis testing is primarily then to infer from the sample data as to whether there is a change in population parameter or not and if yes with what level of confidence. Putting it differently, hypothesis testing is a mechanism of minimizing the inherent risk of concluding that the population has changed when in reality the change may simply be a result of random sampling. Some terms that is used in context of hypothesis testing:

- **Null Hypothesis – H_o** : This is a statement of no change
- **Alternate Hypothesis - H_a** : This is the opposite of the Null Hypothesis. In other words there is a change which is statistically significant and not due to randomness of the sample chosen
- **α-risk** : This is risk of finding a difference when actually there is none. Rejecting H_o in a favor of H_a when in fact H_o is true, *a false positive*. It is also called as *Type-I error*
- **β-risk** : This is the risk of not finding a difference when indeed there is one. Not rejecting H_o in a favor of H_a when in fact H_a is true, *a false negative*. It is also called as *Type-II error*.

The figure-11 below explains the concept of hypothesis tests. Referring to the figure-11, the X-axis is the *Reality or the Truth* and Y-axis is the *Decision* that we take based on the data.

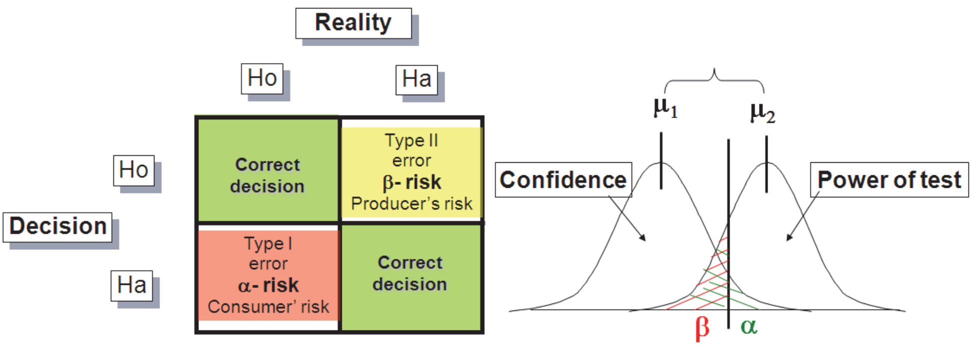

Fig. 11. Concept of Hypothesis Tests

If *"in reality"* there is no change (Ho) and the *"decision"* based on data also we infer that there is no change then it is a correct decision. Correspondingly *"in reality"* there is a change and we conclude also that way based on the data then again it is a correct decision. These are the boxes that are shown in green color (top-left & bottom-right) in the figure-11.

If *"in reality"* there is no change (H_o) and our *"decision"* based on data is that there is change(H_a), then we are taking a wrong decision which is called as *Type-I error*. The risk of

such an event is called as *α-risk* and it should be as low as possible. *(1-α)* is then the "*Confidence*" that we have on the decision. The industry typical value for α risk is 5%.
If "*in reality*" there is change (H_a) and our "*decision*" based on data is that there is no change (H_o), then again we are taking a wrong decision which is called a *Type-II error*. The risk of such an event is called as *β-risk*. This means that our test is not sensitive enough to detect the change; hence *(1-β)* is called as "*power of test*".
The right side of figure-11 depicts the old and the new population with corresponding α and β areas.
Hypothesis tests are very useful to prove/disprove the *statistically significant change* in the various parameters such as mean, proportion and standard deviation. The figure-12 below shows the various tests available in Minitab tool for testing with corresponding menu options list.

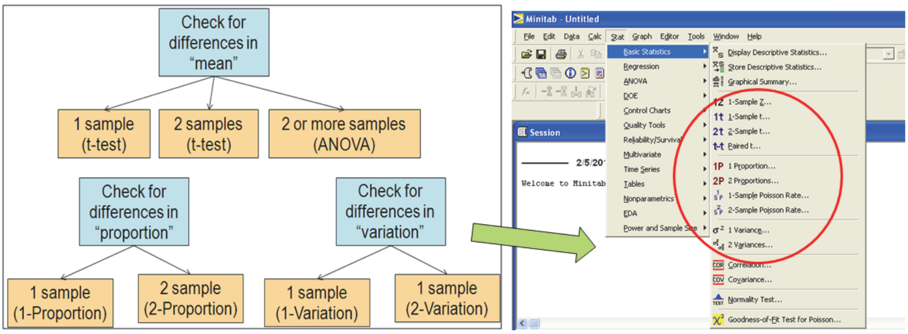

Fig. 12. The Various Hypothesis Tests and the Minitab Menu options

3.3.1 One-sample t-test

1-sample t-test is used when comparing a sample against a target mean. In this test, the null hypothesis is "*the sample mean and the target are the same*".
Practical problem: The "*File Transfer speed*" between the Hard disk and a USB (Universal Serial Bus) device connected to it is an important Critical to Quality (CTQ) parameter for the DVD Recorder product. The target time for a transfer of around 100 files of average 5 MB should not exceed 183 seconds.
This is a case of 1-Sample test as we are comparing a sample data to a specified target.
Statistical problem :
Null Hypothessis ------------ H_o: $\mu_a = 183$ sec
Alternate Hypothesis ------- H_a: $\mu_a > 183$ sec or H_a: $\mu_a < 183$ sec or H_a: $\mu_a \neq 183$ sec
Alpha risk --------------------- $\alpha = 0.05$
The data is collected for atleast 10 samples using appropriate measurement methods such as stop-watch etc. The figure-13 below shows the menu options in Minitab to perform this test.
After selecting 1-sample T-test, it is important to give the "*hypothesized mean*" value. This is the value that will be used for Null hypothesis. The "options" tab gives text box to input the Alternative hypothesis. Our H_a is H_a: $\mu_a > 183$ seconds. We select "*greater than*" because Minitab looks at the sample data first and then the value of 183 entered in the "Test Mean". It is important to know how Minitab handles the information to get the "Alternative hypothesis" correct.

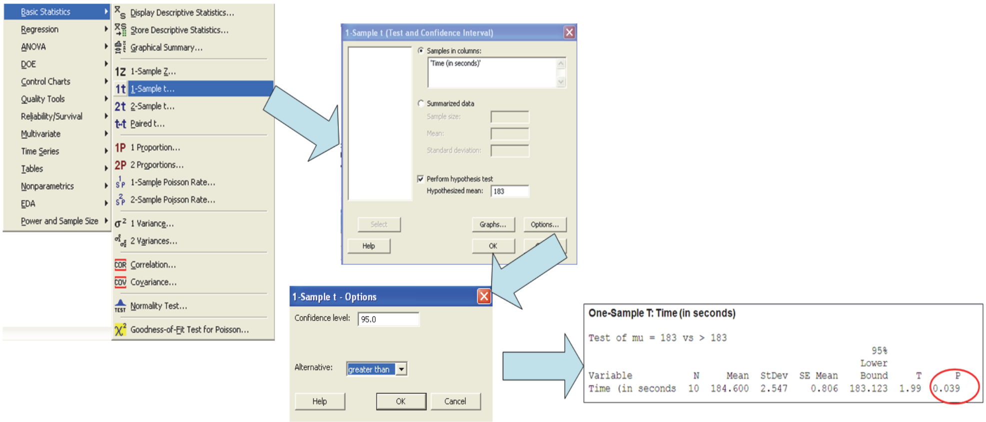

Fig. 13. 1-Sample t-test : Minitab menu options and Sample Results

- The test criteria was α = 0.05, which means we were willing to take a 5% chance of being wrong if we rejected Ho in favor of Ha
- The Minitab results show the p-value which indicates there is only a 3.9% chance of being wrong if we reject Ho in favor of Ha
- 3.9% risk is less than 5%; therefore, we are willing to conclude Ha. The file-transfer, on average, is taking longer than 183 seconds between USB-Hard Disk

The same test would be performed again after the improvements were done to confirm the statistically significant improvement in the file-transfer performance is achieved.

3.3.2 Two-sample t-test

2-sample t-test can be used to check for statistical significant differences in "means" between 2 samples. One can even specify the exact difference to test against. In this test, the null hypothesis is "*there is no difference in means between the samples*".

Practical problem : The "*Jpeg Recognition Time*" is another CTQ for the DVD recorder product. The system (hardware+software) was changed to improve this perfromance. From our perspective the reduction in average recognition time has be more than 0.5 sec to be considered significant enough from a practical perspective.

This is a case of 2-Sample test as we are comparing two independent samples.

Statistical problem :

Null Hypothessis ------------ H_o: $\mu_{Old} - \mu_{New} = 0.5$ sec

Alternate Hypothesis ------- H_a: $\mu_{Old} - \mu_{New} > 0.5$ sec

Alpha risk --------------------- $\alpha = 0.05$

The data is collected for atleast 10 samples using appropriate measurement methods for the old and the new samples.

The figure-14 below shows the menu options in Minitab to perform this test. After selecting 2-sample T-test, either the summarized data of samples can be input or directly the sample data itself. The "options" tab gives box to indicate the Alternative hypothesis. Based on what we have indicated as sample-1 and sample-2, the corresponding option of "*greater than*" or "*less than*" can be chosen. It also allows to specify the "*test difference*" that we are looking for which is 0.5 seconds in this example.

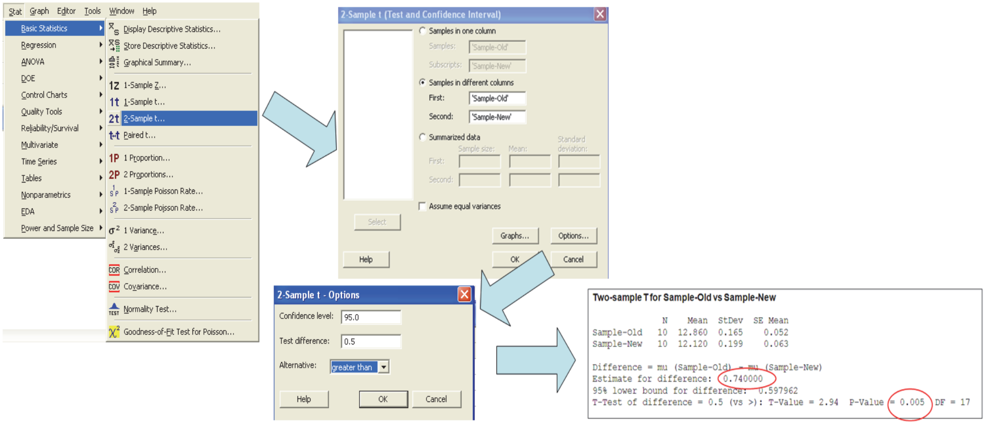

Fig. 14. 2-Sample t-test : Minitab menu options and Sample Results

- The criteria for this test was $\alpha = 0.05$, which means we were willing to take a 5% chance of being wrong if we rejected H_o in favor of H_a
- The Minitab results show the p-value which indicates there is only a 0.5% chance of being wrong if we reject H_o in favor of H_a
- 0.5% risk is less than 5%; therefore, we are willing to conclude H_a. The Sample-New has indeed improved the response time by more than 0.5 seconds
- The estimate for that difference is around 0.74 seconds

The above two sections has given some examples of setting up tests for checking differences in mean. The philosophy remains the same when testing for differences in "proportion" or "Variation". Only the statistic behind the check and the corresponding test changes as was shown in the figure-12 above.

3.4 Transfer functions

An important element of design phase in a Six sigma project is to break down the CTQs (Y) into lower level inputs (Xs) and a make a "*Transfer Function*". The purpose of this transfer function is to identify the "*strength of correlation*" between the "*Inputs (Xs)*" and output (Y) so that we know where to focus the effort in order to optimise the CTQ. The purpose of this exercise also is to find those inputs that have an influence on the output but cannot be controlled. One such category of inputs is "*Constants or fixed variables (C)*"and other category is "*Noise parameters (N)*". Both these categories of inputs impact the output but cannot be controlled. The only difference between the Constants and the Noise is the former has always a certain fixed value e.g. gravity and the latter is purely random in nature e.g. humidity on a given day etc.

There are various mechanisms to derive transfer functions such as regression analysis, Design of experiments or as simple as physical/mathematical equations. These are described in the below sections.

3.4.1 Physics/Geometry

Based on the domain knowledge it is possible to find out the relationship between the CTQ (Y) and the factor influencing it (Xs). Most of the timing/distance related CTQs fall under this category where total time is simply an addition of its sub components. These are called as *"Loop equations"*. For e.g.

Service time(Y) = Receive order(x1) +Analyse order(x2) +Process order(x3) +Collect payment (x4)

Some part of the process can happen in parallel. In such cases

Service time(Y)=Receive order(x1)+Analyse order(x2)+Max(Process order(x3), Collect payment(x3))

Practical problem :

"Recording duration" (i.e. number of hours of recording possible) is one of the CTQs for the DVD recorder as dictated by the marketing conditions/competitor products. The size of hard disk is one of the factors influencing the duration. Each additional space comes at a cost hence it is important to optimise that as well. The transfer function in this case is the one that translates available memory space (in Gigabytes) into time (hours of recording). From domain knowledge this translation can be done using audio bit rate and video bit rate as follows:

b = ((video_bitrate * 1024 * 1024)/8) + ((audio_bitrate*1024)/8) bytes

k = b/1024 kilobytes

no. of hrs of recording = ((space_in GB)*1024*1024)/(k*3600)

3.4.2 Regression analysis

"Regression Analysis" is a mechanism of deriving transfer function when historical data is available for both the Y and the Xs. Based on the scatter of points, regression analysis computes a best fit line that represents the relation of X to Y minimizing the *"residual error"*.

Practical Problem:

"Cost of Non-Quality (CONQ)" is a measure given to indicate the effort/cost that is spent on rework. If it was "right" the first time this effort could have been saved and maybe utilised for some other purpose. In a software development scenario, because there are bugs/issues lot of effort is spent on rework. Not only it is additional effort due to not being right the first time, but also modifying things after it is developed always poses risks due to regression effects. Hence CONQ is a measure of efficiency of the software development process as well as indirect measure for first-time-right quality. Treating it as CTQ (Y), the cause-effect diagram in figure-15 below shows the various factors (Xs) that impact this CONQ. This is not an exhaustive list of Xs and there could be many more based on the context of the project/business.

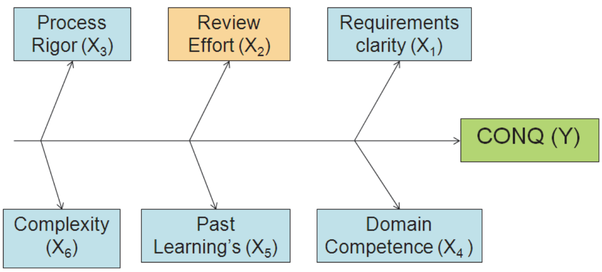

Fig. 15. Factors Impacting CONQ

Since lot of historical data of past projects is available, regression analysis would be a good mechanism to derive the transfer function with Continuous Y and Continuous Xs. Finding the relation between Y and multiple Xs is called *"Multiple Regression"* and that with single X is referred to as *"Simple Regression"*. It would be too complicated to do the analysis with all Xs at the same time; hence it was decided to choose one of the Xs in the list that has a higher impact, which can be directly controlled and most importantly which is "continuous" data for e.g. Review effort. The figure-16 below shows the Regression model for CONQ.

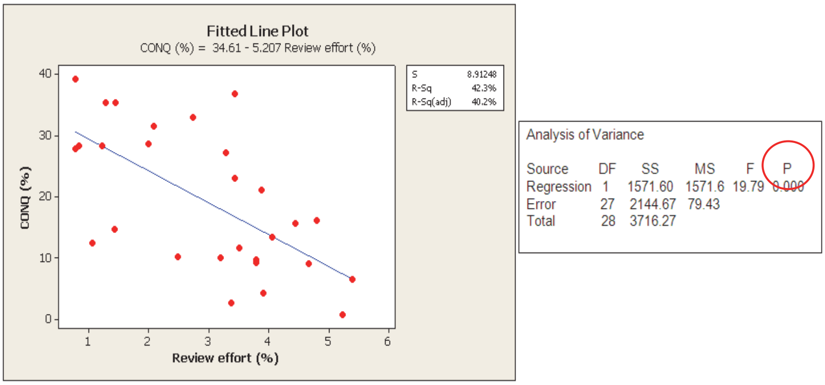

Fig. 16. The Regression Analysis for CONQ

When concluding the regression equation, there are 4 things that need to be considered:-

1. The p-value. The Null hypothesis is that *"there is no correlation between Y and X"*. So if p-value < α, then we can safely reject Null and accept the Alternate, which is that Y and X are correlated. In this case p-value is 0, this means that we can conclude that the regression equation is statistically significant
2. Once the p-value test is passed, the next value to look at is *R^2(adj)*. This signifies that the amount of variability of Y that is explained by the regression equation. Higher the R^2 better it is. Typical values are > 70%. In this case, R^2(adj) value is 40%. This indicates that only 40% of variability in CONQ is explained by the above regression equation. This may not be sufficient but in R&D kind of situation especially in software, where the number of variables are high, R^2(adj) value of 40% and above could be considered a reasonable starting point
3. The third thing is then to look at the residuals. A *Residual* is the error between the fitted line (regression equation) and the individual data points. For the regression line to be un-biased, the residuals themselves must be normally distributed (random). A visual inspection of the residual plots as shown in figure-17 below can confirm that e.g. a lognormal plot of residuals should follow a straight line on the "normal probability plot" and residuals should be either side of 0 in the "versus fits" plot. The "histogram" in the residual plot can also be good indication.
4. Once the above 3 tests pass, the regression equation can be considered statistically significant to predict the relations of X to Y. However one important point to note is the *"range of values for X"* under which this equation is applicable. For e.g. the above CONQ equation can be used only in the range of Review % from 0 to 6% as the regression analysis was done with that range.

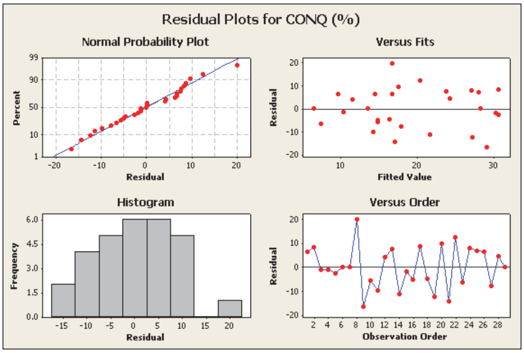

Fig. 17. Residual Analysis for CONQ

The project manager can now use the above regression equation to plan the % review effort in the project based on the target CONQ value. If there is more than 1 X impacting Y, then doing simple regression is not adequate as there could be lot of interaction effects of those Xs (X1, X2...) on Y. Hence it is advisable to do a "*Multiple Regression*" analysis in such cases. The philosophy remains the same for multiple regression, with only one change that p-value test now needs to be checked for each of the Xs in the regression summary.

3.4.3 Design of experiments (DOE)

Design of Experiments (DOE) is a concept of organizing a set of experiments where-in each individual X input is varied at its extreme points in a given spectrum keeping the other inputs constant. The effect on Y is observed for all the combinations and the transfer function is computed based on the same.

Practical Problem:

DVD-recorder has a USB port which can be used to connect digital cameras to view/copy the pictures. "*Jpg Recognition Time*" is a product CTQ which is crucial from a user perspective and the upper specification limit for which is 6 seconds. The Xs that impact the Jpg Recognition time CTQ from a brain storming exercise with domain experts are shown in figure-18 below.

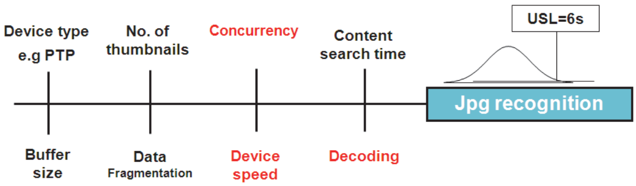

Fig. 18. The Factors Impacting JPG Recognition

Device speed in this case is the speed of USB device connected to the recorder and is then a discrete X which can take 4 values for e.g. USB 1.0 (lowest speed) to USB 2.0 device (highest speed).

Decoding is again a discrete X and can take 4 possible values – completely software, 70-30 software-hardware, 30-70 software-hardware, or completely hardware solution.

Concurrency is number of parallel operations that can be done at the same time and is also a discrete X. In this particular product up to 5 concurrencies are allowed.

"CPU Load" is another CTQ which is a critical for the reliable operation of the product. It is known from embedded software experience that a CPU load of > 65% makes the system unstable hence the USL is placed at 60%. A CPU load of <40% is not an efficient utilization of a costly resource such as CPU. Hence the LSL is defined to be 40%. The factors (Xs) that correlate to this CTQ i.e. CPU load are shown in the figure-19 below.

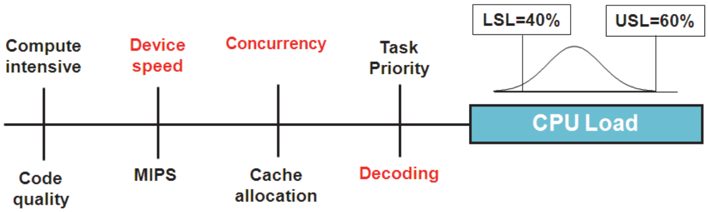

Fig. 19. The Factors Impacting CPU Load

It is interesting to note two things from figure-18 and figure-19 above:-

a. There are 3 factors (Xs) that are common to both the CTQs (Device speed, Decoding and Concurrency)

b. Some of the Xs are continuous such as Search time, buffer size, Cache etc and some others are Discrete such as Concurrency, Task priority etc. DOE is an excellent mechanism in these circumstances where there is a mix of discrete and continuous Xs. Also the focus now is not so much on the exact transfer function but more than "*Main effects plot*" (impact of individual Xs on Y) and "*Interaction Plots*" (impact of multiple Xs having a different impact on Y).

The figure-20 represents the DOE matrix for both these CTQs along with the various Xs and the range of values they can take.

C5	C6	C7	C8	C9
Concurrency	Decoding	Device speed	CPU Load	Jpg Recognition
1	1	1	30	5
5	1	1	60	10
1	4	1	20	3
5	4	1	40	6
1	1	4	60	4
5	1	4	90	7
1	4	4	40	1
5	4	4	60	10

Concurrency (numeric)
Low – minimum – 1
High – maximum - 5

Decoding (can be text or numeric)
Low – only software - 1
High – only hardware - 4

Device speed (text or numeric)
Low – minimum - 1
High – maximum - 4

Fig. 20. The DOE Matrix for CPU Load and JPG Recognition

The transfer function for both the CTQs from the Minitab DOE analysis are as below :-

CPU Load = 13.89 + 8.33*Concurrency – 1.39*Decoding + 11.11*Device-speed – 0.83*Concurrency*Decoding – 1.11*Decoding*Device-speed

Jpg Recognition = 4.08 + 1.8*Concurrency – 0.167*Decoding + 0.167*Device-Speed – 0.39*Concurrency*Decoding – 0.389*Concurrency*Device-Speed

Our aim is to achieve a "nominal" value for CPU load CTQ and "as low as possible" value for Jpg recognition CTQ. The transfer functions themselves are not important in this case as are the Main effects plots and Interaction plots as shown in figure-21 and figure-22 below

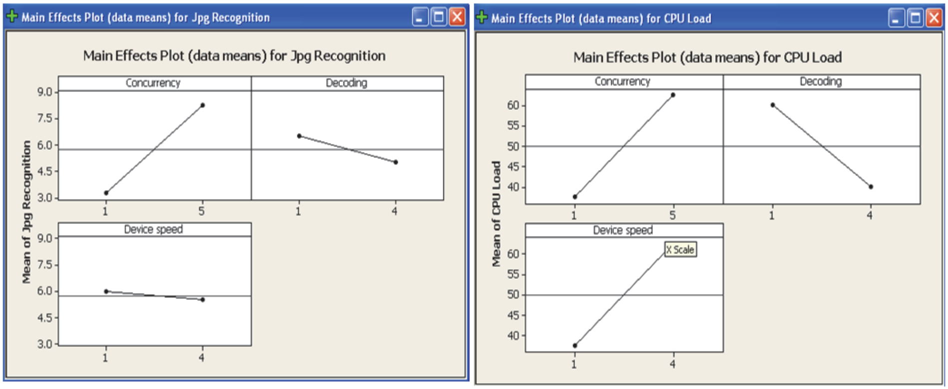

Fig. 21. Main Effects Plots for JPG Recognition and CPU Load

It is evident from the Main effects plots in the figure-21 above the impact of each of the Xs on the corresponding Ys. So a designer can optimise the corresponding Xs to get the best values for the respective Ys. However it is also interesting to note that some Xs have an opposite effect on the 2 CTQs. From figure-21 above – On one hand a Device speed of 4 (i.e. USB 2.0) is the best situation for Jpg recognition CTQ but it is worst case for CPU load CTQ on the other hand. In other words, the Device speed X impacts both the CTQs in a contradictory manner. The Interaction plots shown in figure-22 come in handy during such cases, where one can find a different X that interacts with this particular X in such a manner that the overall impact on Y is minimized or reduced i.e. "*X1 masks the impact of X2 on Y*".

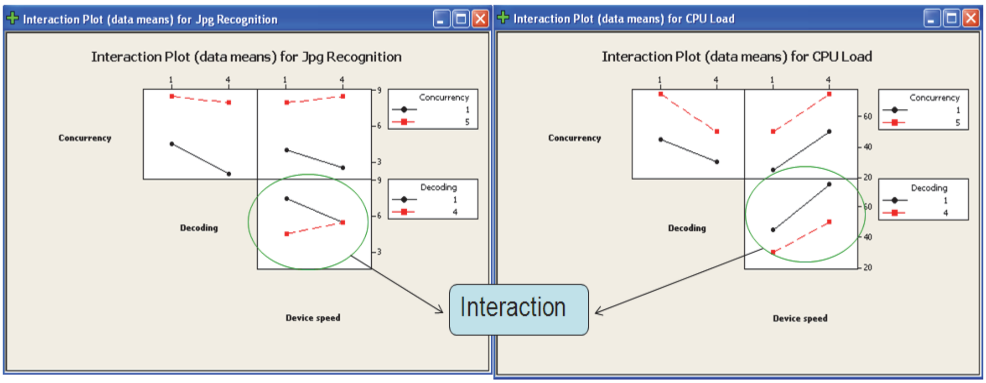

Fig. 22. Interaction Plots for JPG Recognition and CPU Load

From the figure-22 above it is seen that the Device speed X interacts strongly with Decoding X. Hence Device speed X can be optimised for Jpg recognition CTQ, and Decoding X can be used to mask the opposing effect of Device speed X on CPU load CTQ.

With "*Response optimizer*" option in Minitab, it is possible to play around with the Xs to get the optimum and desired values for the CTQs. Referring to Figure-23 below, with 3 concurrencies and medium device speed and hardware-software decoding, we are able to achieve CPU load between 30% and 50% and Jpg recognition time of 5.5s

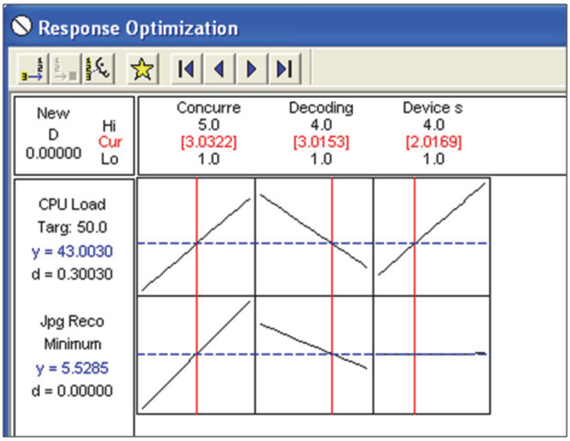

Fig. 23. The Response Optimiser for CPU Load and JPG Recognition

3.5 Statistical process control (SPC)

SPC is an *"Electrocardiogram"* for the process or product parameter. The parameter under consideration is measured in a time ordered sequence to detect shift or any unnatural event in the process. Any process has variation and the control limits (3-sigma from mean on both sides) determine the extent of *natural variation* that is inherent in the process. This is referred to as *"common cause of variation"*. Any point lying outside the control limits (UCL – upper control limit and LCL – lower control limit) indicates that the process is *"out of control/unstable"* and is due to some assignable cause that is referred to as the *"special cause of variation"*. The special cause necessitates a root cause analysis and action planning to bring back process back to control. The figure-24 below shows the SPC concept along with the original mean and the new mean after improvement. Once the improvement is done on the CTQ and the change is confirmed via the hypothesis test, it needs to be monitored via a SPC chart to ensure the *stability* of the same over a long term.

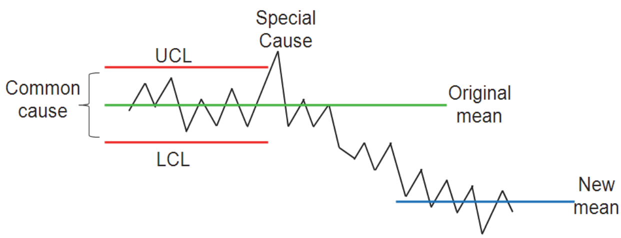

Fig. 24. SPC – Common Cause and Special Cause

It is important to understand that the Control limits are not the same as Specification limits. Control limits are computed based on historical data spread of the process/product performance whereas Specification limits come from Voice of customer. A process may be in control i.e. within control limits but not be capable to meet specification limits. The first step should be always bring the process *"in control"* by eliminating special cause of variation and then attain *"capability"*. It is not possible to achieve process capability (i.e. to be within specification limits) when the process itself is out of control.

Once the CTQ has attained the performance after the improvement is done, it is required to monitor the same via some appropriate SPC chart based on the type of data as indicated in the figure-25 below along with the corresponding Minitab menu options.

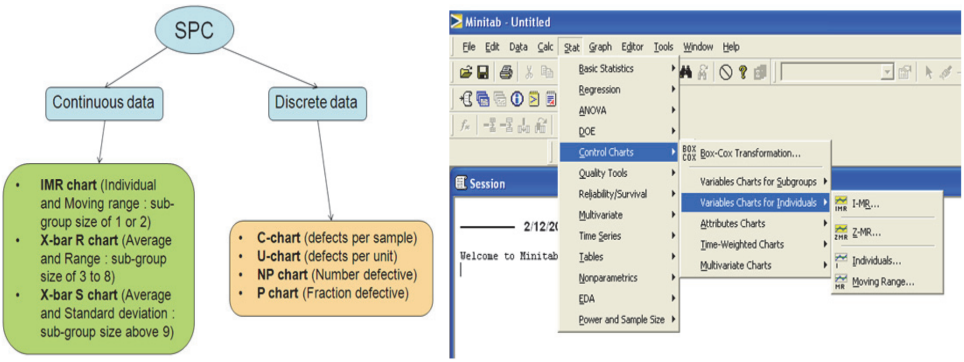

Fig. 25. The Various SPC harts and Minitab menu options

Practical Problem:

"Design Defect density" is a CTQ for a software development activity and number of improvements has been done to the design review process to increase design defect yield. So this CTQ can be monitored via an I-MR chart as depicted in figure-26 below. Any point outside the control limits would indicate an unnatural event in the design review process.

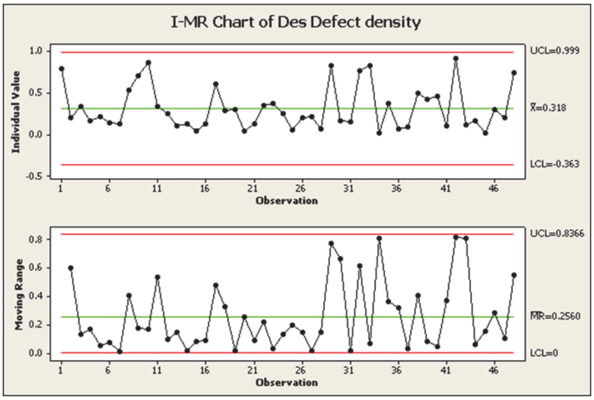

Fig. 26. The I-MR chart for defect density

3.6 Measurement system analysis

All decisions in a Six sigma project are based on data. Hence it is extremely crucial to ascertain that the measurement system that is used to measure the CTQs does not introduce error of its own. The measurement system here is not only the gage that is used to measure but also the interaction of inspectors and the gage together that forms the complete system. The study done to determine the health of the measurement system is called *"Gage Repeatability and Reproducibility (Gage R&R)"*. Repeatability refers to *"how repeatable are the* *measurements made by one inspector"* and Reproducibility indicates *"how reproducible are the measurements made by several inspectors"*. Both repeatability and reproducibility introduces its own set of variation in the total variation. The figure-27 below depicts this relation.

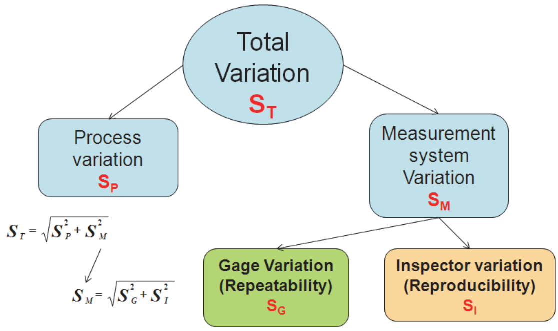

Fig. 27. The Measurement System Analysis : Variation

Since all the decisions are based on the data, it would be a futile attempt to work on a CTQ which has high variation when actually the majority of this is due to the measurement system itself. Hence there is a need to separate out the variation caused by the measurement system by doing an experiment of the measuring few already known standard samples with the gage and inspectors under purview. A metric that is computed as result is called *"%Tolerance GageR&R"* and is measured as *(6*S_M *100)/ (USL-LSL)*. This value should be less than 20% for the Gage to be considered acceptable.

Practical Problem:

There are many timing related CTQs in the Music Juke box player product and stop-watch is the gage used to do the measures. An experiment was set up with a stop watch and known standard use cases with set of inspectors. The results are analysed with Minitab Gage R&R option as shown in figure-28 along with the results.

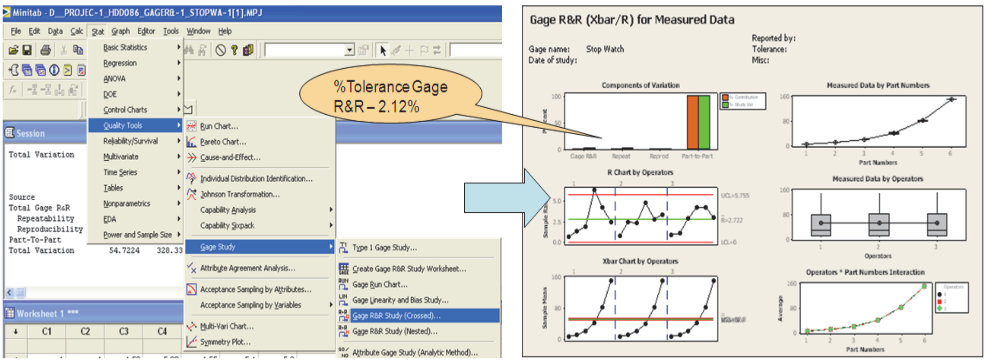

Fig. 28. Gage R&R Analysis : Minitab menu options and Sample results

The Gage R&R gives the total Measurement system variation as well as Repeatability and Reproducibility component of the total variation.

4. Tying It together – the big picture

In the previous sections we have seen number of statistical concepts with number of examples explaining those concepts. The overall big picture of a typical Six sigma project with these statistical concepts can be summarised as depicted in the figure-29 below.

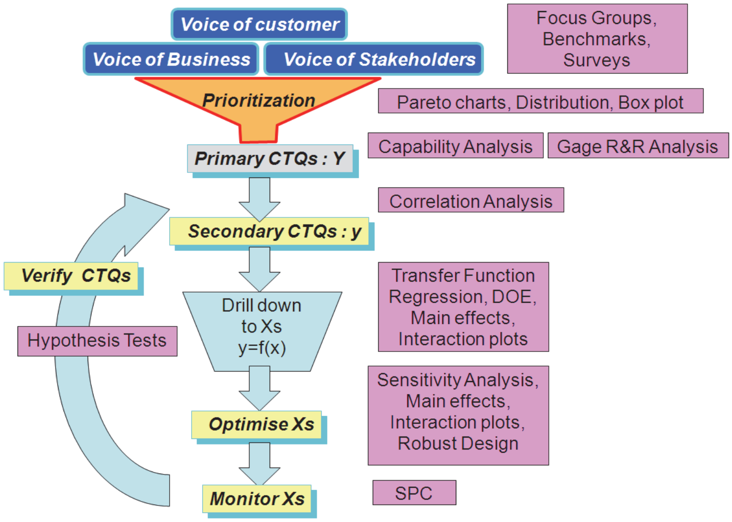

Fig. 29. Snapshot of Statistical Mechanisms in a DFSS project

The Starting point is the always the "*Voice of customer or Voice of Business or Voice of stakeholders*". Concepts like Focus groups interviews, Surveys, Benchmarking etc can be used to listen and conceptualize this "Voice". It is important to understand this "Voice" correctly otherwise all the further steps become futile.

Next this "*Voice of customer*" i.e. the customer needs have to be prioritised and translated into specific measurable indicators i.e. the "*Primary CTQs (Y)*". Tools like Frequency distributions, Box plots, Pareto charts can be some of the techniques to do the prioritisation. Capability analysis can indicate the current capability in terms of *Z-score/Cp* numbers and also help set targets for the six sigma project. This is the right time to do a measurement system analysis using Gage R&R techniques.

The lower level CTQs i.e. the "*Secondary CTQs (y)*" can then be identified from Primary CTQs using techniques such as Correlation analysis. This exercise will help focus on the few vital factors and eliminate the other irrelevant factors.

Next step is to identify the Xs and find mathematical "*Transfer function*" relating the Xs to the CTQs (y). Regression Analysis, DOEs are some of the ways of doing this. In many cases especially software, often the transfer function itself may not be that useful, but rather the "*Main effects and Interaction plots*" would be of more utility to select the Xs to optimise.

"*Sensitivity Analysis*" is the next step which helps distribute the goals (mean, standard deviation) of Y to the Xs thus setting targets for Xs. Certain Xs would be noise parameters and cannot be controlled. Using "*Robust Design Techniques*", the design can be made insensitive to those noise conditions.

Once the Xs are optimised, *"SPC charts"* can be used to monitor them to ensure that they are stable. Finally the improvement in the overall CTQ needs to be verified using *"Hypothesis tests"*.

4.1 The case study
DVD-Hard disk recorder is a product that plays and records various formats such as DVD, VCD and many other formats. It has an inbuilt hard disk that can store pictures, video, audio, pause the live-TV and resume it later from the point it was paused etc. The product is packed with more than 50 features with many use cases in parallel making it very complicated. Also because of the complexity, the intuitiveness of user-interface assumes enormous importance. There are many "Voices of customer" for this product – Reliability, Responsiveness and Usability to name a few.

4.1.1 Reliability
One way to determine software reliability would be in terms of its robustness. We tried to define *Robustness* as CTQ for this product and measured it in terms of *"Number of Hangs/crashes"* in normal use-case scenarios as well as stressed situations with target as 0.
The lower level factors (X's) affecting the CTQ robustness were then identified as:
- Null pointers, Memory leaks
- CPU loading, Exceptions/Error handling
- Coding errors

Robustness = f (Null pointers, Memory leaks, CPU load, Exceptions, Coding errors)
The exact transfer function in this case is irrelevant as all the factors are equally important and need to be optimized.

4.1.2 Responsiveness
The CTQs that would be directly associated with *"Responsiveness"* voice are the Timing related parameters. For such CTQs, the actual transfer functions really make sense as they are linear in nature. One can easily decide from the values itself the Xs that need to be optimized and by how much. For e.g.
Start-up time(y) = drive initialization(x1) + software initialization(x2) + diagnostic check time(x3)

4.1.3 Usability
Usability is very subjective parameter to measure and very easily starts becoming a discrete parameter. It is important that we treat it as a continuous CTQ and spend enough time to really quantify it in order to be able to control its improvement.
A small questionnaire was prepared based on few critical and commonly used features and weightage was assigned to them. A consumer experience test was conducted with a prototype version of product. Users with different age groups, nationality, gender, educational background were selected to run the user tests. These tests were conducted in home-like environment set-up so that the actual user behaviour could be observed.
The ordinal data of user satisfaction was then converted into a measurable CTQ based on the weightage and the user score. This CTQ was called as *"Usability Index"*. The Xs impacting this case are the factors such as Age, Gender etc. The interaction plot shown in the figure-30 below helped to figure out and correct a lot of issues at a design stage itself.

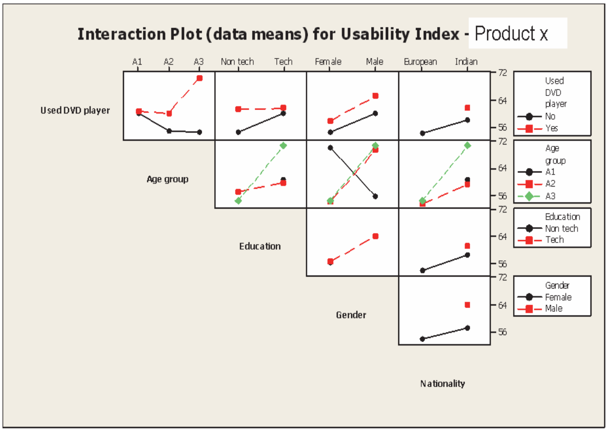

Fig. 30. Interaction Plot for Usability

5. Linkage to SEI-CMMI[R]

Level-4 and Level-5 are the higher maturity process areas of CMMI model and are heavily founded on statistical principles. Level 4 is the "*Quantitatively Managed*" maturity level which targets "special causes of variation" in making the process performance stable/predictable. Quantitative objectives are established and process performance is managed use these objectives as a criteria. At Level 5 called as "*Optimizing*" maturity level, the organization focuses on "common causes of variation" in continually improving its process performance to achieve the quantitative process improvement objectives. The process areas at Level-4 and Level-5 which can be linked to six sigma concepts are depicted in figure-31 below with the text of the specific goals from the SEI documentation

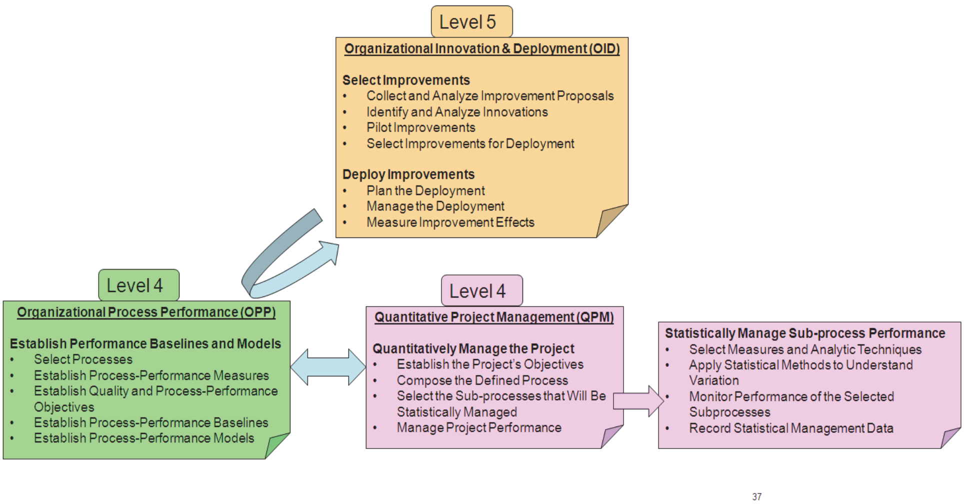

Fig. 31. The CMMI Higher Maturity Process areas

A typical example of the linkage and use of various statistical concepts for OPP, QPM and OID process areas of CMMI is pictorially represented in figure-32 below. In each of the process areas, the corresponding statistical concepts used are also mentioned.
One of the top-level Business CTQ (Y) is the "*Customer Feedback*" score which is computed based on a number of satisfaction questions around cost, quality, timeliness that is solicited via a survey mechanism. This is collected from each project and rolled up to business level. As shown in the figure-32 below, the mean value was 8 on a scale of 1-10 with a range from 7.5 to 8.8. The capability analysis is used here to get the 95% confidence range and a Z-score. The increase in feedback score represents increase in satisfaction and correspondingly more business. Hence as an improvement goal, the desired feedback was set to 8.2. This is part of OID part as depicted in figure-32 below.
Flowing down this CTQ, we know that "*Quality and Timeliness*" are the 2 important drivers that influence the score directly; hence they are lower level CTQs (y) that need to be targeted if we need to increase the satisfaction levels.
Quality in software projects is typically the *Post Release defect density* measured in terms of defects/KLOC. Regression analysis confirms the negative correlation of post release defect density to the customer feedback score i.e. lower the density, higher is the satisfaction.
The statistically significant regression equation is
Cust F/b = 8.6 – 0.522*Post Release Defect Density.
Every 1 unit reduction in defect density can increase the satisfaction by 0.5 units. So to achieve customer feedback of 8.2 and above the post release defect density needs to be contained within 0.75 defects/KLOC. This becomes the Upper spec limit for the CTQ (y) Post release defect density. The current value of this CTQ is 0.9 defects/KLOC. From OPP perspective it is also necessary to further break down this CTQ into lower level Xs and the corresponding sub-processes to control statistically to achieve the CTQ y.

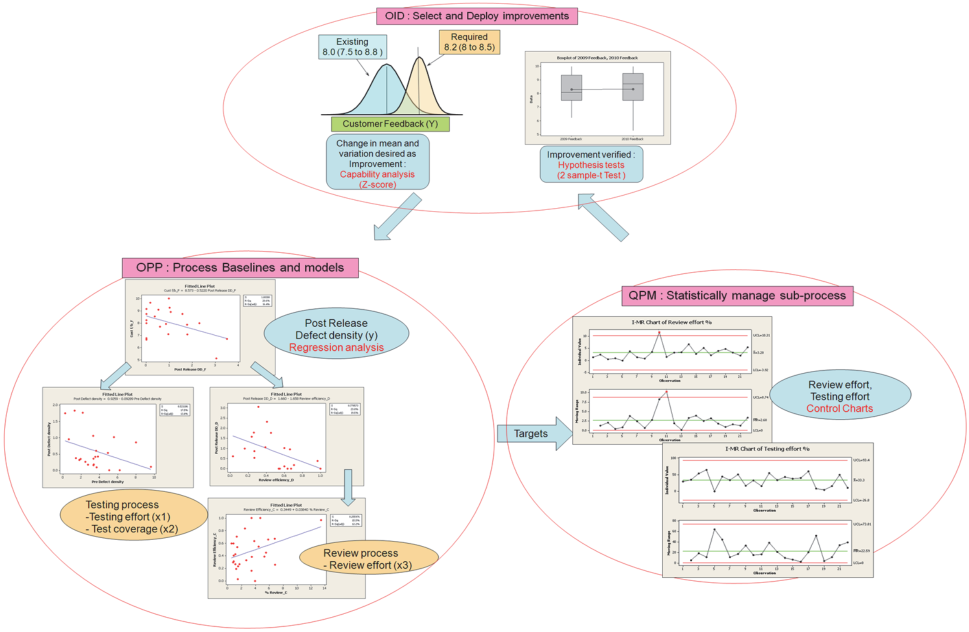

Fig. 32. Linkage of Statistical concepts to CMMI process areas

Further regression analysis shows two parameters that impact post-release defect density:

1. Pre-release defect density influenced by the Testing sub-process
   Regression equation : *Post Defect density = 0.93 – 0.093 * Pre-release Defect density*. To contain the post release defect density within 0.75 defects/KLOC, the pre-release defect density has to be more than 2 defects/KLOC. This means the testing process needs to be improved to catch atleast 2 defects/KLOC. Testing effort and Test coverage are the further lower level Xs that could be improved/controlled to achieve this.
2. *Review efficiency* influenced by the *Review* sub-process

Regression equation : *Post Defect density = 1.66 – 1.658 * Review efficiency*. To contain the post release defect density within 0.75 defects/KLOC, review efficiency has to be more than 55%. This means that review process needs to be improved to catch atleast 55% of defects. Review efficiency is lagging indicator as the value would be known only at the end and is not a directly controllable X. This needs to be further broken down to lower level X that can be tweaked to achieve the desired review efficiency. *Review effort* is one such X. Regression equation : *Review efficiency = 0.34 + 0.038 * Review effort.* To achieve a Review efficiency of 55% and more, a review effort in excess of 5.2% needs to be spent.

The above modeling exercise is part of OPP. Setting objectives at project level and selecting the sub-process to control is then an activity under QPM process area. Based on the business goal (Y) and overall objective (y), the project manager can select the appropriate sub-process to manage and control by assigning targets to them coming from the regression model. As shown in figure-32, the SPC chart for Review effort and Testing effort are used to control those processes. Once the improvement is achieved on the Y and y, hypothesis tests such as 2-sample T tests can be used to confirm a statistical significant change in the CTQ (Y).

6. Conclusion – software specific learning points

Using statistical concepts in software makes it challenging because of 2 primary reasons:-
Most of the Y's and X's in software are discrete in nature as they belong to Yes/No, Pass/Fail, Count category. And many of the statistical concepts are not amenable for discrete data

- The sample size in software is often 1 – the same piece of code evolves throughout

Few points to be kept in mind when approaching with statistics for software :-.

- Challenge each CTQ to see if it can be associated with some numbers rather than simply stating it in a digital manner. Even conceptual elements like Usability, Reliability, Customer satisfaction etc can be quantified. Every attempt should be to made to see if this can be made continuous data as much as possible
- For software CTQs, the specification limits in many of the cases may not be hard targets. For e.g. just because the start-up takes 1 second more than the USL does not render the product defective. So computing Z-scores/Cp numbers may pose a real struggle in such circumstances. The approach should be to see a change in the Z-scores/Cp vales instead of the absolute numbers itself
- Many of the Design of experiments in software would happen with discrete Xs due to nature of software. So often the purpose of doing these is not with the intent of generating a transfer function but more with a need to understand which "Xs" impact the Y the most – the cause and effect. So the Main effects plot and Interaction plots have high utility in such scenarios

- Statistical Capability analysis to understand the variation on many of the CTQs in simulated environments as well as actual hardware can be a good starting point to design in robustness in the software system.
- All Statistical concepts can be applied for the software "Continuous CTQs"

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Gage Repeatability and Reproducibility Methodologies Suitable for Complex Test Systems in Semi-Conductor Manufacturing

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1. Introduction

Six sigma is a highly disciplined process that focuses on developing and delivering near-perfect products and services consistently. Six sigma is also a management stragety to use statistical tools and project work to achieve breakthrough profitability and quantum gains in quality. The steps in the six sigma process are Define, Measure, Analyse, Improve, Control or DMAIC for short (Kubiak T.M, Benhow D.W, 2009). The actions that take place in each of these steps are described in brief in table 1 below.

STEP	DISCREPTION
Define	Select the appropriate critical to quality characteristic.
Measure	Gather data to measure the critical to quality characteristic.
Analyse	Identify root causes of deviations from specification.
Improve	Reduce variability or eliminate cause of deviation.
Control	Monitor the process to sustain the improvement.

Table 1. Description of the steps in the DMAIC process.

During the define stage of the DMAIC process, the critical to quality characteristics of the product are clearly identified. Once these are understood, methods of measuring these are defined and described in more detail within the measurement stage. Once the measurement system and test method are identified, a comprehensive measurement system analysis (MSA) is then required. The objective of this MSA is to evaluate the suitability of the measurement method for its intended function within the DMAIC cycle.

The most commonly used methodologies used for MSA are defined in measurement systems analysis reference manual (Measurement Systems Analysis Workgroup, Automotive Industry Action Group, 1998). In this there are three widely used methods to quantify the measurement error. These are in increasing order of complexity: the range method, the average and range method, and ANOVA. These generally use a small sample of parts, measured by a number of different appraisers to generate estimates of the components of measurement error.

With increasing complexity in semiconductor product test, the measurement equipment is generally automated, and test boards are employed that are capable of testing multiple parts in parallel. These introduce additional measurement error components not accounted for in these traditional methodologies. Updated methodologies capable of accounting for this situation are required. The purpose of this chapter is to describe appropriate experimental designs capable for use in MSA in this situation. The experimental designs used are extensively taken from Montgomery (Montgomery D.C., 1996; Montgomery D.C.,Runger G.C., 1993a, 1993b).

2. Review components of MSA

The quality of measurement data is defined by the statistical properties of multiple measurements obtained from a measurement system operating under stable conditions.
The statistical properties most commonly used to characterize the quality of data are the bias and the variance of the measurement system. Bias refers to the location of the average of the data relative to a known reference and is a systematic error component of the measurement system. Variance refers to the spread of the data. These are shown schematically in figure 1.

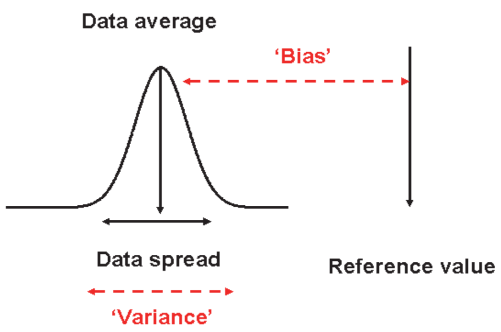

Fig. 1. Schematic of data Bias and Variance

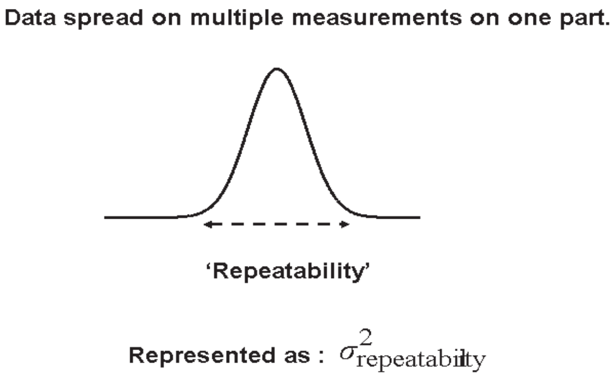

Fig. 2. Schematic test repeatability.

In practice the measurement system or gage is chosen to have a known and acceptable bias, and MSA uses statistical techniques to obtain estimates of the variance.

There are two components of variance for a measurement system. The first is the *repeatability* or *precision* which is the variance within repeated measurements of a given setup by a single appraiser. The second is the *reproducibility* which is the variation in the average measurement made by different appraisers. Repeatability and reproducibility are shown schematically in figure 2 and figure 3.

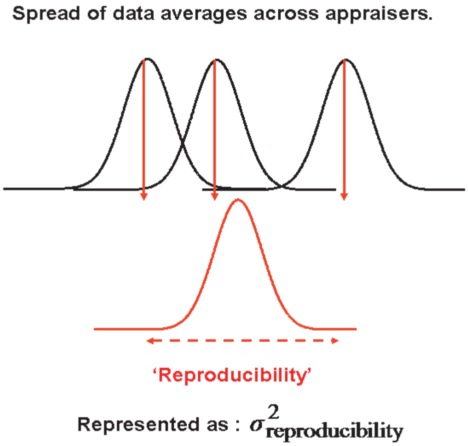

Fig. 3. Schematic of test reproducibility.

The Gage repeatability and reproducibility (Gage R&R) is the combined estimate of the measurement system repeatability and reproducibility variance components. This is given by equation 1.

$$\text{Gage R\&R} = \sqrt{\sigma^2_{repeatability} + \sigma^2_{reproducability}} \tag{1}$$

Within the manufacturing enviornment, this Gage R&R error gets added into the product distribution as a pure error term (Wheeler D, Lyday R, 1989). This has the effect of widening the true product distribution by this amount. Representing the true product distribution as σ_{product}, the resulting total variation (TV) of the manufacturing distribution is given by equation 2.

$$TV = \sqrt{\sigma^2_{product} + \sigma^2_{R\&R}} \tag{2}$$

This total variation is shown schematically in figure 4. Here the true product distribution is represented by the green curve, while the TV distribution seen in manufacturing is represented by the black curve. This black curve is estimated using equation 2 above.

With a knowledge of the components of total variation, some useful performance metrics for the measurement system can be generated. The most commonly used are (a) the percentage of total variation and (b) the percentage contribution to total variance. These are calculated using equations 3 and 4 respectively.

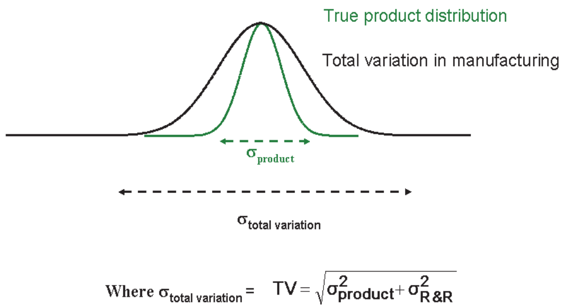

Fig. 4. Schematic total variation in manufacturing

%of total variation:

$$\%GR\,\&\,R = \left(\frac{GageR\,\&\,R}{TV}\right)\times 100 = \left(\frac{\sigma_{R\&R}}{\sqrt{\sigma^2_{product} + \sigma^2_{R\&R}}}\right)\times 100 \quad (3)$$

% contribution to total variance:

$$\%Contribution(GR\,\&\,R) = \left(\frac{GageR\,\&\,R^2}{TV^2}\right)\times 100 = \left(\frac{\sigma^2_{R\&R}}{\sigma^2_{Product} + \sigma^2_{R\&R}}\right)\times 100 \quad (4)$$

These metrics give an indication of how capable the gage is for measuring the critical to quality characteristic. Acceptable regions of gage R&R as defined by the Automotive Industry Action Group (Measurement Systems Analysis Workgroup, Automotive Inductry Action Group, 1998) are as indicated in table 2.

GAGE R&R RANGE	ACTION REQUIRED
<10%	Gage acceptable
10% < Gage R&R < 30%	Action required to understand variance
30% < Gage R&R	Gage unacceptable for use and requires improvement

Table 2. Acceptable regions of Gage R&R.

Note that similar equations can be written for the individual components of variance and also for the product contribution by replacing $\sigma_{R\&R}$ with $\sigma_{repeatability}$, $\sigma_{reproducibility}$ and $\sigma_{product}$ respectively.

Once the MSA indicates that the measurement method is both sufficiently accurate and capable, it can be integrated into the remaining steps of the DMAIC process to analyse, improve and control the characteristic.

3. Review of existing methodologies employed for MSA

Historically gages within the manufacturing enviornment have been manual devices capable of measuring one single critical to quality characteristic. Here the components of variance are (a) the repeatability on a given part, and (b) the reproducibility across operators or appraiser effect. To estimate the components of variance in this instance, a small sample of readings is required by independent appraisers. Typical data collection operations comprised of 5 parts measured by each of 3 appraisers.There are three widely used methods in use to analyse the collected data. These are the range method, the average and range method, and the analysis of variance (ANOVA) method (Measurement Systems Analysis Workgroup, Automotive Inductry Action Group, 1998).

The range method utilises the range of the data collected to generate an estimate of the overall variance. It does not provide estimates of the variance components. The average and range method is more comprehensive in that it utilises the average and range of the data collected to provide estimates of the overall variance and the components of variance i.e. the repeatability and reproducibility. The ANOVA method is the most comprehensive in that it not only provides estimates of the overall variance and the components of variance, it also provides estimates of the interaction between these components. In addition, it enables the use of statistical hypothesis testing on the results to identify statistically significant effects. ANOVA methods capable of replacing the range / average and range methods have previously been described (Measurement Systems Analysis Workgroup, Automotive Inductry Action Group, 1998). A relative comparison of these three methods are summarised in table 3 below.

METHOD	ADVANTAGE	DISADVANTAGE
Range method.	Simple calculation method.	Estimates overall variance only - excludes estimate of the components of R&R.
Average and range method.	Simple calculation method. Enables estimate of overall variance and component variance.	Estimates overall variance and components but excludes estimate of interaction effects.
ANOVA method.	Enables estimates of overall variance and all components including interaction terms. More accuracy in the calculated estimates. Enables statistical hypothesis testing.	Detailed calculations - require automation.

Table 3. Compare and contrast historical methods for Gage R&R

The metrics generated from these gage R&R studies are typically the percentage total variance and the percentage contribution to total variance of the repeatability, the reproducibility or appraiser effect, and the product effect. A typical gage R&R results table is shown in table 4.

With increasing complexity in semiconductor test manufacturing, automated test equipment is used to generate measurement data for many critical to quality characteristic on any given product. Additional sources of test variance can be recognised within this complex test system. More advanced ANOVA methods are required to enable MSA in this situation.

Note that for cycle time and cost reasons, the data collection steps have an additional constraint in that the number of experimental runs must be minimised. Design of experiments is used to achieve this optimization.

Estimate of Variance component	**Standard Deviation**	**% of Total Variation**	**% Contribution.**
Equipment Variation or Repeatability.	Equipment Variaiton (EV) = $\sigma_{repetability}$	$\left(\frac{\sigma_{repeatability}}{\sqrt{\sigma^2_{product}+\sigma^2_{R\&R}}}\right)\times 100$	$\left(\frac{\sigma^2_{repeatability}}{\sigma^2_{product}+\sigma^2_{R\&R}}\right)\times 100$
Appraiser or Operator Variation.	Appraiser Variation (AV) = $\sigma_{reproducibility}$	$\left(\frac{\sigma_{reproducibility}}{\sqrt{\sigma^2_{product}+\sigma^2_{R\&R}}}\right)\times 100$	$\left(\frac{\sigma^2_{reproducibility}}{\sigma^2_{product}+\sigma^2_{R\&R}}\right)\times 100$
Interaction variation.	Appraiser by product interaction = $\sigma_{interaction}$	$\left(\frac{\sigma_{Interaction}}{\sqrt{\sigma^2_{product}+\sigma^2_{R\&R}}}\right)\times 100$	$\left(\frac{\sigma^2_{Interaction}}{\sigma^2_{product}+\sigma^2_{R\&R}}\right)\times 100$
System or Gage Variation.	Gage R&R = $\sigma_{R\&R}$	$\left(\frac{\sigma_{R\&R}}{\sqrt{\sigma^2_{product}+\sigma^2_{R\&R}}}\right)\times 100$	$\left(\frac{\sigma^2_{R\&R}}{\sigma^2_{product}+\sigma^2_{R\&R}}\right)\times 100$
Product Variation.	Product variation (PV) = $\sigma_{product}$	$\left(\frac{\sigma_{product}}{\sqrt{\sigma^2_{product}+\sigma^2_{R\&R}}}\right)\times 100$	$\left(\frac{\sigma^2_{product}}{\sigma^2_{product}+\sigma^2_{R\&R}}\right)\times 100$

Table 4. Measurement systems analysis metrics evaluating Gage R&R.

4. MSA for complex test systems

With increased complexity and cost pressure within the semiconductor manufacture environment, the test equipment used is automated and often tests multiple devices in parallel. This introduces additional components of variance of test error. These are illustrated in figure 5. The components of variance in this instance can be identified as follows.

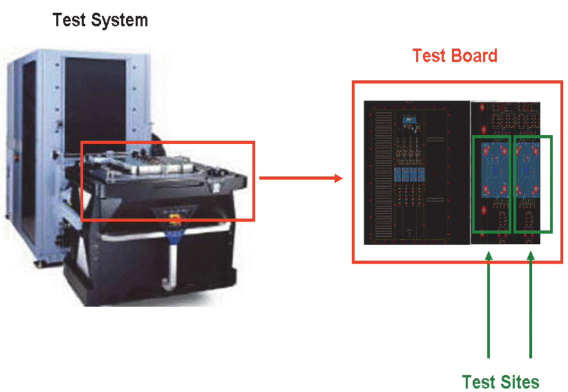

Fig. 5. Components of test variance in manufacturing-System, Boards, Sites

The test repeatability or replicate error is the variance seen on one unit on one test set-up. Because test repeatability may vary across the expected device performance window i.e. a range effect, multiple devices from across the expected range are used in the investigation of test repeatability error.

As the test operation is fully automated, the traditional appraiser affect is replaced by the test setup reproducibility. The test reproducibility therefore comes from the physical components of the test system setup. These are identified as the testers and the test boards used on the systems. In addition, when multi-site testing is employed allowing testing of multiple devices in parallel across multiple sites on a given test board, the test sites themselves contribute to test reproducibility.

In investigating tester to tester and board to board effects a fixed number of specific testers and boards will be chosen from the finite population of testers and boards. Because these are being specifically chosen, a suitable experimental design in this case is a Fixed Effects Model in which the fixed factors are the testers and the boards.

In investigating multisite site-to-site effects, the variation across the devices used within the sites is confounded with the site-to-site variation. The devices used within the sites are effectively a nuisance effect and need to be blocked from the site to site effects. In this instance a suitable experimental design is a blocked design.

5. Fixed effects experimental design for test board and tester effects

In this instance there are two experimental factors – the test boards and the test systems. The MSA therefore requires a two factor experimental design. For the example of two factors at two levels, the data collection runs are represented by an array shown in table 5. To ensure an appropriate number of data points are collected in each run, 30 repeats or replicates are performed.

Run number	Tester level	Board level
1	1	1
2	1	2
3	2	1
4	2	2

Table 5. Experimental Array - 2 Factors at 2 Levels.

An example dataset is shown in figure 6. This shows data from a measurement on a temperature sensor product. Data were collected from devices across two test boards and two test systems. Both the tester to tester and board to board variations are seen in the plot.

5.1 Fixed effects statistical model

Because the testers and boards are chosen from a finite population of testers and boards, in this instance a suitable statistical model is given by equation 5 (Montgomery D.C, 1996):

$$Y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + e_{ijk} \qquad \begin{array}{l} i = 1 \text{ to } t \\ j = 1 \text{ to } b \\ k = 1 \text{ to } r \end{array} \tag{5}$$

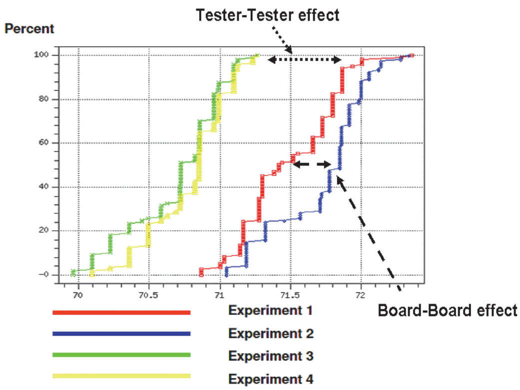

Fig. 6. Example data Fixed Effects Model- Across Boards and Testers.

Where Y_{ijk} are the experimentally measured data points.
μ is the overall experimental mean.
τ_i is the effect of tester 'i'.
β_j is the effect of board 'j'.
$(\tau\beta)_{ij}$ is the interaction effect between testers and boards.
k is the replicate of each experiment.
e_{ijk} is the random error term for each experimental measurement.

Here it is assumed that τ_i , β_j , $(\tau\beta)_{ij}$ and e_{ijk} are random independent variables, where $\{\tau_i\} \sim N(0, \sigma^2_T)$, $\{\beta_j\} \sim N(0, \sigma^2_B)$ and $\{e_{ijk}\} \sim N(0, \sigma^2_R)$.

The analysis of the model is carried out in two stages. The first partitions the total sum of squares (SS) into its constituent parts. The second stage uses the model defined in equation 5 and derives expressions for the expected mean squares (EMS). By equating the SS to the EMS the model estimates are calculated. Both the SS and the EMS are summarised in an ANOVA table.

5.2 Derivation of expression for SS

The results of this data collection are represented by the generalized experimental result Y_{hk}, where h= 1 … s is the total number of set-ups or experimental runs, and k= 1 … r is the number of replicates performed on each experimental run. Using the dot notation, the following terms are defined:

Set-up Total: $Y_{h.} = \sum_{k=1}^{r} Y_{hk}$ denotes the sum of all replicates for a given set-up.

Overall Total: $Y_{..} = \sum_{h=1}^{s}\sum_{k=1}^{r} Y_{hk}$ denotes the sum of all data points.

Overall Mean: $\overline{Y}_{..} = \left(\sum_{h=1}^{s}\sum_{k=1}^{r} Y_{hk}\right) / (sr)$ denotes the average of all data points.

The effect of each factor is analysed using 'contrasts'. The contrast of a factor is a measure of the change in the *total* of the results produced by a change in the level of the factor. Here a simplified "-" and "+" notation is used to denote the two levels. The contrast of a factor is the difference between the sum of the set-up totals at the "+" level of the factor and the sum of the set-up totals at the "-" level of the factor. The array is rewritten to indicate the contrast effects of each factor as shown in table 6.

Run number	Tester level	Board level	Tester x Board Interaction	Generalized Experimental Result
1	-	-	+	Y_{hk}, where: h= 1 to s set-ups (= 4) k= 1 to r replicates (= 30)
2	-	+	-	
3	+	-	-	
4	+	+	+	

Table 6. Fixed Effects Array with 2 Level Contrasts

The contrasts are determined for each of the factors as follows:

$$\text{Tester contrast} = -Y_{1.} - Y_{2.} + Y_{3.} + Y_{4.}$$

$$\text{Board contrast} = -Y_{1.} + Y_{2.} - Y_{3.} + Y_{4.}$$

$$\text{Interaction contrast} = +Y_{1.} - Y_{2.} - Y_{3.} + Y_{4.}$$

The SS for each factor are written as:

Tester: $$SS_T = [-Y_{1.} - Y_{2.} + Y_{3.} + Y_{4.}]^2 / (sr) \quad (6)$$

Board: $$SS_B = [-Y_{1.} + Y_{2.} - Y_{3.} + Y_{4.}]^2 / (sr) \quad (7)$$

Interaction (TXS): $$SS_{TxB} = [+ Y_{1.} - Y_{2.} - Y_{3.} + Y_{4.}]^2 / (sr) \quad (8)$$

Total: $$SS_{TOTAL} = (\sum_{h=1}^{s}\sum_{k=1}^{r} Y^2{}_{hk}) - Y^2{}_{..} / (sr) \quad (9)$$

Residual: $$SS_R = SS_{TOTAL} - (SS_T + SS_B + SS_{TxB}) \quad (10)$$

5.3 Derivation of expression for EMS and ANOVA table

Expressions for the EMS of each factor are also needed. This is found by substituting the equation for the linear statistical model into the SS equations and simplifying. In this case the EMS are as follow.

Tester: $$EMS_T = \sigma^2{}_R + r\sigma^2{}_{TxB} + br\sigma^2{}_T \quad (11)$$

Board: $$EMS_B = \sigma^2{}_R + r\sigma^2{}_{TxB} + tr\sigma^2{}_B \quad (12)$$

Interaction : $$EMS_{TXB} = \sigma^2{}_R + r\sigma^2{}_{TxB} \quad (13)$$

Residual: $$EMS_R = \sigma^2{}_R \quad (14)$$

These EMS are equated to the MS from the experimental data and solved to find the variance attributable to each factor in the experimental design.

The results of this analysis is summarised in an ANOVA table. The terms presented in this ANOVA table are as follows. The SS are the calculated sum of squares from the experimental data for each factor under investigation. The DOF are the degrees of freedom associated with the experimental data for each factor. The MS is the mean square calculated using the SS and DOF. The EMS is estimated mean square for each factor derived from the theoretical model. For the design of experiment presented in this section the ANOVA table is shown in table 7 below.

Source	SS	DOF	MS	EMS
Tester	Eq. (6)	t – 1	$SS_T/(t-1)$	$\sigma^2_R + r\sigma^2_{TxB} + br\sigma^2_T$
Board	Eq. (7)	b – 1	$SS_B/(b-1)$	$\sigma^2_R + r\sigma^2_{TxB} + tr\sigma^2_B$
Interaction	Eq. (8)	(t – 1)(b – 1)	$SS_{TxB}/((t-1)(b-1))$	$\sigma^2_R + r\sigma^2_{TxB}$
Residual	Eq. (10)	tb(r – 1)	$SS_R/(tb(r-1))$	σ^2_R
Total	Eq. (9)	tbr – 1	Sum of above	

Table 7. Fixed Effects ANOVA Table

5.4 Output of ANOVA – complete estimate of robust test statistics

Equating the MS from the experimental data to the EMS from the model analysis, it is possible to solve for the variance estimate due to each source. From the ANOVA table the best estimate for σ^2_T, σ^2_B, σ^2_{TxB} and σ^2_R are derived as S^2_T, S^2_B, S^2_{TxB} and S^2_R respectively. The calculations on the ANOVA outputs to generate these estimates are listed in table 8.

Source	Variance Estimate
Tester	$S^2_T = \dfrac{MS_T - \sigma^2_R - r\sigma^2_{TxB}}{br}$
Board	$s^2_B = \dfrac{MS_B - \sigma^2_R - r\sigma^2_{TxB}}{tr}$
Interaction	$S^2_{TxB} = \dfrac{MS_{TxB} - \sigma^2_R}{r}$
Residual	$S^2_R = MS_R$
Total	Sum of above

Table 8. Fixed Effects Model Results Table

Note that because each setup is measured a number of times on each device, the residual contains the replicate or repeatability effect.

5.5 Example test data – experimental results

For the example dataset, there are two testers and two boards, hence t = b = 2. In addition during data collection there were 30 replicates done on each site, hence r = 30. Using these values and the raw data from the dataset, the ANOVA results are in tables 9 and 10 below.

Here the dominant source of variance is the test system variance, with $S^2_T = 0.403$. This has a P value < 0.01, indicating that this effect is highly significant. The variances from all other sources are negligible in comparison, with S^2_R, S^2_{TXB}, S^2_B variances of 0.015, 0.008, and 0.001 respectively.

Source	SS	DOF	MS	F	P
Tester	24.465	1	24.465	1631	<0.01
Board	0.303	1	0.303	20.2	0.58
Interaction	0.243	1	0.243	15.2	0.62
Residual	1.791	116	0.015		
Total	26.730	119	0.230		

Table 9. Example Data - ANOVA Table Results

Source	Variance Estimate
Tester	$S^2_T = 0.403$
Board	$S^2_B = 0.001$
Interaction	$S^2_{TxR} = 0.008$
Residual	$S^2_R = 0.015$
Total	$S^2_T + S^2_B + S^2_{TxR} + S^2_R = 0.427$

Table 10. Example Data - Calculation of Variances

6. Blocked experimental design for estimating multi-site test boards

For cost reduction, multisite test boards is employed allowing multiple parts to be tested in parallel. In analysing the effect of each test site, the variance of the part is confounded into the variance of the test site. In this instance the variability of the parts becomes a nuisance factor that will affect the response. Because this nuisance factor is known and can be controlled, a blocking technique is used to systematically eliminate the part effect from the site effects.

Take the example of a quad site tester in which 4 parts are tested in 4 independent sites in parallel. In this instance the variability of the parts needs to be removed from the overall experimental error. A design that will accomplish this involves testing each of 4 parts inserted in each of the 4 sites. The parts are systematically rotated across the sites during each experimental run. This is in effect a blocked experimental design. The experimental array for this example is shown in table 11, using parts labled A to D.

Run	Site1	Site2	Site3	Site4
1	A	B	C	D
2	B	C	D	A
3	C	D	A	B
4	D	A	B	C

Table 11. Example Array Blocked Experimental Design.

An example dataset from a quad site test board is shown in figure 7. This shows data from a temperature sensor product. Data were collected using 4 parts rotated across the 4 test sites as indicated in the array above.

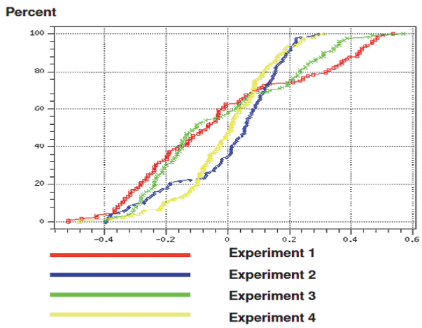

Fig. 7. Example data Blocked Experimental Design – Parts And Sites.

6.1 Blocked design statistical model

In this instance a suitable statistical model is given by equation 15 (Montgomery D.C, 1996):

$$Y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + e_{ijk} \qquad \begin{array}{l} i = 1 \text{ to } p \\ j = 1 \text{ to } s \\ k = 1 \text{ to } r \end{array} \tag{15}$$

Where Y_{ijk} are the experimentally measured data points.
μ is the overall experimental mean.
τ_i is the effect of device 'i'.
β_j is the effect of site 'j'.
$(\tau\beta)_{ij}$ is the interaction effect between devices and sites.
k is the replicate of each experiment.
e_{ijk} is the random error term for each experimental measurement.

Here it is assumed that τ_i , β_j, $(\tau\beta)_{ij}$ and e_{ijk} are random independent variables, where $\{\tau_i\} \sim N(0, \sigma^2_P)$, $\{\beta_j\} \sim N(0, \sigma^2_S)$ and $\{e_{ijk}\} \sim N(0, \sigma^2_R)$.

As before, the analysis of the model is carried out in two stages. The first partitions the total SS into its constituent parts. The second uses the model as defined and derives expressions for the EMS. By equating the SS to the EMS the model estimates are calculated. Both the SS and the EMS are summarised in an ANOVA table.

6.2 Derivation of expression for SS

The generalised experimental array is redrawn in the more general form in table 12.

	Site 1	Site 2	Site 3	Site j	Part Total
Part 1	Y_{11k}	Y_{12k}	Y_{13k}	Y_{1jk}	$Y_{1..}$
Part 2	Y_{21k}	Y_{22k}	Y_{23k}	Y_{2jk}	$Y_{2..}$
Part 3	Y_{31k}	Y_{32k}	Y_{33k}	Y_{3jk}	$Y_{3..}$
Part i	Y_{i1k}	Y_{i2k}	Y_{i3k}	Y_{ijk}	$Y_{i..}$
Site Total	$Y_{.1.}$	$Y_{.2.}$	$Y_{.3.}$	$Y_{.j.}$	$Y_{...}$

Table 12. Generalised Array – Blocked Experimental Design.

The results of this data collection are represented by the generalised experimental result Y_{ijk}, where i= 1 to p is the total number of parts, j= 1 to s is the total number of sites, and k= 1 to r is the number of replicates performed on each experimental run.
Using the dot notation, the following terms are written:

Parts total: $Y_{i..} = \sum_{j=1}^{s}\sum_{k=1}^{r} Y_{ijk}$ is the sum of all replicates for each part.

Site total: $Y_{.j.} = \sum_{i=1}^{p}\sum_{k=1}^{r} Y_{ijk}$ is the sum of all replicates on a particular site.

Overall total: $Y_{...} = \sum_{i=1}^{p}\sum_{j=1}^{s}\sum_{k=1}^{r} Y_{ijk}$ is the overall sum of measurements.

The SS for each factor are written as:
Parts:

$$SS_P = \left(\sum_{i=1}^{p} Y_{i..}^2\right) / (sr) - Y_{...}^2 / (psr) \tag{16}$$

Sites:

$$SS_S = \left(\sum_{j=1}^{S} Y_{.j.}^2\right) / (pr) - Y_{...}^2 / (psr) \tag{17}$$

Interaction:

$$SS_{PXS} = \left(\sum_{i=1}^{p}\sum_{j=1}^{s} Y_{ij.}^2\right) / (r) - \left(\sum_{j=1}^{s} Y_{.j.}^2\right) / (pr) - \left(\sum_{i=1}^{p} Y_{i..}^2\right) / (sr) + Y_{...}^2 / (psr) \tag{18}$$

Total:

$$SS_{TOTAL} = \sum_{i=1}^{p}\sum_{j=1}^{s}\sum_{k=1}^{r} Y_{ijk}^2 - \frac{Y_{...}^2}{psr} \tag{19}$$

Residual:

$$SS_R = SS_{TOTAL} - (SS_S + SS_P + SS_{PxS}). \tag{20}$$

6.3 Derivation of expression for EMS and ANOVA table

Expressions for the EMS for each factor are also needed. This is found by substituting the equation for the linear statistical model into the SS equations and simplifying. In this case the EMS are as follows.
Parts:

$$EMS_P = \sigma^2_R + r\sigma^2_{PxS} + sr\sigma^2_P \tag{21}$$

Sites:

$$EMS_S = \sigma^2_R + r\sigma^2_{PxS} + pr\sigma^2_S \tag{22}$$

Interaction:

$$EMS_{PXS} = \sigma^2_R + r\sigma^2_{PxS} \tag{23}$$

Residual:

$$EMS_R = \sigma^2_R \tag{24}$$

These are equated to the MS from the experimental data. These results for the blocked experimental design are summarised in the ANOVA table shown in table 13.

Source	SS	DOF	MS	EMS
Parts	Eq. (16)	p – 1	$SS_P/(p - 1)$	$\sigma^2_R + r\sigma^2_{PxS} + sr\sigma^2_p$
Sites	Eq. (17)	s – 1	$SS_S/(s - 1)$	$\sigma^2_R + r\sigma^2_{PxS} + pr\sigma^2_S$
Interaction	Eq. (18)	(s – 1)(p – 1)	$SS_{PxS}/((s - 1)(p - 1))$	$\sigma^2_R + r\sigma^2_{PxS}$
Residual	Eq. (20)	sp(r – 1)	$SS_R/(sp(r - 1))$	σ^2_R
Total	Eq. (19)	spr – 1		

Table 13. ANOVA Table - Blocked Design.

6.4 Output of ANOVA – complete estimate of robust test statistics

Equating the MS from the experimental data to the EMS from the model analysis, it is possible to solve for the variance due to each source. From the ANOVA table the best estimate for σ^2_P, σ^2_S, σ^2_{PxS} and σ^2_R are derived as S^2_P , S^2_S , S^2_{PxS} and S^2_R respectively. The calculations on the ANOVA outputs to generate these estimates are listed in table 14.

Source	Variance Estimate
Parts	$S_P^2 = \dfrac{MS_P - \sigma_R^2 - r\sigma_{PxS}^2}{sr}$
Sites	$S_S^2 = \dfrac{MS_S - \sigma_R^2 - r\sigma_{PxS}^2}{pr}$
Interaction	$S_{PXS}^2 = \dfrac{MS_{PxS} - \sigma_R^2}{r}$
Residual	$S_R^2 = MS_R$

Table 14. Results Table – Blocked Design.

Note that because each setup is measured a number of times on each part, the residual contains the replicate effect.

6.5 Example test data – experimental results

For the example from a quad site test board, there are 4 sites and 4 parts rotated across these sites, hence s = p = 4. In addition during data collection there were 30 replicates done on each site, hence r = 30. Using these values and the raw data from the dataset, the results of the ANOVA are shown in tables 15 and 16.

Source	SS	DOF	MS	F	p
Parts	0.063	3	0.021	2.6	0.05
Sites	8.800	3	2.933	366.6	<0.01
Interaction	9.414	9	1.04	130.0	<0.01
Residual	4.057	464	0.008		
Total	22.335	479			

Table 15. Example Data - ANOVA Table.

Source	*Variance Estimate*
Parts	$S^2_P = 0$
Sites	$S^2_S = 0.021$,
Interaction	$S^2_{PxS} = 0.035$
Residual	$S^2_R = 0.009$

Table 16. Example Data Calculation of Variance.

Here the dominant sources of variance are the test site variance, with $S^2_S = 0.021$, and the interaction variance estimate $S^2_{PxS} = 0.015$. Both these effects are highly significant with P values < 0.01. The variances estimates from other sources are negligible in comparison, with S^2_R, S^2_P of 0.009, and 0 respectively.
Figure 8 shows a replot of the original data with results grouped by site. It is clearly seen that site 4 has an offset difference of about 0.2 compared to the other sites. It is primarily this offset that is responsible for the site variance reported in the ANOVA.

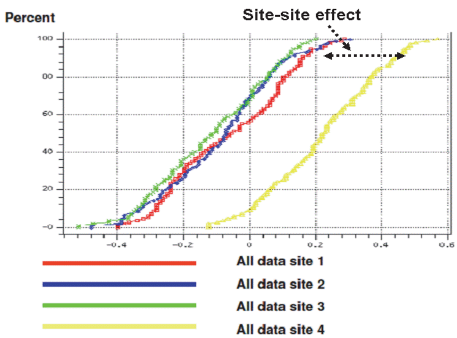

Fig. 8. Temperature Sensor Offset – Replotted by Site.

7. Complete experimental design for MSA on quad site test system

For a complete MSA on a quad site test system both the fixed effects and blocked experimental design are brought together. This enables optimisation within the data collection stage. The complete experimental design is shown in table 17. Here four parts are used – these are labelled A to D. These are rotated across the test sites in runs 1 through to 4. The data from these first 4 rows is analysed as a blocked experimental design to estimate the site-to-site and part-to-part effects. In runs 5 to 7 a second test board and test system are used to test the parts. The data from row 1 and rows 5 through to 7 is analysed as a fixed experimental design to estimate the tester-to-tester and board-to-board effects.

Run	Tester	Board	Site 1	Site 2	Site 3	Site 4
1	1	1	A	B	C	D
2	1	1	B	C	D	A
3	1	1	C	D	A	B
4	1	1	D	A	B	C
5	1	2	A	B	C	D
6	2	1	A	B	C	D
7	2	2	A	B	C	D

Table 17. Complete experimental design for quad site example

7.1 Complete experimental design for MSA on quad site test system

Example results obtained using this design of experiment are shown in table 18 and table 19 below. Table 18 presents the blocked design results, while table 19 presents the fixed design results. Note that 30 repeats were done for each experimental run.

Source	SS	DOF	MS	F	P
Tester	0.01199	1	0.01199	1.38	0.24
Board	0.01337	1	0.01337	1.54	0.21
Interaction	2.08E-05	116	1.79E-07	2.07E-05	1
Repeatability	1.031162	119	0.00866		

Table 18. Fixed Factor Design Experimental Results.

Source	SS	DOF	MS	F	P
Parts	4.1325	3	1.3775	152.30	<0.01
Sites	9.0550	3	3.0183	333.72	<0.01
Interaction	0.1653	9	0.0183	2.030	0.04
Repeatability	4.1966	464	0.0090		

Table 19. Blocked Design Experimental Results.

From the ANOVA tables it is seen that both the sites and parts are statistically significant with P values < 0.01, while the tester and board effects are not showing significance. The variance estimates from both the fixed and blocked design are summarised in Table 20. The total variance is obtained by summing the components of variance for both the fixed effects design and the blocked design. The repeatability is taken as the largest value obtained from either designs.

Source	Variance Estimate
Fixed effects model results	
Tester = S^2_T	5.18E-5
Board = S^2_B	7.47E-7
TXB = S^2_{TXB}	0.0000
Repeatability = S^2_R	0.0086
Blocked design results	
Parts = S^2_P	0.0226
Sites = S^2_S	0.0499
PXS = S^2_T	0.0031
Repeatability = S^2_R	0.0090
Test Gage R&R	0.0616
Total Variance (TV) = sum all components	0.0846

Table 20. Calculation of Components of Variances.

Using the equations (3) and (4) from section 2, the overall MSA metrics including gage R&R results from these ANOVA are presented in table 21 .

Component	Variance Estimate	Standard Deviation	% Total Variance	%Contribution to variance
Components R&R :				
Tester	5.18E-05	0.0071	2.4	0.06
Board	7.47E-07	0.0008	0.2	0.00
TesterXboard	0	0	0.0	0.00
Site	0.0499	0.2233	76.8	58.9
SiteXPart		0	0.0	0.00
Repeatability	0.0090	0.0948	32.6	10.6
Overall Gage R&R	0.0616	0.2481	85.3	72.8
Part	0.0226	0.1503	51.6	26.7
Total Variation	0.0846	0.2908	100.0	100

Table 21. Calculation of MSA metrics from experimental dataset.

8. Conclusions

Traditional measurement systems analysis methodologies are aimed at obtaining estimates of test error components. These are identified as equipment repeatability and reproducibility effects arising from independent appraisers. Gage R&R metrics can be generated using the data gathered. The most commonly used metrics are the percentage of total variation, and the percentage contribution to overall variance of each component.
With increasing complexity in semiconductor product test, the measurement equipment is generally automated, and test boards are employed that are capable of testing multiple parts in parallel. This introduces additional variance components not accounted for in these traditional methodologies. These components are identified as the tester, board and test sites effects. Updated ANOVA methodologies capable of accounting for this situation are required to enable MSA.

The purpose of this chapter is to describe the appropriate experimental designs appropriate for use in MSA in this situation. As the testers and boards come from a fixed population, a suitable design of experiments for tester-to-tester and board-to-board effects is a fixed effects experimental model. To evaluate site-to-site effects, the variation of the parts must be blocked from the variation of the sites. A suitable design of experiments for site-to-site and part-to-part effects is a blocked experimental design. Within this the parts are rotated across the test sites to allow the independent variation of both the parts and the sites.

The derivations of the ANOVA tables for both designs are presented. The data collection operation is optimised by merging the two designs. Experimental data gathered on a product within a manufacturing environment is analysed using these designs, and the results discussed. These designs enable the performance of MSA within the semiconductor environment in a streamlined fashion.

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9

Adapting Lean Processes for the Hospital/Surgical Environment

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1. Introduction

Hospital operating theatres are a focus for cost reduction, especially as expenses can run into billions of dollars (in the United Kingdom's National Health Service, theatres have been estimated to cost >£1 billion). About 46% of patients discharged from hospital have undergone surgery (Gordon et al. 1988; Audit Commission, 2003; Berwick, 2005; Cegan, 2005). Yet, cancellation rates can reach up to 20% and waiting lists for surgery exist in many countries (Gauld & Derrett, 2000; Buhaug, 2002; Bellan, 2008).

The concepts of 'Lean' or 'Six Sigma' thinking have shown great promise in industry, because they seek to reduce variations in inputs (eg, in quality of raw materials or steps in manufacturing processes), which increases efficiency and reduces costs. Although attempts have been made to apply these concepts to healthcare, it is not proven that their introduction has made progress or reduced costs (Vest & Gamm, 2009; Pandit et al., 2010). Therefore, these ideas may need considerable adaptation for the healthcare setting. This article focuses on three approaches to help understand the problems, and therefore to solve them: first, the notion of matching surgical capacity to demand for surgery; second, the idea of what constitutes 'efficiency' and 'productivity' in a surgical list; and third, we describe how effective planning of a surgical list using quantitative data reduces over-runs and patient cancellation. Together these ideas demonstrate how 'Lean' is suitably adapted to the existing circumstances in the surgical-anaesthetic setting.

At the outset, it is important to distinguish between operational, strategic and tactical decision-making in relation to operating theatre management. *Operational* decisions concern day-to-day local problems (eg, late starts or transportation problems). The relevant solutions are hospital-specific and may not apply to all hospitals and set the environment in which the organisations function. *Strategic* decisions concern the global direction/delivery of the service (for example, socialised vs private healthcare, relationships between funders and providers, etc). These decisions affect all hospitals. *Tactical* decisions are short-to-medium term concerning service planning to implement the strategic decisions (for example, optimum models for theatre scheduling, theatre allocations etc). Tactical analyses apply to all hospitals working within the same strategic environment.

Whereas Lean/Six Sigma approaches are usually focussed upon processes within a patient's journey in hospital (see: http://www.institute.nhs.uk/) and so are traditionally considered to function at an operational level, we believe that there is scope for translating Lean ideas to the tactical level, in a quantitative approach to demand-capacity and list planning.

2. Choosing the right surgical capacity for prevailing demand

It is a common problem to try ascertain how many hours of operating a particular surgical team needs per week. In some countries (eg, US) theatre time is not scheduled as block-time, but variable for each team (specialty) depending upon how many referrals it receives. Thus, 'capacity' is not a fixed quantity, but adjusted to match a variable demand and also to create incentives. In these settings, hospitals can modify their capacity for certain surgical services as a means to compete for business (Dexter & O'Neill, 2004; Pandit & Dexter, 2009). In other countries (eg, UK), surgical capacity is largely agreed and fixed long in advance and regarded merely as a passive means to cope with an ever-present demand in a socialised system of healthcare (Pandit et al., 2010).

If surgical 'capacity' matches (or exceeds) 'demand' for surgery, then patients are promptly treated and there are no surgical waiting lists. However, both the terms 'demand' and 'capacity' require some mathematical explanation. Only then can be understood what is meant by 'matching' these two quantities. In the context of healthcare - and surgery in particular - 'time' is more relevant a measure than is the absolute number of patients. Thus, demand is best understood as the total minutes or hours required for the surgical procedures, and not simply by the number of patients booked for surgery. It is notable that this ‚demand' arises from the patients the surgeon sees in the outpatient clinics each week. Correspondingly, 'capacity' is the weekly operating time available to the surgeon.

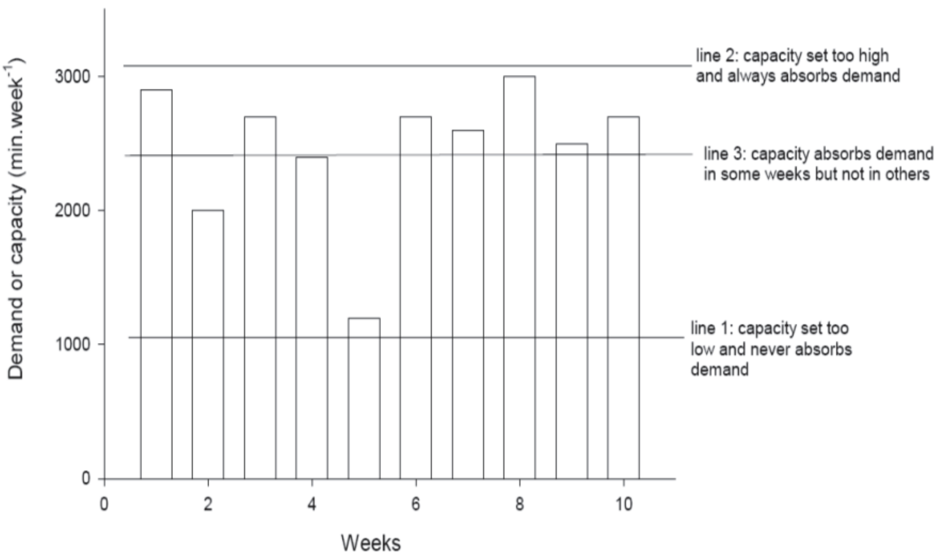

Fig. 1. Demand generated in a surgical clinic over 10 weeks.

If demand were known and constant then the problem would be simple. However, the surgeon sees a different number of patients each week, needing different procedures.

Therefore, the variation in demand (not just the mean demand) influences any mathematical analysis. However, whenever we introduce 'variation' into the equations, and whenever that 'variation' is unpredictable, then we have to deal with concepts like ‚likelihoods' and ‚probability'.

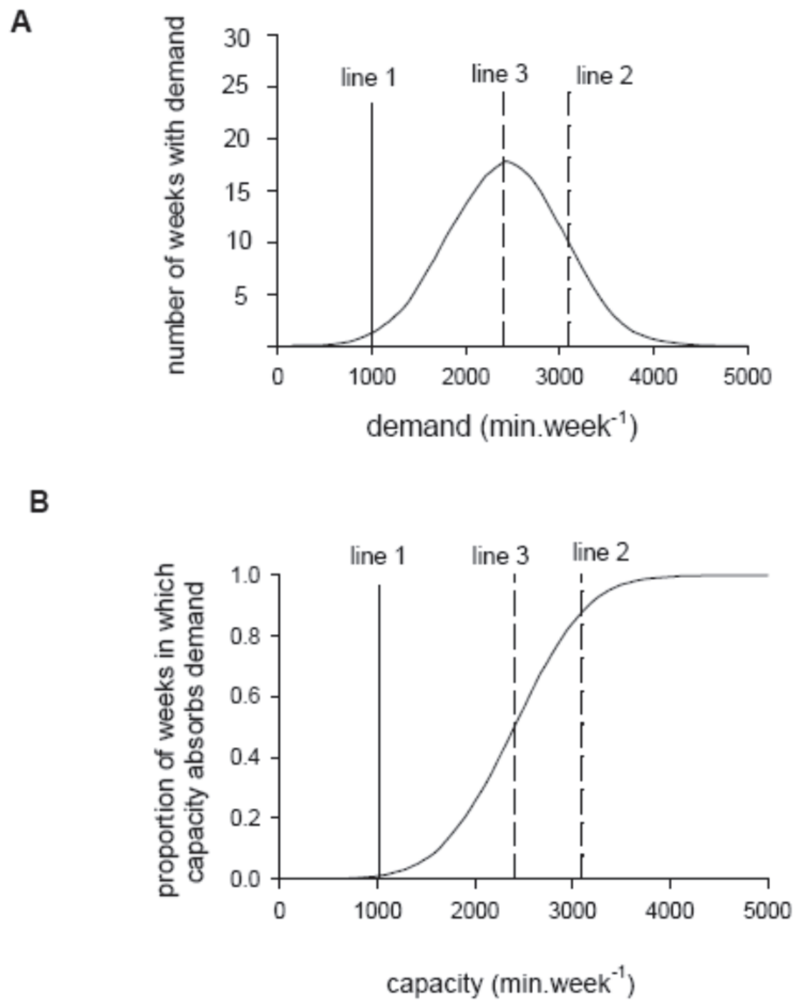

Fig. 2. A: Histogram for expanded set of data in Figure 1, showing the three possible capacity levels that could be set. The area under the curve to the left of each line yields the probability of meeting the demand at the chosen level of capacity. B: Integral of Figure 2A. The probability is now shown on the y-axis for the levels of capacity chosen.

Figure 1 shows a variable demand (a surgeon books a variable number of hours of surgery per week). If capacity is set too low (line 1), a waiting list will result. If, however, set too high, then demand is reliably absorbed, but there is considerable potential waste of resources (line 2). Between these limits, capacities absorb demand in some weeks but not in others (line 3). What is the correct level of demand?

One way of approaching this problem systematically is to consider the histogram of demand generated from the clinic activity (Figure 2A). We simplify the considerations to a normal distribution, but similar calculations can be performed for non-normal distributions (Pandit et al., 2010). For any capacity hypothetically set (eg, at lines 1, 2 or 3 in Figure 2A that approximately correspond to these lines in Figure 1), we can now estimate the likelihood of absorbing demand as the area under the curve to the left of each hypothetical vertical line for capacity (Figure 2A). In other words, mathematically integrating the area under the normal curve gives us a probability density function (Figure 2B) for the relevant levels of capacity. This density function tells us the likelihood of absorbing that demand on a regular basis for a chosen level of capacity. Whether a likelihood of 70%, 80% or 90% is chosen depends on several factors, of which one is 'waste'.

There are at least two concepts of 'waste' in the current context. One is the notion that money is spent with little gain. With reference to Figure 2B, increasing surgical capacity by a given quantum (eg, by 1000 min/wk) will cost a certain amount of money. Theatre costs have been estimated as between £12-20.min^{-1}, so this would costs £12,000 – £20,000.wk^{-1} per theatre (Abbott et al, 2011). If surgical capacity is increased by this amount from 2,000 min.week^{-1} to 3,000 min.week^{-1}, this would increase the proportion of weeks in which demand was met by ~40% (from ~40% to ~80%; Figure 2A).

However, increasing surgical capacity by the same quantum from 3,000 min.week^{-1} to 4,000 min.week^{-1} increases the probability of meeting demand by only ~10% (from 80% to ~90%; Figure 2A). These diminishing returns on investment represent a form of waste, and must be appreciated by all organisations that wish to be 'lean'

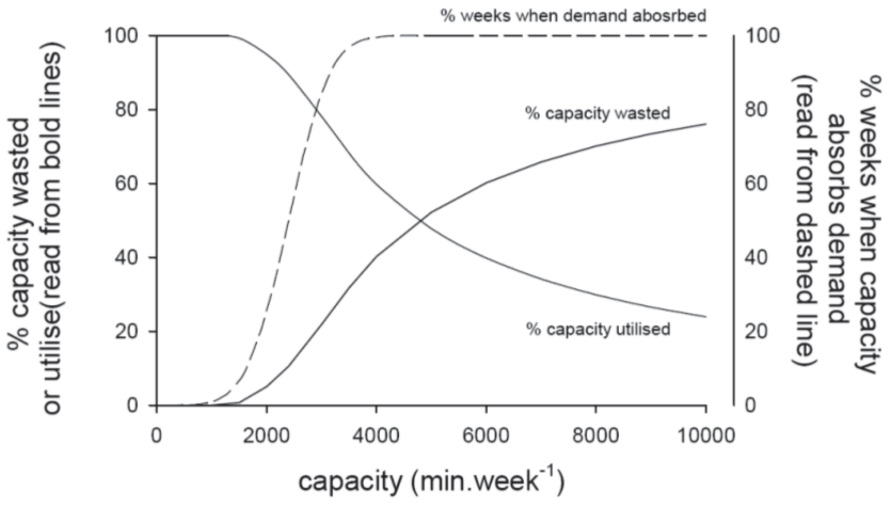

Fig. 3. The inverse relationship between utilisation and waste (bold lines; read from left axis) for given levels of capacity for the data shown in Figures 1 and 2. Superimposed (dashed line; read from right axis) is the same plot as in Figure 2B.

The second notion of 'waste' is that of unused capacity. For any given level of capacity for the hypothetical demand, we can calculate the proportion of capacity that will be wasted.

The proportion of time wasted rises as capacity is increased (while the proportion of time utilised correspondingly declines) (Figure 3).

A very low capacity of ~ 1,000 $min.wk^{-1}$ is associated with almost no wasted time and there is high utilisation. But this level of capacity will absorb demand in very few weeks, causing a huge rise in the waiting list (Figure 3). On the other hand, capacities of ≥4000 $min.wk^{-1}$ which absorb demand every week are associated with ≥50% of time wasted (ie, <50% time utilised; Figure 3). There is therefore an inevitable trade-off between choosing a capacity which reliably absorbs prevailing demand, and choosing a capacity that minimises waste (Macario, 2010). The optimum balance between these greatly depends on the local, social, or political priorities.

In a flourishing economy, it may be possible to absorb all demand despite a degree of waste. In times of economic hardship it may be necessary to minimise all waste and accept prolonged waiting times or waiting lists as one of the prices to pay for potential economic recovery. In other words, achieving too high a utilisation is as bad as achieving too low a utilisation (Table 1). In healthcare, the 'lean' option not simply attaining the highest possible utilisation; rather it is achieving a balance between utilisation of resources and several other factors, one of which is waste.

Utilisation	Implication
100%	Not realistic and/or implies insufficient capacity
90%	Exceptional; may not be sustainable
80%	Implies a good scheduling algorithm and is achievable
70%	Acceptable, but room for improvement
50%	Implies poor management or profligate approach (ie, theatre capacity possibly excessive)
30% or less	Unacceptable, implying very poor theatre management

Table 1. Degrees of theatre utilisation and their implications.

3. Measuring efficiency in a surgical list

Another aspect of utilisation is the proportion of time used within a single surgical list (say, each list is of 8 hours duration). Ideally, the amount of time wasted in non-productive activity (eg, waiting for the patient to arrive, opening equipment packs, etc) should be minimised and as much of the 8-hour list as possible should be spent in productive anaesthetic-surgical tasks. Yet, the list should not over-run its allotted time as this is expensive (due to overtime payments and unbudgeted consumables), and unplanned over-runs can disrupt other aspects of the clinical service, including emergency work. An over-running list can also result in patient cancellation (ie, where patients are still waiting on the ward to be called to theatre and have their surgery but the original end-time of the list is long past and staff cannot or will not stay despite offer of overtime payments). Indeed, over-runs are possibly the main cause of cancellation (Pandit & Carey, 2006; Pandit et al, 2007). Given these considerations, what is an 'efficient' surgical list?

Simple list 'utilisation' can be excluded as an appropriate measure of efficiency for several reasons. First, optimal list utilisation differs among surgical specialties. Not all specialties can achieve equally high utilisation (Dexter et al., 1999). For example, orthopaedic surgeons specialising in joint replacements are more likely to know in advance which cases they are doing and so utilise their time fully as compared with, say, cardiac surgeons who only know a day or two in advance which patients admitted with unstable angina will need revascularisation. Second, measured utilisation can be highly variable from week to week (eg, from 38% - 85%; Dexter et al., 2003) so questions arise as to whether means or ranges are most relevant. Third, utilisation is irrelevant when some specialties are fostered to promote the general status of the hospital. For example, a new service such as robotic prostatectomy will naturally have low utilisation initially but will serve the hospital well over time (Macario, 2010). Finally, utilisation figures can be artificially maximised by poor practice. For example, teams can slow down simply to occupy the theatre for the 'target time'. Or, since it is easier to fill the list with shorter cases than longer cases, the former may be preferentially booked at the expense of the latter (Macario, 2010).

By contrast, all can agree that the following sentiment encapsulates the notion of good efficiency on a surgical operating list: a theatre is used most efficiently when as much of the time available is utilised, when there are no over-runs and no patients are cancelled (Widdison, 1995). This can be expressed mathematically as:

Equation 1:

$$Efficiency = \left[\begin{pmatrix} fraction\ of \\ scheduled\ time \\ utilised \end{pmatrix} - \begin{pmatrix} fraction\ of \\ scheduled\ time \\ overrunning \end{pmatrix}\right] \times (fraction\ of\ scheduled\ operations\ completed)$$

If an 8 hour list finishes in 6 hours, then the 'fraction of scheduled time utilised' is 0.75 and the 'fraction of scheduled time over-running' for this same list is zero. If an 8 hour list over-runs by 2 hours, then the 'fraction of scheduled time over-running' 0.25, and the fraction of scheduled time utilised for this list = 1. Thus the first two terms of the equation operate in a mutually exclusive manner: i.e. a single list cannot be both under- or over-utilised at the same time. If 4 of 5 patients scheduled on a list are completed and one is cancelled, the 'fraction of scheduled operations completed' is 0.80. The formula therefore theoretically yields a result for efficiency ranging from 0 to 1.0 (or 0–100% if this result is multiplied by 100). The value of 100% is obtained when all booked cases are complete at the scheduled time, which is our sense of perfect efficiency. The formula can also give 'credit' for a list that completes its own booked cases early (e.g. four cases) and accepts and completes extra cases (e.g. a fifth case from another list). Thus a number > 1 in the last term (i.e. the fraction of patients completed = 1.25 for this example) could translate as an efficiency > 100% for that particular list.

The formula can be shown graphically where cancelled operations 'set the envelope' for the maximum efficiency (i.e. there are 'isopleths' set by the cancellation rate) and efficiency increases to a maximum if the list finishes at the scheduled list end-time, but then declines thereafter (Figure 4). Plotting a list on this graph will show whether inefficiency results from under-utilisation (point A) or over-running (point B) or cancellation (point C). Combinations can also be readily visualised (point D is an under-running list with a cancellation; point E is an over-running list with a cancellation). This measure of efficiency is being recognised as a useful standard, with efficiencies of ~85% being a reasonable goal (Pandit et al, 2009; Joshi, 2008).

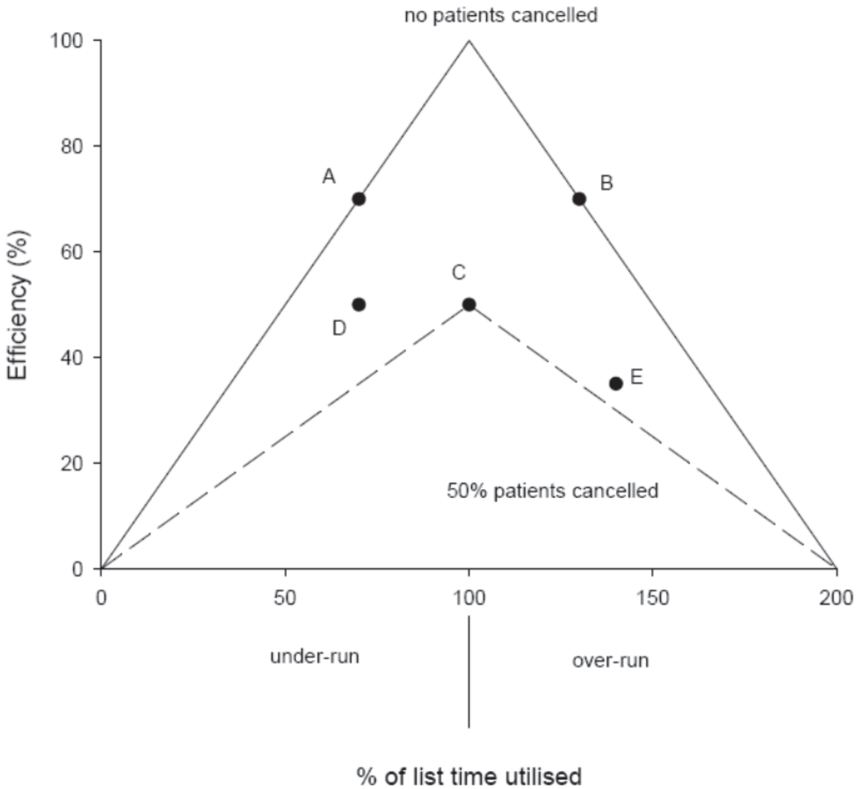

Fig. 4. Plots of efficiency from Equation 1. Points for a list will lie on solid line when there are no cancellations. Where there is a cancellation, the line will be within this ‚triangle' (eg, line for 50% patients cancelled is shown, dashed). Points A-E: explanation in text.

4. Measuring 'productivity' in addition to 'efficiency'

One limitation of this notion of 'efficiency' is that it does not recognise actual work completed. Thus, where two teams work equally efficiently in performing, say, knee replacements (that is, they utilise equal proportions of their list-time in productive activity, without over-run or cancellation) it is still possible that one team completes 4 operations in 8 hours while the other completes only 3. We would of course like to conclude that the former is more 'productive' than the other, if they have otherwise worked equally efficiently.

An acceptable measure of relative productivity in a scenario like this is simply the number of operations completed ('operations per hour'). However, this cannot be a universal measure as teams rarely undertake just one operation and do not all work equally efficiently (one team may complete more cases but cancel more patients). 'Operations per hour' as a measure also biases in favour of shorter operations, while other measures such as 'income' favour operations – arbitrarily – priced highest (Abbott et al., 2011): and avoiding such biases enables comparison of teams across specialties.

If we were to develop a measure of 'productivity' (in addition to that of 'efficiency' above) that would suitably apply to all surgical lists, it would need to fulfil the following criteria, from first principles:

1. the measure should be independent of casemix. The procedures undertaken or the co-morbidities of patients should not influence whether a team is regarded as 'productive' or not. In other words, inherently short and long procedures should be regarded as potentially equally productive (speed in this sense being the time from the start of anaesthesia to the time of arrival of the patient in the recovery area);
2. for any given surgical procedure, productivity is inevitably related to the speed with which the operation is completed. For the same operation (eg, hernia repair) the faster team is reasonably regarded as the more productive;
3. however, adoption of new techniques which are inherently slower to achieve the same surgical aim should not result in a team being regarded as no longer productive. For example, laparoscopic techniques improve safety, pain scores or postoperative stay but can take longer to perform (Maione et al., 2005). A team which once completed, say, three open operations and now completes only two laparoscopically does not automatically make it less 'productive';
4. the greater the total anaesthetist-surgeon contact time with the patient during a list (ie, as a proportion of list-time), the greater should be the productivity measure for this list;
5. productivity should only be regarded as having increased when any time savings made by improved practices, reducing idle gaps or greater speed are used to accommodate extra cases, rather than finish the list early;
6. any measure 'productivity' should be applied only to lists that are acceptably 'efficient' (by Equation 1). Or expressed another way, any measure of 'productivity' should incorporate the measure of efficiency; if the list is inefficient, this should be reflected proportionately in a reduced measure of productivity.

It is possible to reflect these six sentiments in an empirical mathematical formula (Pandit et al. 2009):

Equation 2:

$$\text{Productivity} = 111 \times [\ \text{Efficiency} - (10^{[0 - \{\text{Speed} \times \text{Patient Contact}\}]})]$$

Where 'efficiency' is calculated from Equation 1. 'Speed' is simply the relative speed of completing the surgical procedure. It is assigned any value, where 1.0 indicates average speed while, for example, 2.0 indicates working twice as fast. It is calculated by reference to published values or the team's or hospital's own average speed, or is assigned an arbitrary value of 1.0 if speed is unknown. 'Patient contact' is the proportion of list time spent in productive anaesthetic or surgical activity (the converse of this is 'gap' or 'turnover time'). It can have any value from 0 (whole list wasted) to 1.0 (no gaps at all). Equation 2 yields a value for 'productivity' ranging from 0 to 100% (the last is attained when efficiency is 100%, speed is 1.0 and patient contact is 1.0).

Graphically, this formula can be plotted (Figure 5). Here, a list lies on its specific efficiency curve and its place depends on the product of speed and patient contact. Thus list A is ~75% efficient; list B is a little more efficient but has a little less patient contact and/or speed of surgery. List C has the same amount of patient contact and/or speed as A, but is far less efficient (eg, perhaps through over-runs and/or patient cancellation). List D has similarly poor efficiency as C, but even worse patient contact and/or speed. List E has the same efficiency as A, but poorer patient contact and/or speed: E can increase its efficiency (eg, by reducing patient cancellations) and so move in the direction marked by the arrow.

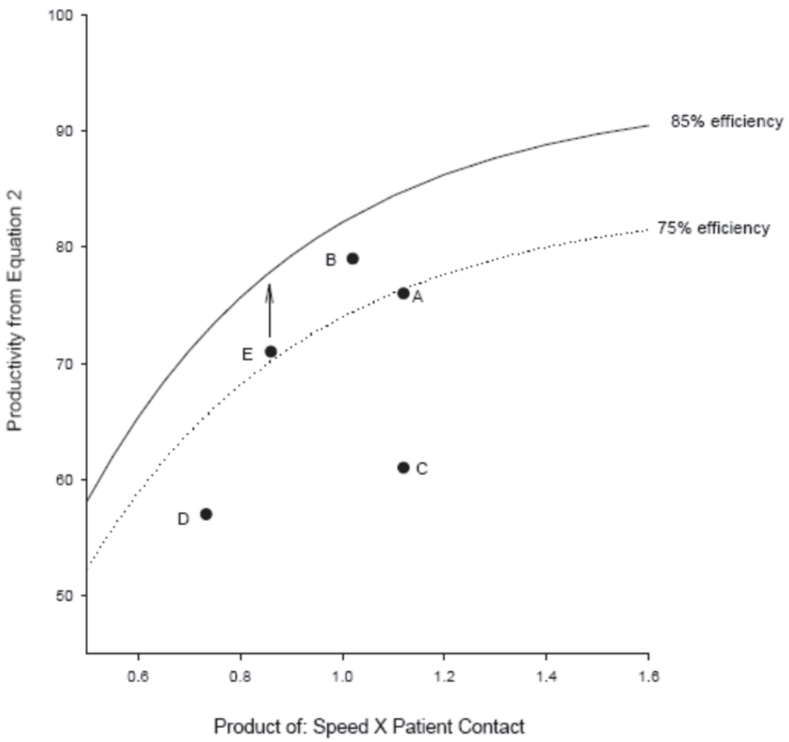

Fig. 5. Productivity calculated by Equation 2 plotted against the product of speed and patient contact for lists A-E. Also shown are two lines of efficiency.

Although these relationships are empirical, they have been usefully modelled (Pandit et al., 2009). The six criteria which a measure of productivity should fulfil (listed above) have some analogy with measuring productivity in businesses that undertake skilled, complex tasks such as antique clock repair, as opposed to low skilled, repetitive tasks (Schmenner, 2004). High productivity results when the business accurately estimates its workload. That is, only accepting enough clocks for repair that occupy its capacity without overwhelming it and cancelling orders or postponing work. This is akin to sensible booking of patients onto operating lists (see below). Staff in the business should spend as much of their time working on the clocks, rather than in idle gaps or breaks (a notion akin to maximising patient contact on a surgical list). Finally, for any given clock, staff should ideally take no longer than the average time in repair for the complexity of the task. This is akin to the notion of speed.

We have assumed throughout that quality of service is maintained in all aspects of our desire for efficiency and productivity, as that is an essential aspect of service delivery. Without quality standards being met, there can be no true measures of efficiency/productivity at all (ie, a factory making televisions has zero productivity, regardless of how many it makes, if its televisions do not work).

5. Planning cases for a surgical list

If it is desirable to utilise a list as much as possible, but not over-run and to complete all the cases booked, it follows that effective list planning is an important aspect of a properly 'lean organisation'. Is it possible to book a list rationally so that these aims are more easily met?
In many organisations, lists are booked directly by surgeons or their secretaries (or occasionally by managers) in an ad hoc manner, using their own experience to estimate whether the number and type of operations booked is appropriate for the time available on the list. However, they may face several pressures that cause them to over- or under-book the list. Surgeons may feel that over-booking demonstrates to others how hard they work, or their past surgical training may not have included organisational training, or surgeons may possess or develop character traits that make them prone to exceeding their own capacity for work or the presence of a large waiting list may be a worry. All these factors may cause them to over-fill lists. On the other hand, other demands on their time (teaching, lecturing, committee meetings) may prevent them from fully utilising a list. These issues have been discussed elsewhere (Jones & McCullough, 2007).

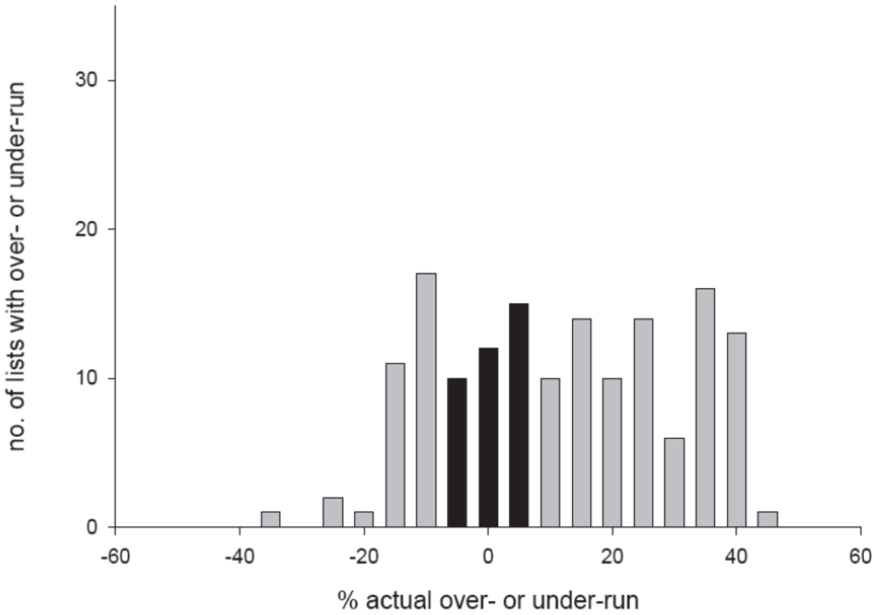

Fig. 6. Histogram of the number of surgical lists (of 150) with the degree of over- or under-run. The majority of lists over-ran, and only a minority (dark boxes) finished within 10% of the scheduled list time.

If patients scheduled for elective surgery first enter a 'pool' or waiting list (where they wait for several months; see http://www.nhs.uk.org/18weeks) then the problem appears to be a relatively simple one of ensuring a series of cases from this readily-available pool fills the pre-allocated block-time, with no over-running. Key to planning the list, therefore, should be knowledge of the average time (plus the standard deviation, SD) each case is likely to take.

The ad hoc method is distinctly poor at booking lists well (Figure 6). A more quantitative method can use the mean and SD of the published surgical procedure times (this referring to the time from start of anaesthesia to the arrival of the patient in the recovery area after the end of surgery) using the following equations (Pandit & Tavare, 2011):
Equation 3:

$$estimated\ mean\ duration\ of\ list = (M_1 + M_2 + \cdots M_x) + \ (G_t . S_t)$$

Equation 4:

$$pooled\ SD = \sqrt{\frac{SD_1{}^2 + SD_2{}^2 + \ \ldots\ SD_x{}^2}{x}}$$

M_1, M_2, etc refer to the mean times for the cases to be scheduled; G_t is the proportion of list time estimated to be wasted as gaps (usually ~10%, or 0.1) and S_t is the scheduled list time in min (eg, 480 min for an 8 hour list); SD_1, SD_2, etc are the corresponding SDs for the respective operation times M_1, M_2 etc. The results of these equations, including the pooled SD can be used using the t-distribution to generate a probability that the proposed list will finish within the scheduled list time.

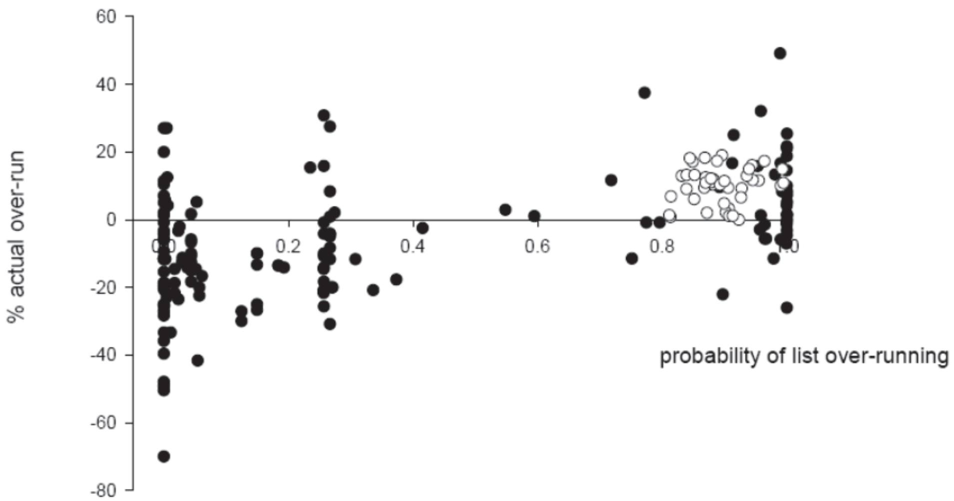

Fig. 7. For 150 surgical lists booked by the ad hoc method, the % actual over-run or under-run (y-axis) was plotted against the calculated probability that the list would over-run using Equations 2 and 3 and the t-distribution. Lists that suffered a cancellation are shown as hollow circles. Note that the ad hoc method yields a majority of lists that are predicted to over-run (and actually do so) or predicted to under-run (and actually do so).

Furthermore – and most importantly – the same t-distribution can be used to generate a probability that the proposed series of cases will exceed a certain minimum list time that should be fulfilled in order to utilise the list appropriately. In other words, if a list is scheduled for 480 min but it is judged that at least 450 min should be utilised, this forms a lower boundary (B1): the probability estimated that the proposed list of cases exceeds this time should be relatively high (eg, >80%). Yet, if it is also judged that the list should not over-run beyond 510 min then this becomes a higher boundary B2. The probability that the proposed list of cases exceeds B2 should be low (eg, <20%). Taken together, therefore, B1 and B2 and the generated probabilities form a heuristic (a rule of thumb) that can be used to book lists (see: http://links.lww.com/EJA/A19).

Figure 7 shows that the ad hoc method of list booking is generating lists with probabilities of near-100% that they will over-run (many of these suffer a cancellation) and that many are booked so that they have a near 100% chance of under-running.

Equally, this same figure suggests that these probabilities can be used to book the lists in the first place. If this were done, Figure 8 shows that there would be good agreement with the predicted list time and the actual list time.

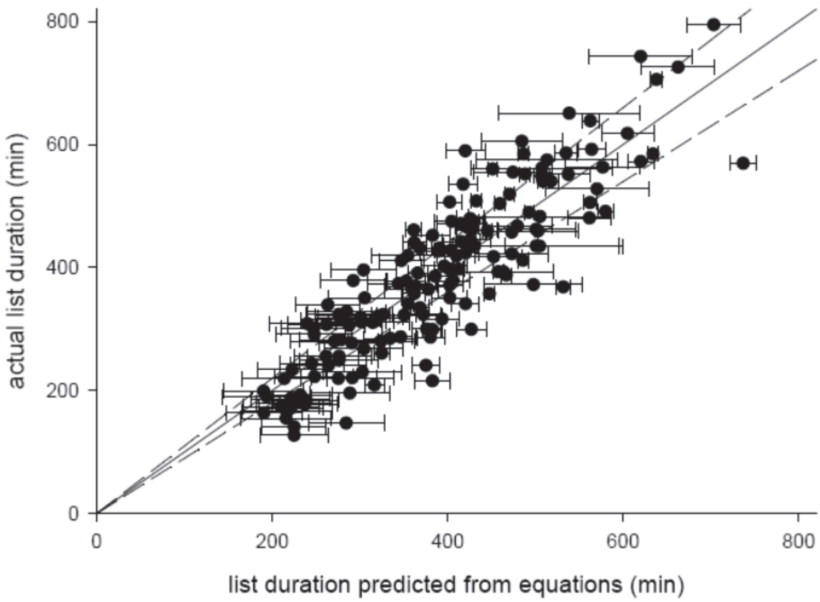

Fig. 8. The predicted list duration from Equations 3 and 4 (x-axis) fits the real data (y-axis) very well for the lists in Figure 6. Error bars are 95% confidence intervals of the estimate; the solid line is the line of best fit superimposed on the line of identity; dashed lines are 95% confidence intervals for the fit.

6. Conclusion

'Lean' can be adapted to the healthcare (surgical-anaesthetic) situation in a quantitative and tactical way, extending its application to just the operational level of management. This, as shown above, should result in the appropriate surgical capacity being provided for the workload, it should attain 'efficiency' and 'productivity' on the surgical list and it should facilitate proper scheduling of the cases on the list to achieve that efficiency.

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