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A multi-factor model for evaluating manufacturing defect opportunities in six sigma analysis

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ABSTRACT

A MULTI-FACTOR MODEL FOR EVALUATING MANUFACTURING DEFECT OPPORTUNITIES IN SIX SIGMA ANALYSIS

by

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Six Sigma Quality Analysis provides a structured method for manufacturing quality problems and defect opportunities to be defined, measured, analyzed, improved, and controlled. The technique is now being widely used in both the manufacturing and service industries to evaluate the classical "defects per million" metric. An underlying assumption of classical Six Sigma Analysis is that all defects contribute equally to the derivation of the defect rate. In the thesis, it is proposed that this assumption skews and often distorts the derived defect rate. Using classical Six Sigma the user is able to list a large number of often border-line defect opportunities and hence inflate their six sigma capability. Here, a new multi-factor model is developed for calculating the Defect Per Million Opportunities (DPMO). The proposed DPMO equation undergoes a rationalized transition from the normal formulation based on the following factors: (i) defect severity, (ii) occurrence frequency, (iii) detection ease, (iv) correction time, and (v) cost impact. This new equation accounts for all possible differentiating characterizations between possible defects. In effect we get a scaled down number of defect opportunities which eliminates the six sigma inflation problem. For each factor, a Six Sigma Opportunity rating scale is presented in the 0-1 range. An MS-Excel implementation of the proposed multi-factor scheme is presented along with a case-study example.

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by
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A MULTI-FACTOR MODEL FOR EVALUATING MANUFACTURING DEFECT OPPORTUNITIES IN SIX SIGMA ANALYSIS

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This Thesis is dedicated to
my parents, sisters and friends.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

Figure **Page**

CHAPTER 1

INTRODUCTION

Six Sigma is a very popular tool in many companies because of its efficiency in identifying and reducing the number of defects. Six Sigma was initially developed by Motorola and was then adopted by many companies in both the manufacturing and service sectors. While the concept of Six Sigma is based primarily on statistical analysis, the input data and follow-up defect elimination activity are more akin to traditional quality control. Clearly, achieving a defect rate of 3.4 defects per million is not a trivial task. We find that in many cases, the inability to accurately classify the defect opportunity could lead to wrong predictions of Six Sigma capability. This is addressed in this thesis.

1.1 Introduction to Six Sigma

Sigma is a statistical measure that reflects process capability. The sigma scale of measure is perfectly correlated to such characteristics as defects-per-unit, parts per million defective (PPM), and a probability of a failure/error. The sigma value indicates how often defects are likely to occur. The higher the sigma, the less likely it is for a process to produce defects. As sigma increases, costs go down, cycle time goes down, and customer satisfaction goes up. The Figure 1.1 shows the normal distribution curve for six sigma and also the various levels of sigma attained at different parts per million defects. As the figure clearly indicates, as the sigma level increases, the percentage of non-defective products approaches 100%.

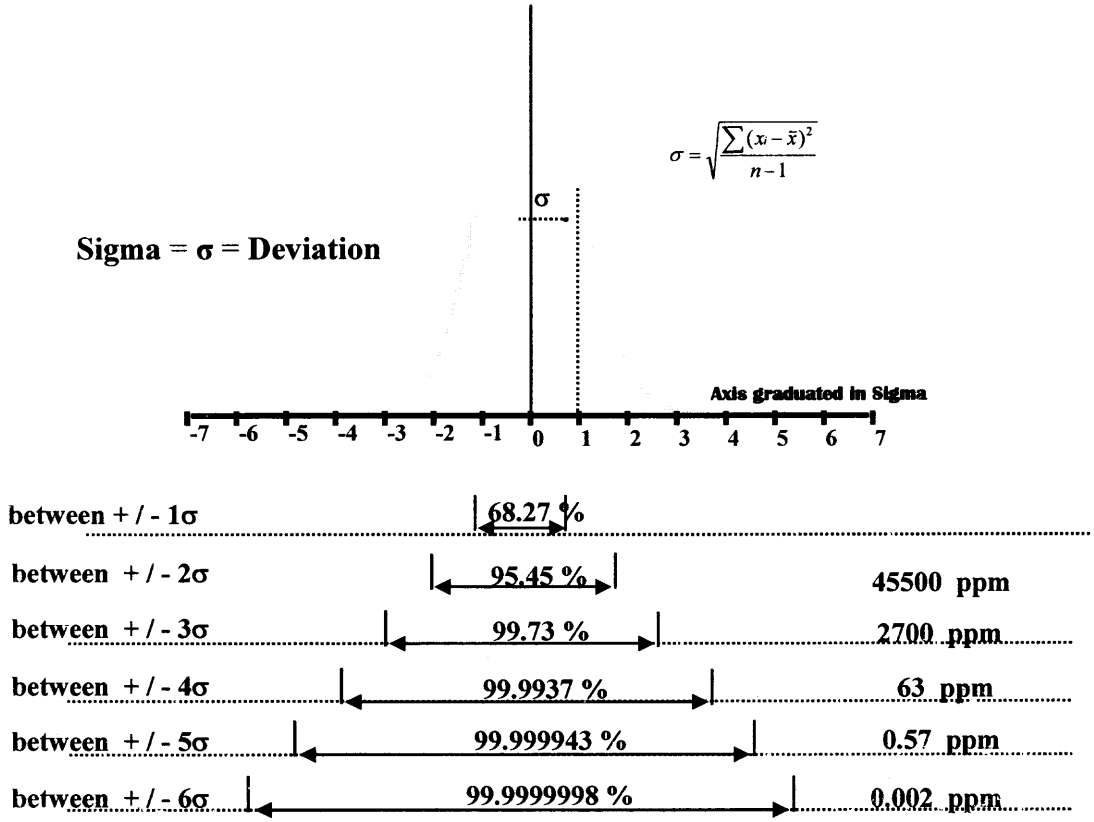


Figure 1.1 Six Sigma Normal Distribution and Statistics.

1.2 Six Sigma Quality

The objective of Six Sigma Quality is to reduce process output variation so that on a long term the customer's aggregate product experience results in no more than 3.4 defective parts per million (PPM). For a process with only one specification limit (Upper or Lower), this results in six process standard deviations between the mean of the process and the customer's specification limit (hence, Six Sigma).

Many processes are prone to being influenced by special and/or assignable causes that impact the overall performance of the process relative to the customer's specification. That is, the overall performance of a process, as the customer views it, might be 3.4 PPM (corresponding to Long Term performance of 4.5 sigma). However, any process could indeed be capable of producing a near perfect output (Short Term capability – also known

as process entitlement – of Six Sigma). The difference between the "best" a process can be, measured by Short Term process capability, and the customer's aggregate experience (Long Term capability) is known as Shift or "Sigma Shift". The figure 1.2 shows the "typical" shift from the target.

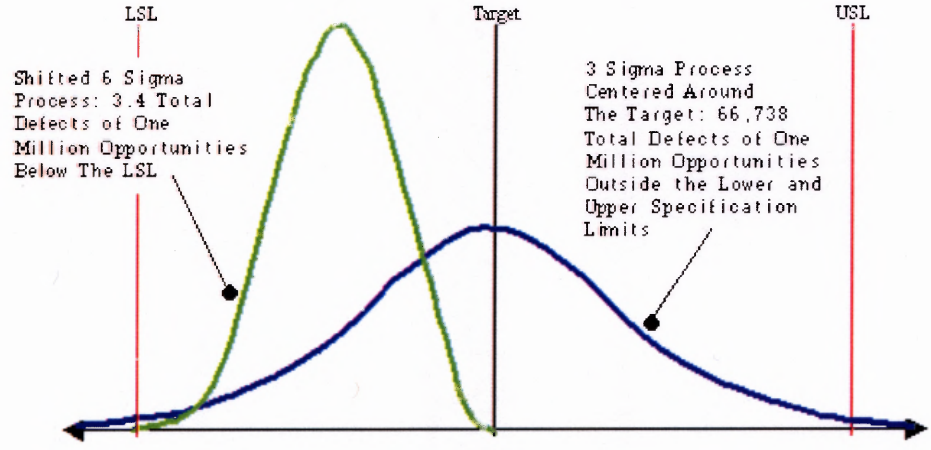


Figure 1.2 Six Sigma Shift.

For a "typical" process, the value of the shift is 1.5; therefore, when one hears about "6s" inherent in that statement is that the short term capability of the process is 6, and the long term capability is 4.5 with an assumed shift of 1.5.

1.3 Six Sigma Concept

Any process which analyzes the defect for a product will have two deliverables, namely, input and output. The traditional concept will mainly look into making the output better and achieve standard results. But the concept of Six Sigma perceives the analysis using a unique methodology. The concept of Six Sigma manages the input and then responds to the outputs. Hence both the deliverables are considered and analyzed which makes it a

better technology than the traditional and existing methods. The Figure 1.3 shows the deliverables and also shows the insight of the concept.

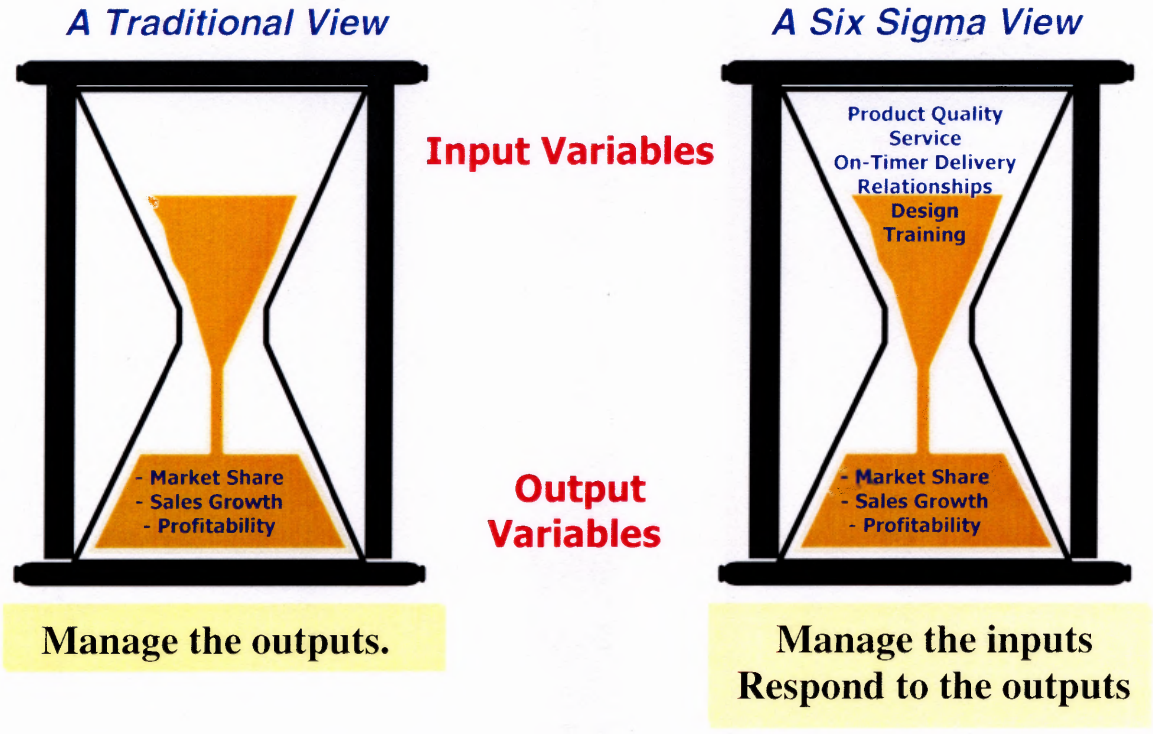


Figure 1.3 Concept of Six Sigma.

1.4 Defect Opportunities

The defect opportunities play a vital role in the calculation of the sigma level. The main focus should be on the number of opportunities which are a part of the Defect Per Million Opportunities (DPMO) calculation, which finally leads to the sigma level. There are various opportunities in various departments during various stages of the development process. All the opportunities must be summed together to arrive at coherent scaled opportunities from which the inflation factor can be analyzed and solved. Figure 1.4 shows the various opportunities that can arise in any area. For example, if a product is shipped to the storing locations, then shipping forms one opportunity per packaging unit.

Hence minute details must be listed while considering the opportunities, and all the opportunities are summed up to get the scaled opportunities.

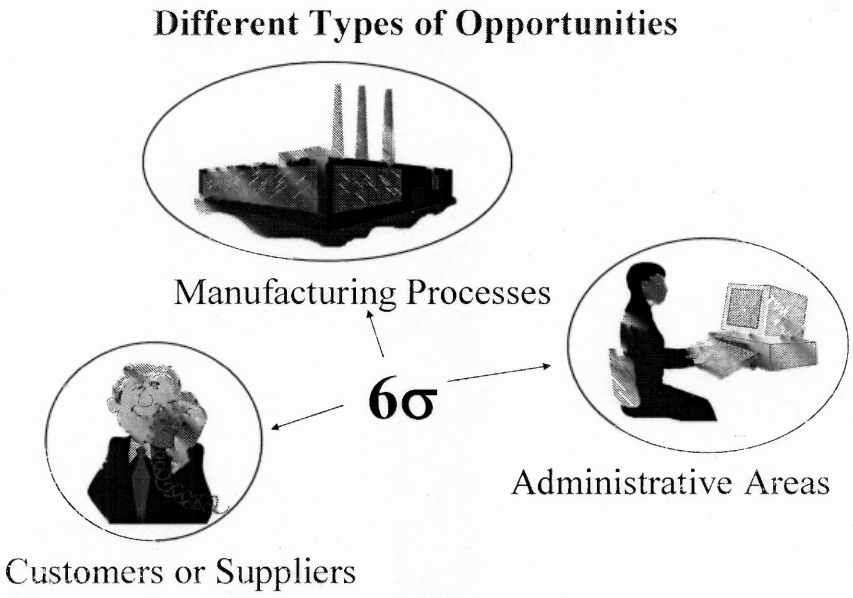


Figure 1.4 Different Types of Opportunities.

The main idea behind a successful Six Sigma formulation is to define the opportunity and the defect for any process and thereby use the rationalized formulation using a multi-factor scheme developed exclusively for the process to achieve the final sigma level.

1.5 Rationalization of the Formulation

The rationalization is done to the DPMO formula (DPMO = Defect per unit / No. of opportunities) in which the denominator undergoes a change. For converting this calculation of DPMO into a more reasonable argument, a different methodology has been adopted in this research. The DPMO calculation undergoes a rationalized transformation

wherein the defects are characterized and then the final sigma level is obtained with a scaled down factor for each opportunity under consideration. The inflation problem is analyzed with the opportunity inflation factor and an analysis is conducted to understand their behavior. The denominator in the DPMO formula is introduced with two decision variables and thus the number of opportunities is modified to bring meaning to the analysis. This has been analyzed and implemented in this research on the six sigma formulation with a case study.

1.6 Research Approach

The opportunities calculation and analysis has not received much attention in the six sigma literature. Almost all processes have employed some assumptions for the defect analysis using probability and assumptions based on experience. There has not been any methodology for the opportunities calculation in the Six Sigma field. The number of opportunities in the formulation needs attention for the following reasons:

- There must be a sufficient methodology to find out how the defects are accounted
- There must be a sufficient formulation by which the opportunities can be understood.
- There must be a clear picture of the defect analysis so that the defect does not go unnoticed.

The most important considerations for the opportunities calculation are:

- Selection of the factors which account for the defect of the products.
- Proper scale or point ratings for the factors.
- Influence of the factors on the process.

1.7 Research Objective

The objective of the research is to develop a rationalized sigma scale for the defect calculation by taking the opportunities as a consideration and thereby giving a meaning to the six sigma DPMO calculation. This is very important because there must be a proper method for analyzing the defects, otherwise the entire method remains meaningless. Hence the opportunities are characterized into five factors and each factor is assigned a scale between 1 and 10. Each factor is assigned 20% and multiplied with the ratings. Finally all the ratings are added and then divided by 10 so that a scale between 0 and 1 is obtained, with 1 being severe and those tending to 0 being inconsequential. Using classical Six Sigma the user is able to list a large number of often border-line defect opportunities and hence inflate their six sigma capability. Here a new multi-factor model is designed for calculating the Defect Per Million Opportunities (DPMO). This model is done using MS Excel and then various trials are performed where different factors take center-stage and the final scale deviations are noted. Finally, the rationalized multi-factor scheme is implemented to find the DPMO using the rationalized formula developed for the formulation and the sigma scale is attained. The entire analysis is then made flexible using the help of the Excel macros so that the process becomes easy for inputs and trials.

CHAPTER 2

LITERATURE REVIEW

Six Sigma is arguably a better strategy which aims at improvement by the implementation of various methodologies and tools. There has been a major impact in the field of manufacturing, research and development, and even in the IT industry because of Six Sigma. It has reached the pinnacle of success in many facets of various fields where achieving quality is the major concern. With the concept of defect-free manufacturing, Six Sigma has really tasted the fruit of success. However there are still many criticisms revolving around the methodology and few of them have been cleared. One among them is the number of opportunities consideration in the defect per million opportunities (DPMO) calculation. A USA today article presented different opinions about the value of six sigma in "Firms Air for Six Sigma Efficiency" (Jones, 1998) stating the opinion that Six Sigma is "malarkey", while Larry Bossidy, CEO of AlliedSignal, counters" "The fact is, there is more reality with the concept than anything that has come down in a long time in business. The more you get involved with it, the more you are convinced." Hence there is no concept without criticism and hence improvements can be obtained by continuous analysis and corrections.

Several prominent researchers have expressed their views on Six Sigma. Lucas (2002) has described Six-Sigma as a statistical business system and a functional methodology for disciplined quality improvement that achieves successful outcomes. Pearson (2001) has described Six-Sigma as a program that combines the most effective statistical and non-statistical methods to make overall business improvements. Triechler *et al.* (2002) have concluded that Six-Sigma is a highly disciplined process that helps

organizations to focus on developing and delivering near-perfect products and services. It is also, in their view, a change-acceleration process that focuses on pursuing success and the rapid adoption of change. Slater (2001) has stated that the Six-Sigma approach provides a very specific control program with control techniques that ensure continuation of improved processes. The General Electric (GE), CEO remarked that Six Sigma is "the most challenging and potentially rewarding initiative that has ever been undertaken by GE."

Breyfogle III *et al.*, (2001) have stated that Six-Sigma is more than a simple repacking of the best from other TQM programs. Pande, Neuman and Cavanach, (2000) had already taken a similar approach when they provided a review of some of the major TQM gaffes, and then compared TQM and GE-6σ in the light of these problems with a view to showing how a successful implementation of Six-Sigma can overcome these failures. They have also commented that Six-Sigma is a comprehensive and flexible system for achieving, sustaining, and maximizing business success. It is driven by close understanding of customers' needs and disciplined use of facts, data, and statistical analysis.

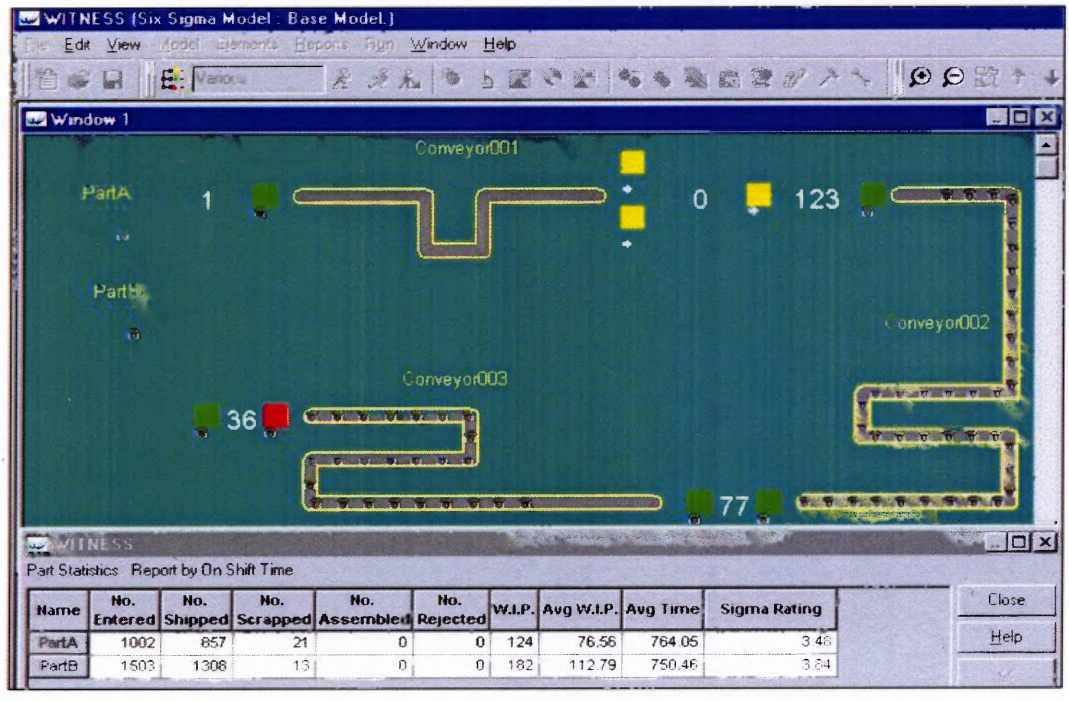
To find a consensus between TQM and Six Sigma (GE), Ching- Chow Lang (2004) made a comparison of TQM and Six Sigma. For this, he did a extensive research on the papers of other authors, integrated the research into 12 dimensions, and then compared them individually. He commented on each dimension to show how they co-relate TQM and Six Sigma. He developed a model showing the relationship and concluded that TQM and Six Sigma have several common aspects and integration of both

will be a new trend which should receive favorable response from practitioners and academics.

James M. Lucas (ASQ 2002) explained that the relationship between the Sigma Level (SL) and the Defects Per Million Opportunities (DPMO) is calculated using the cumulative distribution function [f(z)] of the normal distribution where f(z) is the probability of observing a value less than z. The table showing the relationship between SL and DPMO is shown in Appendix A. The calculations show the SL ranging from 0 to 7 in steps of 0.25 in the first column. The second and the third columns calculate f (SL+1.5) and f (1.5-SL) where 1.5 accounts for the process shift. The fourth column gives the probability of an observation that is not a defect. The values in this column are simply the difference between the second and third column and the column is called "probability good". The fifth column gives the probability of a defect as 1-(probability good). The last column converts the probability of a defect to DPMO by multiplying by 1,000,000. The six sigma is achieved when the sigma level of 6 has 3.4 defects per million opportunities. The calculations were done using Excel functions.

Anthony P. Waller (WITNESS product manager) has thrown some light on the six sigma project modeling which is carried out by means of WITNESS simulation and analysis software. The major idea behind the paper was to calculate the sigma ratings for the processes and the exporting of key statistics to MINITAB for further analysis. The WITNESS optimizer six sigma algorithm is also formed. The software helps in various phases of a project by providing detailed statistics on the effect of any proposed change in terms of throughput, utilizations, delays, service levels and much more. It allows for easy use of data from databases and Microsoft Excel. It also calculates the scrap and

rework rates, and can capture all defect information during a simulation run and automatically translate them into process sigma rating for each part or entity in the model. But nothing has been said about the opportunities in the calculation of the sigma ratings. The WITNESS software is powerful and many of the black belts use it as their tool for six sigma as it has various box plots and histograms and simulation runs which can give an idea of the production level and also about the process variation. Figure 2.1 shows the WITNESS Six Sigma model screen with sigma ratings.



Name	No. Entered	No. Shipped	No. Scrapped	No. Assembled	No. Rejected	W.I.P.	Avg W.I.P.	Avg Time	Sigma Rating
PartA	1002	857	21	0	0	124	76.56	764.05	3.48
PartB	1503	1308	13	0	0	182	112.79	750.46	3.84

Figure 2.1 WITNESS model with results screen showing sigma rating.

Various graphs were also plotted with the results and the evaluations and one of the many graphs that were obtained by the WITNESS optimizer is shown in Figure 2.2.

Narahari, Viswanadham, Bhattacharya (2000) have developed a synchronized supply chain using the six sigma tolerancing approach. They have clearly brought out the notion of process capabilities and the meaning of six sigma performance with a real life example from the plastics industry. They designed experiments using the nominal and

variance pool for the lead times and thereby have achieved six sigma performance. They believe that this paper is an important contribution towards applying statistical

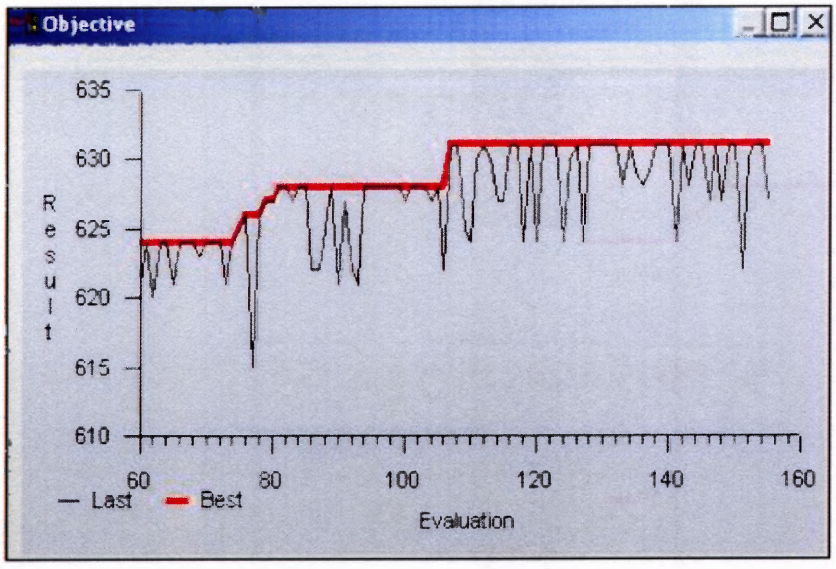


Figure 2.2 One of the many graphs and reports from WITNESS optimizer.

tolerancing techniques and best practices to design supply chain networks with high levels of delivery performance.

David L. Hallowell addressed in his article that a roadmap can be created between the DMAIC (Define, Measure, Analyze, Improve, and Control) methodology and DFSS (Design For Six Sigma) methodology. DMAIC always outstand DFSS because the former points at the problem root causes while the latter is more like improvement works. But at various stages of the project, the team finds it difficult to locate whether the process is to be treated with DMAIC or DFSS. To avoid such complications, the author developed a table so that one can find out at any point during the project as to where he/she is in the DMAIC-DFSS continuum. He developed a "The Project Translation" column which shows where the transition takes place and where the project needs attention. The author concluded that while considering a "branched" and a "parallel"

approach to integrating DMAIC and DFSS, one must be armed with as much insight at possible before deciding what is best in their particular environment. Thus there had been a distinction between the two methodologies and this roadmap will definitely help the project teams to follow the right path in their analysis.

Gary A. Gack brought in a new interest to the six sigma field by incorporating a relationship with Project Management Body of Knowledge (PMBoK). He explained that there are many shades of similarities between the two disciplines. Both seek to reduce failures, prevent defects, control costs and schedules, and manage risk. Project Management professionals mostly achieve the same goals by encouraging sound practices in a project-by-project basis, or by critical path method, or perform periodic project reviews. Figure 2.3 shows the process groups and knowledge areas.

Production Management Process Groups and Knowledge Areas

Process Groups / Knowledge Area	Initiating	Planning	Executing	Controlling	Closing
4. Project Integration Management		4.1 Project Plan Development	4.2 Project Plan Execution	4.3 Integrated Change Control	
5. Project Scope Management	5.1 Initiation	5.2 Scope Planning 5.3 Scope Definition		5.4 Scope Verification 5.5 Scope Change Control	
6. Project Time Management		6.1 Activity Definition 6.2 Activity Sequencing 6.3 Activity Duration Estimating 6.4 Schedule Development		6.5 Schedule Control	
7. Project Cost Management		7.1 Resource Planning 7.2 Cost Estimating 7.3 Cost Budgeting		7.4 Cost Control	
8. Project Quality Management		8.1 Quality Planning	8.2 Quality Assurance	8.3 Quality Control	
9. Project Human Resource Management		9.1 Organizational Planning 9.2 Staff Acquisition	9.3 Team Development		
10. Project Communications Management		10.1 Communications Planning	10.2 Information Distribution	10.3 Performance Reporting	10.4 Administ Closure
11. Risk Project Management		11.1 Risk Management Planning 11.2 Risk Identification 11.3 Qualitative Risk Analysis 11.4 Quantitative Risk Analysis 11.5 Risk Response Planning		11.6 Risk Monitoring and Control	
12. Project Procurement Management		12.1 Procurement Planning 12.2 Solicitation Planning	12.3 Solicitation 12.4 Source Selection 12.5 Contract Administration		12.6 Contract Closeout

Figure 2.3 Production Management Process Groups and Knowledge Areas.

Six Sigma is more focused towards the solution of a problem at its root cause and prevention of recurrence, as opposed to attempting to control potential causes of failure on a project-by-project basis. Six Sigma's set of tools are more broadly applicable, than those commonly applied within the discipline of professional project management. Recognizing that project management is itself a process, Six Sigma is potentially applicable to its improvement. Hence the author suggested a Six Sigma PMBoK Process by Process methodology which had four processes and some sub processes. Thus he created a bond between the two disciplines and concluded that Six Sigma complements and extends professional project management, but does not replace it. He also concluded that both disciplines make important contributions to successful business outcomes.

Alastair Horn (2003) illustrated a Business Improvement System comprising of five components by combining Balanced Scorecard elements with Six Sigma thereby linking Performance Management with Process Excellence. The Voice Of the Customer (VOC) was the center of the system and revolving around it were the other four key factors, namely Performance Management, Process Excellence, Project Selection and Project Execution. He considered the Voice of the Customer as the major criterion as an organization losing its stakeholders can never flourish. He introduced VOC upon which the Critical To Quality (CTQ) in six sigma can fit. Process Excellence is created by combining the Balanced Scorecard with Six Sigma approaches which breaks VOC, and hence measure objectives against targets and focuses attention on variation of metrics against targets. Performance Management monitors whether the business is on track to delivers the required outcomes and identifies any areas requiring intervention. Project Selection and Project Execution mainly listens to the VOC and then focuses attention on

variations thus making the best use of the Balanced Scorecard and Six Sigma approaches. The author expresses very clearly that by combining both these approaches, an organization can deliver breakthrough business performance.

Professor Martin Christopher and Christine Rutherford (2004) aimed at creating a resilient supply chain by employing Agile Six Sigma. Because of the growth in the supply chain complexity, the authors wanted to make a system which takes care of the supply chain effectively and then they came up with the idea of making the supply chain leaner. They characterized supply chain into two types- robust and resilient supply chain. They developed the shifting, stabilizing and re-synchronizing of the process, and there came face to face with the six sigma philosophies and measures. The aim was to reach the quality measures of six sigma, and hence they implemented the DMAIC methodology to reach the quality aspect for the supply chain. The lean supply chain came into existence when they wanted a sufficient way to take care of waste elimination and this triggered the agile way of thinking. They developed an "Agile Six Sigma Route" by which they felt they could build a resilient supply chain of robust six sigma processes with spare process capacity where it is needed, mostly along the critical path. Thus they concluded that through an Agile Six Sigma approach, supply chains can reduce internal sources of risk whilst improving supply chain efficiency and effectiveness.

Andreas Vlahinos and Subhash Kelkar (2002) designed a robust optimization using CAE (Computer Aided Engineering) for Six Sigma quality. They designed a Reliability Based Design Optimization (RBDO) which not only provides improved designs but also a confidence range for simulation-based optimum designs. In this research effort, a six sigma robust design formulation was made along with an example

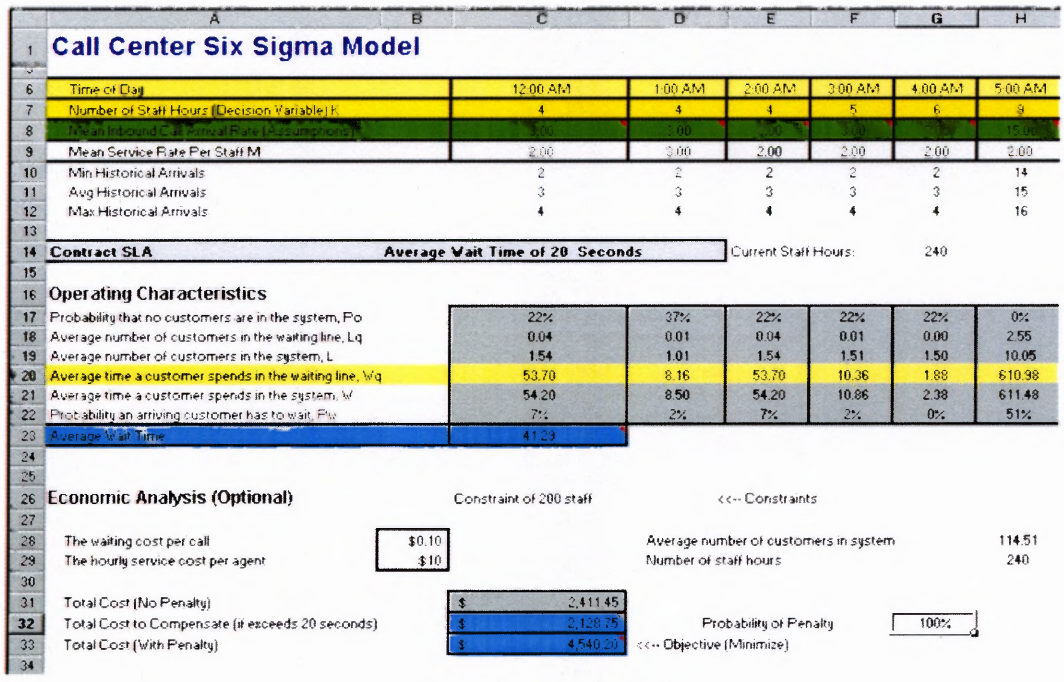
that demonstrates the advantage of a robust versus a deterministic approach. They developed a technique to perform probabilistic analysis, reliability based optimization and robust optimization. The robust design optimization approach not only shifts the performance mean to the target value but also reduces a product's performance variability, achieving the desired sigma level robustness on the key product performance characteristics with respect to the quantified variation. The example presented demonstrates the advantage of using an automated probabilistic design process that enables engineers to identify better designs that meet the performance objectives and are less sensitive to manufacturing variations. For a given sigma quality level, that is six sigma, the mean and standard deviation values can be determined using the design process developed by the authors. Hence by employing CAE, they were able to design a six sigma quality with robust optimization.

Michael Sullivan (2004) brought together the two seemingly independent initiatives that are capturing the attention of corporate managers, namely RFID and Six Sigma for the UPS consulting service. The paper illustrated how these two initiatives can be complementary, especially for process improvements. The intersection of six sigma and RFID offers companies the ability to balance demand with supply of process-centric information. Both of these change programs provide an abundance of data, but the data may neither be sufficiently qualitative nor quantitative. The author throws light on the inconsistencies and insufficiency in the M component of DMAIC methodology. With some limitations, RFID may be the means to acquiring more comprehensive, accurate, and time-sensitive data particularly when the characteristics to be measured include location changes, duration, temperature etc. By combining radio frequency tags, readers,

information networks, RFID can automatically capture and manage data for process automation, asset tracking, and error prevention, identify assurance and a host of other applications. Because RFID offers the potential to collect and store data without human intervention, the technology can provide a relatively low-cost solution when spread over a large number of units. RFID can also provide insights that can identify issues early in their lifecycle and supplement the "M" component of the six sigma process. The author also takes two case examples for better understanding of the analysis. The author concludes that investment in Six Sigma is typically justified or driven by a distinct customer benefit or internal cost savings. It is often internally driven. On the other hand, RFID is being externally driven by customer mandates. Companies should consider both of these process changes as opportunities to enhance their business practices, source internal benefits, improve operations and recognize new cost savings.

Lawrence I. Goldman and Hilary Emmett (2003) developed an easy-to-use Microsoft Excel add-in software, to demonstrate how stochastic simulation and optimization can be used in a six sigma analysis of a technical support call center. In an increasingly competitive market, they felt that concepts like six sigma must be helped by Monte-Carlo simulation to understand the variation inherent in a process or product, and in turn, can be used to identify and test potential improvements. They developed a tutorial called Crystal Ball Professional Edition for this purpose. Monte Carlo Simulation, a tool for understanding the process variations, has a critical role in the Define, Analyze, and Improve phases of six sigma and this underlying connection is the variability inherent in all business processes. Crystal Ball Professional Edition is a general desktop software suite that features spreadsheet-based analysis tools for Monte Carlo Simulation (Crystal

Ball), time-series forecasting and optimization. It also includes interfaces and processes using Visual Basic for Applications (VBA). Firstly a call center spreadsheet model is developed and the phases of six sigma are analyzed. Figure 2.4 shows the model that was developed for the technical call center project to improve performance.



	A	B	C	D	E	F	G	H
1	**Call Center Six Sigma Model**							
6	Time of Day		12:00 AM	1:00 AM	2:00 AM	3:00 AM	4:00 AM	5:00 AM
7	Number of Staff Hours (Decision Variable) K		4	4	4	5	6	9
8	Mean Inbound Call Arrival Rate (Assumption)		3.00	3.00	3.00	3.00	3.00	15.00
9	Mean Service Rate Per Staff M		2.00	3.00	2.00	2.00	2.00	2.00
10	Min Historical Arrivals		2	2	2	2	2	14
11	Avg Historical Arrivals		3	3	3	3	3	15
12	Max Historical Arrivals		4	4	4	4	4	16
13								
14	**Contract SLA**	**Average Wait Time of 20 Seconds**			Current Staff Hours:		240	
15								
16	**Operating Characteristics**							
17	Probability that no customers are in the system, Po		22%	37%	22%	22%	22%	0%
18	Average number of customers in the waiting line, Lq		0.04	0.01	0.04	0.01	0.00	2.55
19	Average number of customers in the system, L		1.54	1.01	1.54	1.51	1.50	10.05
20	Average time a customer spends in the waiting line, Wq		53.70	8.16	53.70	10.36	1.88	610.98
21	Average time a customer spends in the system, W		54.20	8.50	54.20	10.86	2.38	611.48
22	Probability an arriving customer has to wait, Pw		7%	2%	7%	2%	0%	51%
23	Average Wait Time		41.23					
24								
25								
26	**Economic Analysis (Optional)**		Constraint of 200 staff		<<-- Constraints			
27								
28	The waiting cost per call	$0.10			Average number of customers in system			114.51
29	The hourly service cost per agent	$10			Number of staff hours			240
30								
31	Total Cost (No Penalty)		$ 2,411.45					
32	Total Cost to Compensate (if exceeds 20 seconds)		$ 2,128.75		Probability of Penalty		100%	
33	Total Cost (With Penalty)		$ 4,540.20		<<-- Objective (Minimize)			
34								

Figure 2.4 Six Sigma Model for the Technical Call Center.

Thus the authors concluded that simulation and optimization have a crucial role to play in the multiple phases of six sigma analysis project and the six sigma analysts can better quantify the effects of variability and can implement process improvements with greater insight and confidence. Figure 2.5 shows the performance graph for the requirement feasibility.

Martin J. Miller, David M. Ferrin and Jill M. Szymanski (2003) developed simulated six sigma improvement ideas for a hospital emergency department. They utilized simulation to aid the project leaders in advancing to the next level of

sophistication with six sigma. The project produced an ongoing, workable model to simulate potential process improvements in their Emergency Departments (ED).

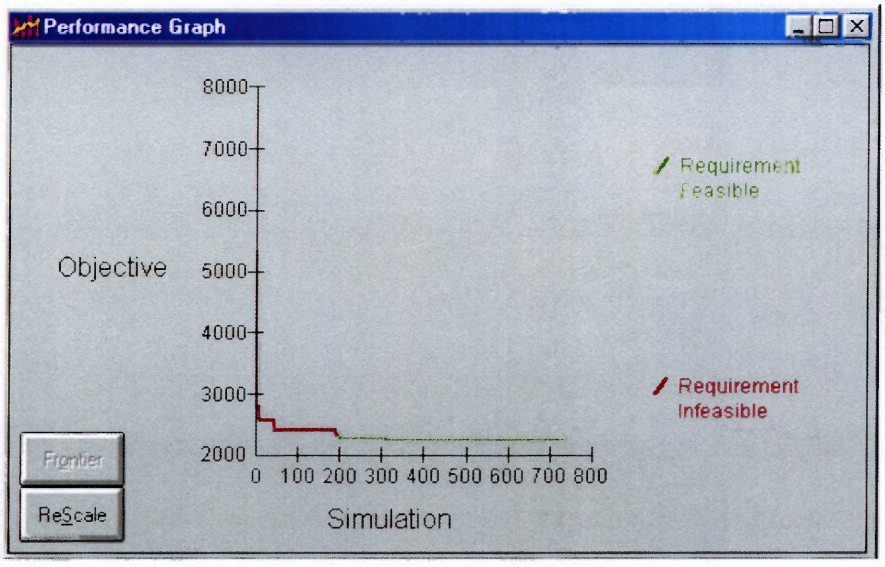


Figure 2.5 Performance Graph.

The project approach focused on the simulation approach which had five major phases, namely developing, programming, testing, experimentation and presentation. For developing the codes, they implemented a simulation software (Extend) with which they developed the hospital layouts and obtained the queues associated with them. Each f the deliverables was instrumental in bringing a complete solution to the client. The process model provided an end-to-end view of the ED and the team members were able to visualize how their piece of the process impacts the overall customer experience. The simulation provided a quantitative comparison of process improvement. The authors concluded that modeling and simulation enabled the client to better understand the patient experience, process performances and staffing inter-relationships for their proposed emergency departments. The team brought out clarity to difficult internal debates. With a powerful tool which can be used repetitively to aid the decision making process, it is

important to regularly verify if the clients expectations are being met. An open and proactive communication is always the best way to ensure the success of the project.

John Maleyeff and Daren E. Krayenvenger presented a comprehensive approach to quality goal setting that is consistent with Motorola's six-sigma metric development. In particular, the process mean shifts are determined and incorporated into the goal setting process. The Methodology includes basic probability theory, statistical control charts, and capability indices. As a result of applying the methods, quality goals are customized based on the number of opportunities for defect, the target end-product quality level, and the mean shift shown to exist for the processes involved in the product's manufacture. The methods described overcome the mistakes implicit in blindly conforming to the standard six sigma goal of 3.4 defects per million. The goal setting process is a step by step analysis in which first the fraction of the defect-free final product is determined and then the Opportunities For Defect (OFD) is found. The average defect rate is also determined which already has an equation with a variable of defect-free units. Then the sigma unit distance from process mean is determined by the NORMSINV function in Excel and then the sigma unit distance from nominal is found by the mean shift analysis. The Process capability and the process capability index are also determined for the analysis and finally the mean shift analysis is done. The sigma level is determined by the Cp value which is obtained by drawing the X bar S chart after mean shift and the value corresponding to it gives the sigma level. Thus the formulation is meaningful because it takes into consideration the opportunity for defect as a count. The authors concluded that the approach that results in a customized goal base is recommended. The paper presented the comprehensive analysis which sets goals for each individual process

based on the product's complexity, the anticipated process mean shift, and the quality goal for the completed product.

R.S. Buell, S.P. Turnipseed, Chevron Texaco (2003) summarized the experience and the results of improving business performance using Lean Six Sigma in an upstream oil and gas operation. The role ISO quality systems can play in supporting Lean and Six sigma is explained and demonstrated with examples. For various operations in the oilfield, Lean Six Sigma was employed and results were obtained. A brief history of the Lean six sigma, and ISO quality systems was also presented together with the tools of the Lean six sigma methodologies. For every oilfield operations, the Lean Six Sigma analysis was done and analyzed. The authors concluded that the Lean Six Sigma adapted from other industries and ISO system concepts can be synergistically combined to improve business results in oilfield operations. Also they concluded that the systematic application of Lean Six Sigma provides a disciplined structure for gaining process knowledge and delivering business results safer, better, and with lower cost.

Anthony R. Benedetto adapted a Manufacturing-based Six Sigma methodology to the service environment of a Radiology film library. A radiology film library performs service activities almost exclusively and the author hypothesized that manufacturing-based six sigma methods might need significant modifications for the project. The most important findings were that Six Sigma dramatically improved service activities, personnel with limited education were to be given coaching, valid quantitative data would be difficult to gather, and change management must be an integral component to achieve and sustain dramatic changes. The author then shifts the focus on the basics of the film library and also on the six sigma and reengineering concepts and then talks about

the difficulties that were encountered like the information systems, the manual data collection, tracking film librarian error etc. The author also developed a model showing the plan of action for the radio film library. Then a solution was developed for the process using the various techniques and methodologies. The author concluded that Six Sigma can be an effective tool for making dramatic improvements in a service activity. The data-related challenges cannot be understated, nor can the "people" challenges. If an institution is willing to make the necessary commitments, Six Sigma works.

CHAPTER 3

ANALYSIS OF DEFECTS AND OPPORTUNITIES

The calculation of opportunities in the defect per million opportunities formulation had a slight mismatch because of the inconsistency in the analysis. As discussed in chapter 1, this weakness was overcome with the point rating scale between 0-1 with 1 being severe and those tending to 0 being inconsequential. This chapter deals with the analysis of the consistency of the scale and the efficiency of the process.

The characterization of the opportunities provides a better understanding of the gravity of the defect for any product or process. This also paves way for a better analysis of the sigma rating rather than going through the calculation using the formulation given in the classical six sigma process. The defect rating for each factors, and how they are efficient in the final analysis and sigma rating becomes the major question of importance. This chapter deals with the analysis of those factors which are the forerunner for the defect analysis and are the basis on which the sigma rating are to be decided.

3.1 Example of a Classical Six Sigma Calculation

The classical Six Sigma identifies opportunities in the product and each opportunity is taken as one opportunity count. But in the rationalized approach, each defect opportunity is divided into five factors and the factors are scaled appropriately. The scaled factors are then summed up to attain the final scale for the opportunity. This concept is illustrated in Figure 3.1 showing the classical approach and Figure 3.2 showing the rationalized approach. The basic idea is to sum all the opportunities at various levels to get a "scaled" opportunity.

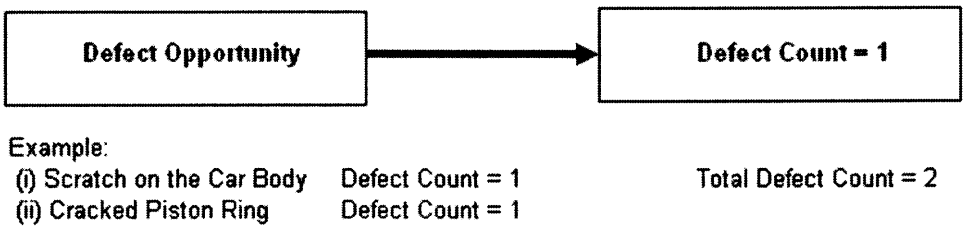


Figure 3.1.1 Classical Six Sigma approach.

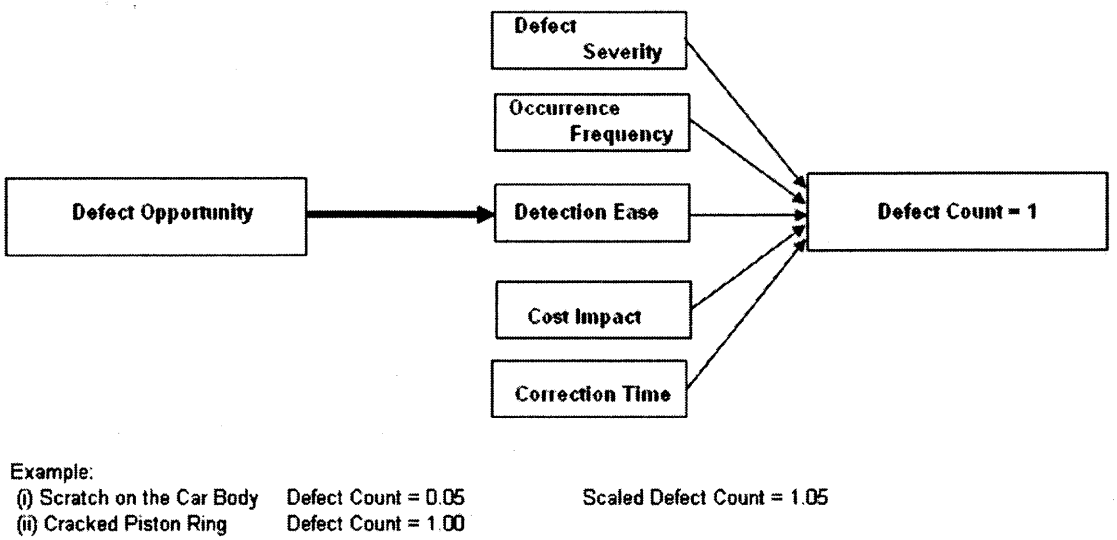


Figure 3.1.2 Rationalized Six Sigma approach.

Let us consider a classical example for the Six Sigma calculation. Suppose 400 defects are identified while producing 8000 controllers and the manufacture of one controller allows for 2215 defect opportunities, then with the classical Six Sigma approach will have the following calculation.

Defect Per Unit (D.P.U) = 400 / 8000 = 0.05

Defect Per Million Opportunity (DPMO) = (0.05 / 2215) * 1000000 = 22.5

The Sigma Level corresponding to 22.5 DPMO is 5.58 and is shown in figure 3.3

Sigma -- DPMOp Conversion Table

Sigma*	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
5.30	72.3	69.5	66.7	64.1	61.5	59.1	56.7	54.4	52.2	50.1
5.40	48.1	46.1	44.3	42.5	40.7	39.1	37.5	35.9	34.5	33.0
5.50	31.7	30.4	29.1	27.9	26.7	25.6	24.5	23.5	22.5	21.6
5.60	20.7	19.8	18.9	18.1	17.4	16.6	15.9	15.2	14.6	13.9
5.70	13.3	12.8	12.2	11.7	11.2	10.7	10.2	9.77	9.34	8.93
5.80	8.54	8.16	7.80	7.46	7.12	6.81	6.50	6.21	5.93	5.67
5.90	5.41	5.17	4.94	4.71	4.50	4.29	4.10	3.91	3.73	3.56
6.00	3.40	3.24	3.09	2.95	2.81	2.68	2.56	2.44	2.32	2.22
6.10	2.11	2.01	1.92	1.83	1.74	1.66	1.58	1.51	1.43	1.37
6.20	1.30	1.24	1.18	1.12	1.07	1.02	0.97	0.92	0.88	0.83

MOTOROLA

*Shifted 1.5 sigma

Figure 3.1.3 Sigma conversion table for the Example.

3.2 Defect, Opportunity and Defects Per Million Opportunities

Defect is defined as the failure to meet the conformance level. A simple example could be the dimension analysis of any product that is being manufactured in any industry. Suppose a particular dimension is 29.5 mm +/- 0.5 mm, then any product falling beyond the tolerance level is considered a defective component. A defective component can have one or more defects. Defects can be anything like errors, omissions, the need for reworking, or scrapping a product as described by the Juran Institute's Six Sigma Breakthrough and Beyond. Hence the defects can mar the productivity of the process.

Defect is an integral part in six sigma methodology because reduction of defects to 3.4 per million opportunities is the goal of Six Sigma.

Suppose there are "n" units for production and "p" are the defects which are defined characteristically, then opportunity is defined as the number of possible ways the product can fail for each characterization. Typical example, as described by Forrest.W.Breyfogle III, is the soldering of components onto circuit boards. For this case, the total number of opportunities for failure could be the number of components plus the number of solder joints. Sometimes insertion is also included as an opportunity for failure. Hence, whatever be the case, the opportunity for the process could be the number of components or units that are produced plus the possibility of failures that the product can undergo during various stages of the process completion.

Defect per unit is merely defined as the simple ratio of the number of defects to the total population (total Number of units) for a process. Defect Per Million Opportunities or DPMO is a common measurement index in six sigma which takes into account the entire opportunities and the defects involved and thereby has a final level called the sigma level which explains the nature of the process whether it is six sigma or not. DPMO is the average number of defects per unit observed during an average production run divided by the number of opportunities to make a defect on the product under study during that run normalized to one million. As explained previously, the DPMO is the area of interest and so is the number of opportunities in the calculation.

Given the above, the question arises of how to unite them into a meaningful formulation. The characterizations for the formulation are divided into five factors and

are the basis for the formulation. Before going deep into the characterization, the need for characterization has to be discussed.

3.3 Defects Per Million Opportunities

Defects per million opportunities (DPMO) is the average number of defects per unit observed during an average production run divided by the number of opportunities to make a defect on the product under study during that run normalized to one million

$$\textbf{Defect Per Million Opportunities} = \frac{\textbf{Defect Per Unit} * 1{,}000{,}000}{\textbf{Number Of Opportunities}}$$

Main Focus

The main focus as said earlier was on the Number Of Opportunities in the DPMO calculation. The six sigma scale is based on the DPMO and hence it becomes very important to make sure that the formulation becomes clear. Let us analyze an example and continue the discussion as to why the formulation is not clear.

Suppose there is a process which involves the assembling of computer parts. Basically there can be "n" number of defect and each defect is an opportunity. So the number of defect possibilities becomes the number of opportunities. To achieve Six Sigma, the DPMO should decrease. For the DPMO to decrease, the number of opportunities should increase. Many companies have a fool proof method of increasing the number of opportunities and thereby calculate the DPMO and say that they are Six Sigma. Apparently that is not the case. Say if the company assembling the computer parts needs to achieve Six Sigma then they must obtain less than 3.4 defects per million opportunities. In doing so they can increase the number of opportunities in order to get

the magic number of 3.4 defects per million opportunities. But how are the opportunities accounted for? How do they decide it? Hence this formulation sounds unclear though it had been helpful in achieving Six Sigma.

In order to avoid this discrepancy, it is better to throw light on the Number Of Opportunities which forms the basis for Sigma scale in the formulation. In doing the formulation, it is first necessary to characterize the opportunity into various factors. Then each factor has to be given a rating and all are combined at the end to a final scale ranging from 0 to 1 with 1 being severe and those tending to 0 being inconsequential. How do we get to that 0-1 rating?

3.4 Characterization of the Defects

Basically each defect arises because of some faulty mechanisms and errors. Hence it becomes evident that the defect should be characterized in types so that they can be grouped. The DPMO can then be grouped in a pareto chart based on the calculations and the defects can be compared. The best feature of characterizing them is to find out where the defect is centered. Let us assume that there are 4 types of defects A, B, C, D. The DPMO is calculated for each of the defect type by the general formulation and then the pareto chart is prepared based on this characterization of defect types as shown in Figure 3.4. Here the defect type D looks more disturbing with DPMO figure of around 16000. Hence the type D defect is located and then the necessary correction is done to achieve sigma level for the defect.

Based on the characterization, it becomes easy to analyze what actually the defect is and what can be done to reduce the complexity of the defect. This is an important step

in the defect analysis for the fact that the sigma rating becomes meaningful if they can be interpreted as a defect correction method.

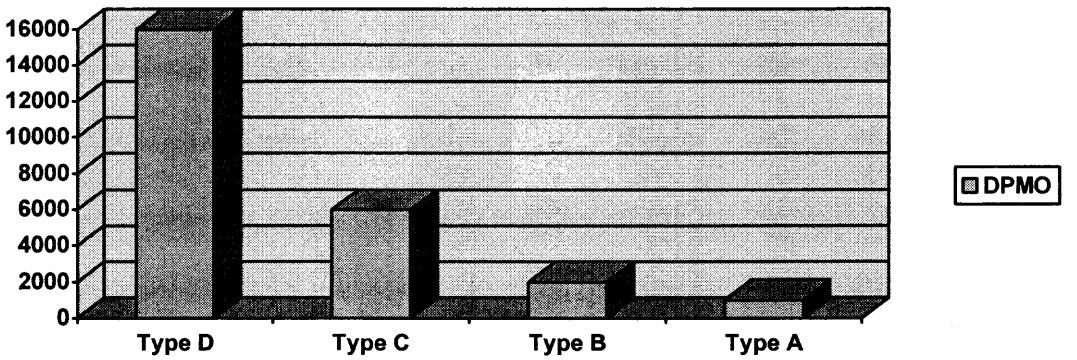


Figure 3.4 Chart depicting the Concentration of the Defects and corresponding DPMO.

3.5 Characterization of Factors for Opportunity Analysis

Based on the above discussion, the characterization is done by considering the defect opportunities to be factors and analysis is done. In this factor analysis, three factors are taken from the Failure Mode and Effects Analysis (FMEA) and two other interdependent factors are scaled appropriately to achieve the final formula scale.

3.5.1 Defect Severity

Defect Severity is the extent to which the design of the product can go wrong. It is the impact of failure on the defect and how far it will be hazardous. It is also the measure of consequences of the failure that has happened. In short, Defect Severity is a rating corresponding to the seriousness of an effect of a potential failure mode.

Example:

Considering the example of the automotive airbag, we have various potential modes of failure. The most severe case is when the airbag doesn't open when group or crash of the automobile occurs and cause the person may be injured or die. So the severity is more

pronounced in the failure mode analysis and it can be understood by a point scale ranging from 1-10 which shows the severity rating for any analysis. The evaluation criteria are given in the Table 3.5.1.

3.5.2 Occurrence Frequency

Occurrence Frequency is the rating corresponding to the rate at which a first level cause and its resultant failure mode will occur over the design life of the system, over the design life of the product, or before any additional process controls are applied. Occurrence is the likelihood that the failure occurs. Occurrence frequency analyzes the causes that are possible for the failure to happen.

Example:

Considering the example of the automotive airbag, we have various causes that can produce the failure. For instance, if the sensor in the automobile does not function then the entire system will collapse. The automobile without the functionality of the sensor for the airbag will cause extensive damage and thereby prove to be hazardous. Hence this factor is of more interest in the failure analysis and this also has a point scale from 1 to 10 which shows the occurrence rating for any analysis. The evaluation criteria are given in the Table 3.5.2.

3.5.3 Detection Ease

Detection ease is a rating corresponding to the likelihood that the detection methods or current controls will detect the potential failure mode before the product is released for production, or before it leaves the production facility. Detection is also the likelihood of missing a defect.

Table 3.5.1 Defect Severity Evaluation Rating.

Defect Severity Evaluation Criteria		
Effect	**Criteria: Severity of Effect**	**Rank**
Hazardous - without warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning	10
Hazardous - with warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning	9
Very High	Vehicle/item inoperable, with loss of primary function.	8
High	Vehicle/item operable, but at reduced level of performance. Customer dissatisfied.	7
Moderate	Vehicle/item operable, but Comfort/ Convenience item(s) inoperable. Customer experiences discomfort.	6
Low	Vehicle/item operable, but Comfort/ Convenience item(s) operable at reduced level of performance. Customer experiences some dissatisfaction.	5
Very Low	Fit & finish/Squeak & Rattle item does not conform. Defect noticed by average customers.	4
Minor	Fit & finish/Squeak & Rattle item does not conform. Defect noticed by most customers.	3
Very Minor	Fit & finish/Squeak & Rattle item does not conform. Defect noticed by discriminating customers.	2
None	No effect.	1*

***Note:** *Zero (0) rankings for Severity, Occurrence or Detection are not allowed*

Example:

Considering the example of the automotive airbag, if the system malfunctioning is not reported to the quality inspection teams then the detection possibility will become haphazard. Hence the flow of information from one area to the other must be planned so that the other members in the chain get to know the possible causes and effects of failure

so as to make detection better. Detection also has a point scale from 1 to 10 which shows the detection analysis. The evaluation criteria are given in Table 3.5.3.

Table 3.5.2 Occurrence Frequency Evaluation Rating.

Suggested Occurrence Evaluation Criteria			
Rank	**CPK**	**Failure Rates**	**Probability of Failure**
10	≥ 0.33	> 1 in 2	**Very High:** Failure almost inevitable
9	≥ 0.33	1 in 3	
8	≥ 0.51	1 in 8	**High:** Repeated failures
7	≥ 0.67	1 in 20	
6	≥ 0.83	1 in 80	**Moderate:** Occasional failures
5	≥ 1.00	1 in 400	
4	≥ 1.17	1 in 2000	
3	≥ 1.33	1 in 15 000	**Low:** Relatively few failures
2	≥ 1.50	1 in 150 000	
1*	≥ 1.67	≤ 1 in 1 500 000	**Remote:** Failure is unlikely

***Note:** *Zero (0) rankings for Severity, Occurrence or Detection are not allowed*

3.5.4 Correction Time Factor

Correction Time factor is the rating corresponding with the time it takes to fix a defect. How fast can the defect be fixed is the major concern in the defect analysis.

Example:

Suppose the defect is such that it will reduce the quality of the product. The first thing that has to be analyzed while considering this factor is how long it will take to fix the defect.

Table 3.5.3 Detection Ease Evaluation Criteria.

Suggested Detection Ease Evaluation Criteria		
Detection	**Criteria**	**Rank**
Absolute Uncertainty	Design Control will not and/or cannot detect a potential cause/ mechanism and subsequent failure mode; or there is no Design Control.	10
Very Remote	Very Remote chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	9
Remote	Remote chance the Design Control will detect a potential cause/ mechanism and subsequent failure mode.	8
Very Low	Very Low chance the Design Control will detect a potential cause/ mechanism and subsequent failure mode.	7
Low	Low chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	6
Moderate	Moderate chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	5
Moderately High	Moderately High chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	4
High	High chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	3
Very High	Very High chance the Design Control will detect a potential cause/mechanism and subsequent failure mode.	2
Almost Certain	Design Controls will almost certainly detect a potential cause/mechanism and subsequent failure mode.	1*

***Note:** *Zero (0) rankings for Severity, Occurrence or Detection are not allowed*

If the time required to fix the defect is 10 minutes when the operating time for the product is, say 15 minutes (say) then there is no point in performing the operation of rework because in that time 2/3rd of another product can be completed. Hence the time factor rating is also a critical factor.

The rating for the time factor must have a defined formulation. The scale must be chosen so that it makes sense. Let us formulate a Time ratio for the process so that we can scale it according to the range within which the ratio falls.

$$\text{Time Ratio} = \frac{\text{Time required correcting a defect}}{\text{Total Time to manufacture the product}} * 100$$

The following calculations illustrate how values for this factor were determined.

Trial 1:

Time required to correct the defect = 10 min

Total Time to manufacture the product = 15 min

Time Ratio = (10/15)*100 = 66.66.

Trial 2:

Time required to correct the defect = 0.5 min

Total Time to manufacture the product = 15 min

Time Ratio = (0.5/15)*100 = 3.33

Suppose that the time required to correct a defect is very near the time that is needed to manufacture the product. Then, the time ratio is very high and hence the rating for it will also be fixed at 10. If the time to correct the defect is much smaller than the time it takes the make the product, the time ratio will be small and the scaling for it will be 1. According to the trials that were made, let us make a tabulation which shows the range of the Time ratio and their corresponding rating. The time ratio and the ratings are shown in Table 3.5.4.

Table 3.5.4 Time Ratio and Corresponding Rating.

Time Ratio	Six Sigma Rank for Time
0.05	1
0.2	2
0.5	3
0.75	4
1	5
2	6
4	7
5	8
10	9
25	10

Based on the above tabulation let us form an explanation for the rating from 1-10. The values for the time factor are shown in Table 3.5.5.

3.5.5 Cost Impact Factor

Cost factor is the rating corresponding to the cost of fixing the defect.

Example:

Suppose the defect is such that it will reduce the quality of the product. The first thing that has to be analyzed while considering this factor is how much it will cost to fix it. If the cost required to fix the defect is $10 when the production cost for the product is $20, then there is no point in performing the operation of rework because the rework cost is ½ of the cost to make another product. Hence, the cost factor rating is also a critical factor.

Table 3.5.5 Correction Time Evaluation Rating.

Suggested Correction Time Factor Evaluation Criteria		
Time	**Criteria**	**Rank**
Absolute Waste	The time involved to correct the defect is considerably high and hence can be discarded	10
Very High	The time involved is very high and hence the product rework is not likely to fetch better results	9
High	The time involved is high and hence the defect analysis and rework is not worth doing	8
Moderately High	The time involved is moderately high and hence the defect analysis and rework takes more time	7
Moderate	Reworking time is moderate and hence can be used for smaller batches	6
Low	Time involved is low and hence can be employed for smaller batches and some moderately large batches	5
Very Low	Time involved is very low and hence can be used for large and small batch.	4
Better	Time is better and hence can be used for smaller and larger batches and for defects which can be certain of correction with lesser defects	3
Much Better	Time involved is much better and hence can be used for almost all products	2
Best	Time involved is best and hence used for all defect rework and detection	1*

***Note:** *Zero (0) rankings for Time Factors are not allowed*

The rating for the cost factor must have a defined formulation. The scale must be chosen so that it makes sense. Let us formulate a cost ratio for the process so that we can scale it according to the range within which the ratio falls.

$$\text{Cost Ratio} = \frac{\text{Cost required correcting a defect}}{\text{Total Cost to manufacture the product}} * 100$$

The following calculations illustrate how values for this factor were determined.

Trial 1:

Cost required to correct the defect = $10

Total Cost to manufacture the product = $15

Cost Ratio = (10/15)*100 = 66.66

Trial 2:

Cost required to correct the defect = $0.50

Total Cost to manufacture the product = $15

Cost Ratio = (0.5/15)*100 = 3.33

Suppose that the cost required correcting a defect is very near the cost that is needed to manufacture it. Then, the cost ratio is very high and hence the rating for it will be fixed at 10. If the cost to correct the defect is very small then the cost ratio will also be small and hence the scaling for it will be 1. According to the trials that were made let us make a tabulation which shows the range of the Cost ratios and their corresponding rating. The values of the cost ratio are shown in Table 3.5.6.

Here for the sake of Excel convenience in the later part, the ratios have been represented by one number. Basically 0.05 means that the range is 0-0.05 and so on.

Table 3.5.6 Cost Ratio and Corresponding Rating.

Cost Ratio	Six Sigma Rank for Cost
0.05	1
0.2	2
0.5	3
0.75	4
1	5
2	6
4	7
5	8
10	9
25	10

Based on the above tabulation let us form an explanation for the rating from 1-10. The values for the cost factor are shown in Table 3.5.7.

The three factors from FMEA have been scaled from the original data from Six Sigma while the scaling for the two other factors namely the cost factor and the time factor have been scaled appropriately. The scaling is also checked by a trial and error (permutation) method and on the basis of this, they have been scaled from 1 to 10. Now all these five factors have to be grouped together and a final formula scale ranging between 0 and 1 is to be achieved. Using the final scale, the formulation for the DPMO is modified and the final sigma level is obtained.

Table 3.5.7 Cost Impact Evaluation Rating.

Suggested Cost Impact Factor Evaluation Criteria		
Cost	**Criteria**	**Rank**
Absolute Waste	The cost involved to correct the defect is considerably high and hence can be discarded	10
Very High	The cost involved is very high and hence the product rework is not likely to fetch better results	9
High	The cost involved is high and hence the defect analysis and rework is not worth doing	8
Moderately High	The cost involved is moderately high and hence the defect analysis and rework takes more cost	7
Moderate	Reworking cost is moderate and hence can be used for smaller batches	6
Low	Cost involved is low and hence can be employed for smaller batches and some moderately large batches	5
Very Low	Cost involved is very low and hence can be used for large and small batch.	4
Better	Cost is better and hence can be used for smaller and larger batches and for defects which can be certain of correction with lesser defects	3
Much Better	Cost involved is much better and hence can be used for almost all products	2
Best	Cost involved is best and hence used for all defect rework and detection	1*
***Note:** Zero (0) rankings for Cost and Time Factors are not allowed*		

CHAPTER 4

METHODOLOGY FOR THE DEFECT OPPORTUNITIES ANALYSIS

The Defect Per Million Opportunities (DPMO) calculation has been restructured by introducing new factors which account for the number of defect opportunities while manufacturing of the product. These factors have been scaled appropriately based on their importance to the contribution of the defect. Now based on this scale, the methodology has been adopted using a spreadsheet so as to convert them into a 0-1 scale. There are various trials that have been employed for the methodology and each one is different from the other in order to sort out the best result. Though all the methods are equally scaled, the best can be chosen and used depending on the nature of the defect. The trials are useful because they not only employ and follow the nature of FMEA analysis but also take care of all the possibilities that can be accounted for while considering a defect. Though some of the factors have been adopted from FMEA, they have been used here for the opportunities analysis for any product that is being manufactured so that calculation becomes meaningful. By using this scale of 0-1, the product which turns out to be defective can be analyzed for all possible extremities and finally given a rating which describes whether the final product is worth reworking or rejecting. Based on the final scale, the DPMO and sigma level are also determined.

Six Sigma is about the quality performance of the process and by defining it, the motto of a process is to attain less than 3.4 defects per million opportunities. Keeping this definition in mind, whenever a product is manufactured, it is analyzed keeping all the factors in mind to find an opportunity for defect. Once a rating has been given for all the

factors, the final formula scale is in the 0 to 1 range and those falling closer to 1 are rejected while those falling closer to 0 are reworked if necessary or accepted as a defect free product.

4.1 Formulation of the Defect Opportunities

Defect opportunities can occur anytime for any product in a process. There is a possibility that some of the defects might go unnoticed. They have to be taken into account for finding the sigma level of the process. There are three trials that have been performed and the flow diagrams for the trials are shown in figures.

The first is based on characterizing into factors. A 0-1 scale is made by assigning 20% for each factor (as 80% of process defects arise from 20% of the process issues), with 1 being severe and those tending to 0 being inconsequential. This is taken as trial 1 and the flow diagram depicting the trial is shown in Figure 4.1

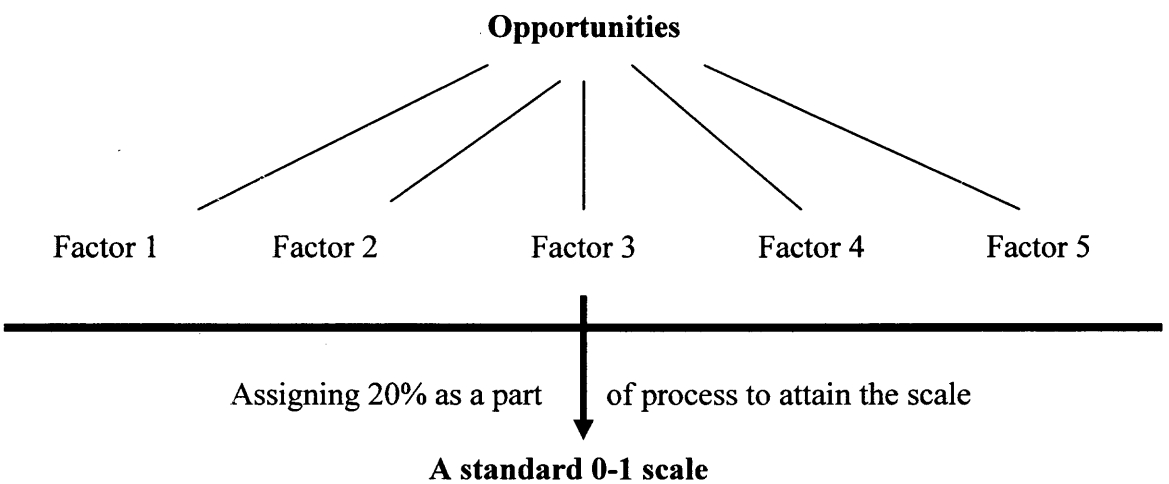


Figure 4.1.1 Flow Diagram for Trial 1.

The Factors are now grouped together in another form. The FMEA analysis is used here. The initial three factors as shown in Figure 4.2 are multiplied to get the Risk Priority Number and their corresponding scale is multiplied with the Cost /time factor and finally divided by 100 to get a scale of 0-1 with 1 being severe and 0 being better.

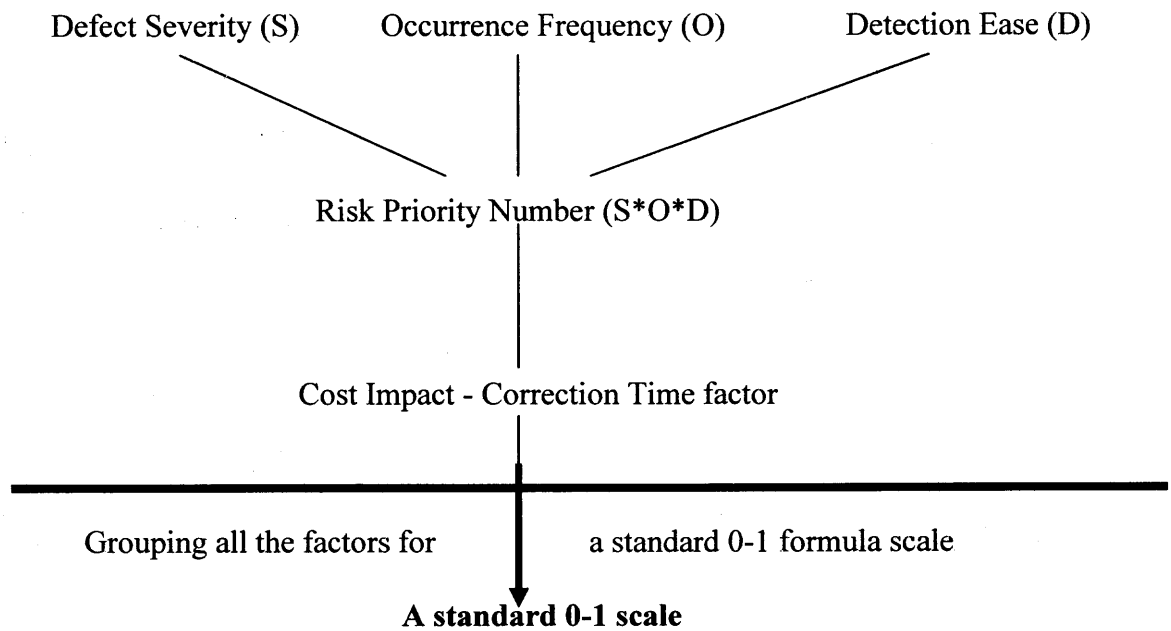


Figure 4.1.2 Flow Diagram for Trial 2.

The Factors are now grouped together in another form. The initial three factors as shown in the Figure 4.3 are multiplied to get the Priority Number and their corresponding scale is multiplied with the Cost impact – correction time factor and finally divided by 100 to get a scale of 0-1 with 1 being severe and 0 being better.

To make the method more flexible, Excel Macros are to be used which will make the spreadsheet usage still flexible and also the sigma rating can be obtained with relative ease. Before going into the macros part of Excel, the methodology is first employed with the common spreadsheet method wherein there are many columns for each factors before they are converted into a final formula scale ranging between 0 and 1.

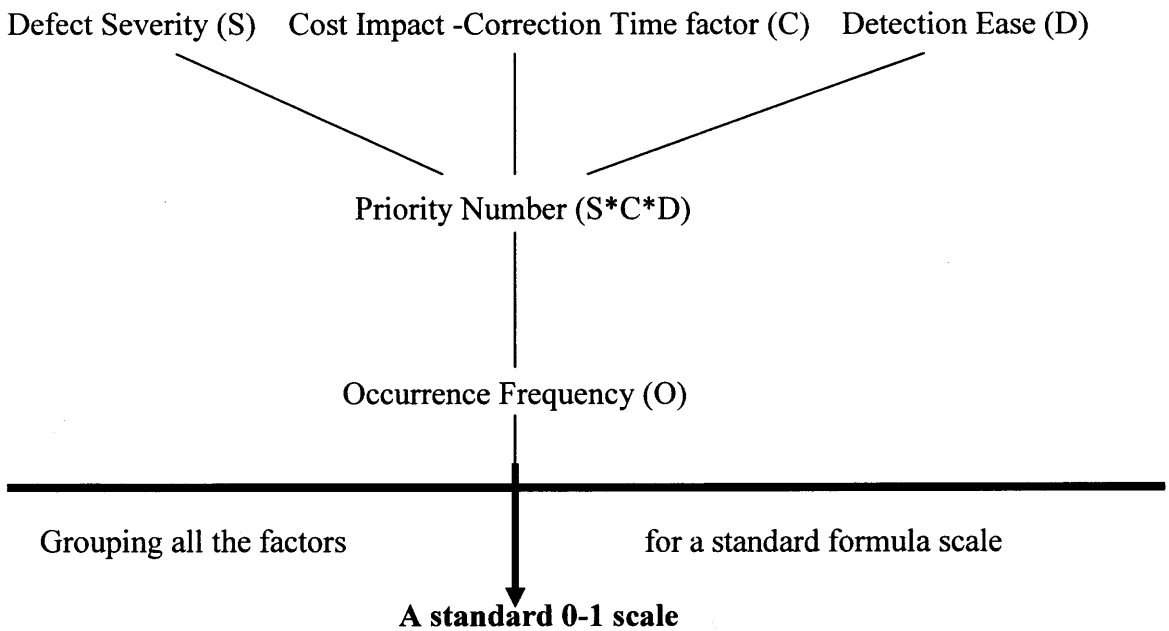


Figure 4.1.3 Flow Diagram for Trial 3.

The trials for the sigma ratings are explained and the final outcome 0-1 is obtained in each case and there are graphs for some trials which show the behavior of the factors when used separately. Thus the trials are made flexible with the analysis of all the factors and the option is left to the user to determine which one is best for the process. The final sigma level discussions are done using the macros in Excel.

4.2 Methodology for the Sigma Ratings

There are basically three trials that are involved in the methodology. The first trial is the normal trial where all the factors are grouped together to obtain the scale. The second and third trials involve the risk priority number, again a concept of FMEA to get the final formula scale. Now the trials and the spreadsheet screenshots are shown below along with the graphs for the second and third trial.

4.2.1 Trial 1

Given the scale of the five factors the sigma scale can be found. For this, we have a Six Sigma methodology namely the Pareto Analysis or the 80/20 rule. According to this, "80% of process defects arise from 20% of the process issues". Going by this analysis, the process issues here in discussion are the five factors. So let us assign 20% for all the five factors and then multiply the ratings with the 20% for all the factors. Finally add all the ratings with the 20% and divide it with 10. We get a scale between 0-1 with 1 being sever and those tending to 0 being inconsequential. Figure 4.2.1 shows the various values that have been used as input and those linked using lookup.

The Excel spreadsheet for the sigma rating trial 1 is shown in Figure 4.2.2 wherein the values for the occurrence and cost is linked using the lookup function in Excel and thereby when the ratio is typed it directly gives the ranking. When a value for all the five factors has been entered, the final value is shown up automatically.

Cost Ratio and ranking:

Cost Ratio	Cost Rank
0.05	1
0.2	2
0.5	3
0.75	4
1	5
2	6
4	7
5	8
10	9
25	10

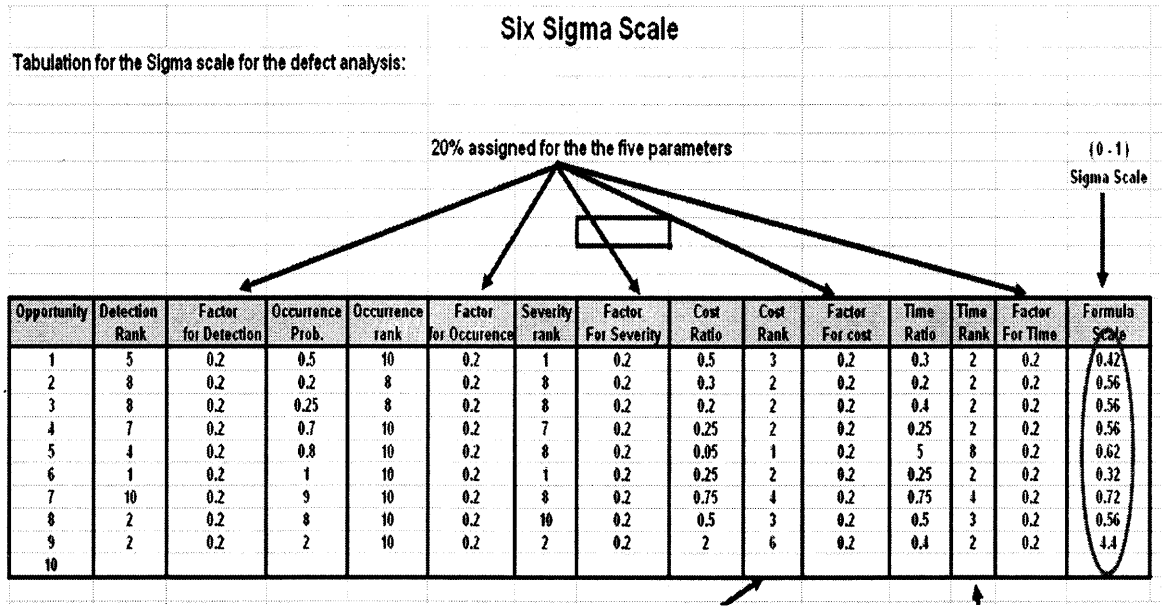
Probability of Occurrence and ranking:

Occurrence Probability	Occurrence Rank
6.66667E-07	1
6.66667E-06	2
6.66667E-05	3
0.0005	4
0.0025	5
0.0125	6
0.05	7
0.125	8
0.333333333	9
0.5	10

Time Ratio and ranking:

Time Ratio	Time Rank
0.05	1
0.2	2
0.5	3
0.75	4
1	5
2	6
4	7
5	8
10	9
25	10

Figure 4.2.1 Screenshot of the Values of Factors used as input for Trial 1.



Opportunity	Detection Rank	Factor for Detection	Occurrence Prob.	Occurrence rank	Factor for Occurence	Severity rank	Factor For Severity	Cost Ratio	Cost Rank	Factor For cost	Time Ratio	Time Rank	Factor For Time	Formula Scale
1	5	0.2	0.5	10	0.2	1	0.2	0.5	3	0.2	0.3	2	0.2	0.42
2	8	0.2	0.2	8	0.2	8	0.2	0.3	2	0.2	0.2	2	0.2	0.56
3	8	0.2	0.25	8	0.2	8	0.2	0.2	2	0.2	0.4	2	0.2	0.56
4	7	0.2	0.7	10	0.2	7	0.2	0.25	2	0.2	0.25	2	0.2	0.56
5	4	0.2	0.8	10	0.2	8	0.2	0.05	1	0.2	5	8	0.2	0.62
6	1	0.2	1	10	0.2	1	0.2	0.25	2	0.2	0.25	2	0.2	0.32
7	10	0.2	9	10	0.2	8	0.2	0.75	4	0.2	0.75	4	0.2	0.72
8	2	0.2	8	10	0.2	10	0.2	0.5	3	0.2	0.5	3	0.2	0.56
9	2	0.2	2	10	0.2	2	0.2	2	6	0.2	0.4	2	0.2	44
10														

Figure 4.2.2 Screenshot of Trial 1 with the final formula scale.

4.2.2 Trial 2

Now let us extend the rating determination in a different way, by finding the Risk Priority Number (R.P.N), which is obtained by multiplying the Defect Severity, Occurrence Frequency and Detection Ease. This is obtained by the Failure Mode and Effects Analysis (FMEA), a sub-methodology of Six Sigma. In this method instead of taking the cost and time as two separate entities, they are grouped into one single factor. The correction time and cost impact factors are grouped into one separate entity and they are considered interdependent. After finding the R.P.N, find the factor for the R.P.N number and multiply that number with the Cost/time factor (single entity and so a single number) and then the final value is divided by 100 to get a rating between 0 and 1. The values that are inputs for this scale is shown in Figure 4.2.3.

The Excel spreadsheet for the sigma rating trial 2 is shown in Figure 4.2.4 wherein the values for the occurrence frequency and cost impact etc. are linked using the lookup function in Excel and thereby when the ratio is typed, it directly gives the ranking.

Similarly for the R.P.N, the corresponding six sigma factor can be determined from the product of the three factors. The six sigma factor for the R.P.N numbers are shown in Figure 4.2.3. From there, the final value is formulated in Excel which gives a rating between 0 and 1.

Values input for the Six Sigma Scale

Occurrence	Occurrence rank
6.66667E-07	1
6.66667E-06	2
6.66667E-05	3
0.0005	4
0.0025	5
0.0125	6
0.05	7
0.125	8
0.333333333	9
0.5	10

Cost Factor	Factor for cost
0.05	1
0.2	2
0.5	3
0.75	4
1	5
2	6
4	7
5	8
10	9
25	10

R.P.N	Six Sigma Factor
0	0
25	0.5
100	1
200	2
300	3
400	4
500	5
600	6
700	7
800	10

Figure 4.2.3 Screenshot of the Values of Factors used as input for Trial 2.

No.	IDENT NO	Detection Rank	Occurence	Occurence rank	Severity rank	R.P.N (S * O *D)
1		9	0.5	10	10	900
2		2	0.25	8	9	144
3		3	0.7	10	8	240
4		4	0.8	10	7	280
5		5	0.05	7	6	210
6		6	0.005	5	5	150
7		7	0.0025	5	4	140
8		8	0.000005	1	3	24
9		9	0.35	9	2	162
10		10	0.000001	1	1	10

(0 -1) Scale

Six Sigma Weightage:

No	IDENT NO	R.P.N	Six Sigma Factor (R.P.N)	Cost/Time Factor	Six Sigma Factor for Time/Cost	F * H/100	Normal weightage for defect	Six Sigma Weightage for defect
1		900	10	13	9	0.9	1	0.9
2		144	1	1	5	0.05	1	0.05
3		240	2	50	10	0.2	1	0.2
4		280	2	15	9	0.18	1	0.18
5		210	2	30	10	0.2	1	0.2
6		150	1	1	5	0.05	1	0.05
7		140	1	0.4	2	0.02	1	0.02
8		24	0	2	6	0	1	0
9		162	1	10	9	0.09	1	0.09
10		10	0	5	8	0	1	0

Figure 4.2.4 Screenshot of Trial 2 with the final formula scale.

A graph is drawn with the Defect number on the x-axis and the final 0-1 sigma rating along the y-axis. Here the Normal maximum scale of 1 is being compared with the final sigma scale using the trial. This is done to understand how far the process needs attention and the depth of defect on the product. The graph is shown in figure 4.2.5.

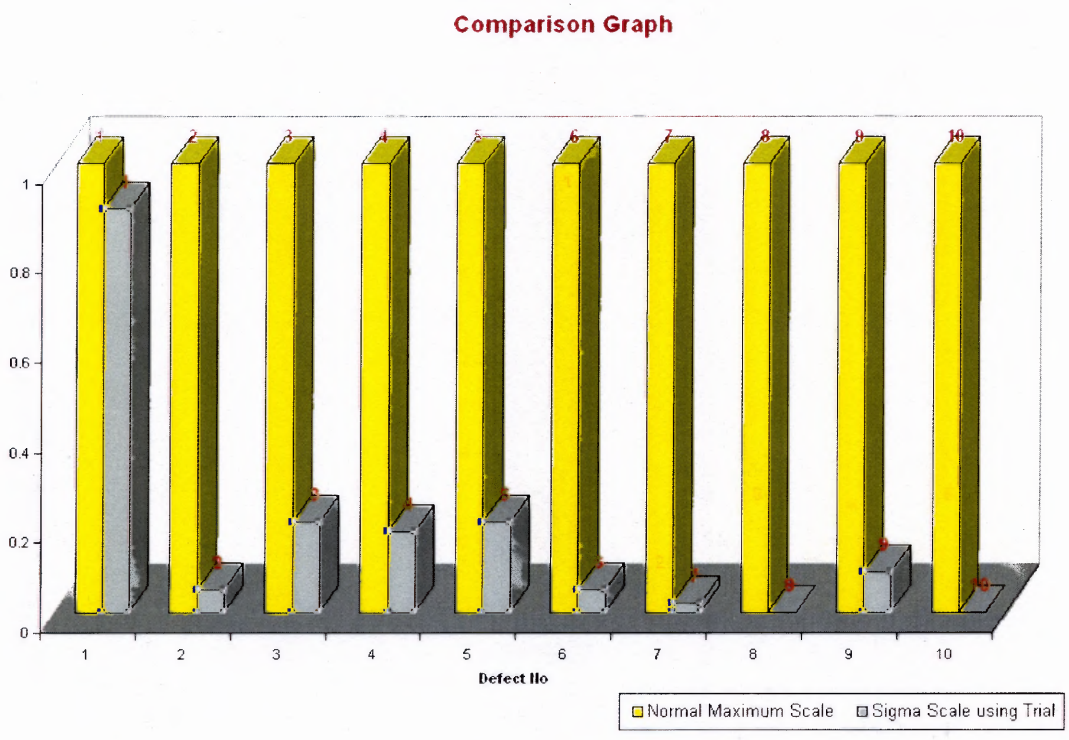


Figure 4.2.5 Graph for Trial 2 showing sigma scales.

4.2.3 Trial 3

Now let us extend the rating determination in a different way using the Priority Number (P.N) determined by multiplying the Severity, Cost impact – correction time factor and Detection. In this method again instead of taking the cost and time as two separate entities, let us group them into one single factor. The time and cost are directly proportional in this case and hence we can group them into one separate entity and they are interdependent. After finding the P.N, find the factor for the P.N number and multiply that number with the Occurrence rating. Then the final value is divided by 100 to get a

rating between 0 and 1. The screenshot of the spreadsheet for trial 3 is shown in figure 4.2.7. The values used for input is shown in figure 4.2.6.

Occurrence	Occurrence Rank
6.66667E-07	1
6.66667E-06	2
6.66667E-05	3
0.0005	4
0.0025	5
0.0125	6
0.05	7
0.125	8
0.333333333	9
0.5	10

Cost Factor	Factor for cost
0.05	1
0.2	2
0.5	3
0.75	4
1	5
2	6
4	7
5	8
10	9
25	10

P.N	Factor for PN
0	0
25	0.5
100	1
200	2
300	3
400	4
500	5
600	6
700	7
800	10

Figure 4.2.6 Screenshot of the Values of Factors used as input for Trial 3.

No.	IDENT NO	Detection Rank	Cost Factor	Six Sigma Factor for COST	Severity rank	(S * C *D)
1		9	13	9	10	810
2		2	1	5	9	90
3		3	50	10	8	240
4		4	15	9	7	252
5		5	30	10	6	300
6		6	1	5	5	150
7		7	0.4	2	4	56
8		8	2	6	3	144
9		9	10	9	2	162
10		10	5	8	1	80

Six Sigma Weightage:

(0 - 1) Scale

No	IDENT NO	S*C*D	Six Sigma Factor (S.C.D)	Occurence	Occurrence rank	F * H/100	Normal weightage for defect	Six Sigma Weightage for defect
1		810	10	0.5	10	1	1	1
2		90	0.5	0.25	8	0.04	1	0.04
3		240	2	0.7	10	0.2	1	0.2
4		252	2	0.8	10	0.2	1	0.2
5		300	3	0.05	7	0.21	1	0.21
6		150	1	0.005	5	0.05	1	0.05
7		56	0.5	0.0025	5	0.025	1	0.025
8		144	1	0.000005	1	0.01	1	0.01
9		162	1	0.35	9	0.09	1	0.09
10		80	0.5	0.000001	1	0.005	1	0.005
							10	1.83

Figure 4.2.7 Screenshot of Trial 3 with the final formula scale.

The Excel spreadsheet for the sigma rating trial 3 is shown above wherein the values for the occurrence and cost etc. are linked using the lookup function in Excel and thereby when the ratio is typed, it directly gives the ranking. Similarly for the P.N when the number is found, the corresponding sigma factor is also known. From there the final

value is formulated in Excel which gives a rating between 0 and 1. In this case, the P.N is similar to the R.P.N rating. Basically the range of risk involved with both numbers is the same except that in the previous trial it was named risk priority number and here as priority number. Though Trials 2 and 3 are similar, they have a major difference in the graph comparison with the normal maximum scale. The graph for the Trial 3 is shown in Figure 4.2.8.

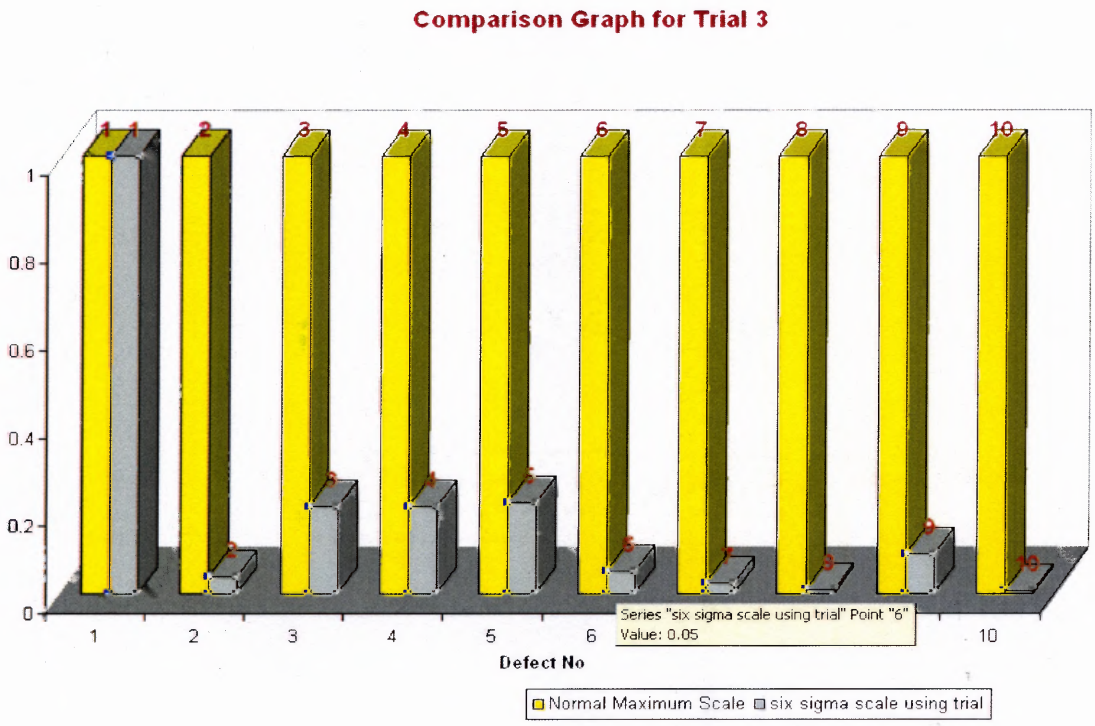


Figure 4.2.8 Graph for Trial 3 showing six sigma scales.

The first wall in figure 4.2.8 shows that the sigma scale reaches 1and is equivalent with the normal maximum scale. The graphs for Trials 2 and 3 were made to show the intensity of the product defects. A close look at the graph reveals that, for the same set of values for all the factors, the final six sigma scale changes in both Trials. The first wall in Trial 3 reaches the maximum scale which shows that all the defect opportunities are considered. Hence Trial 3 is better than Trial 2.

CHAPTER 5

NEW FORMULATION FOR THE DEFECTS PER MILLION OPPORTUNITIES

The formulation for the DPMO as discussed in the previous chapters was modified to account properly for the number of opportunities and make the analysis more meaningful. The characterizations were scaled according to the intensity of the defect and a formula scale was developed based on the scaling. The scaling had taken into account the Pareto analysis according to which 80% of the process defects were caused by 20% of the factors which contribute to the defects. Hence those factors were categorized and accordingly scaled and finally a formula scale was developed.

Now, after forming the formula scale, the next question is to find the justification for the formula scale. The formula scale has to be implemented in the formulation for DPMO to bring meaning to the analysis. Here we introduce two decision variables α and β where $\alpha + \beta = 1$. These variables are basically employed to bring meaning to the analysis when modifying the denominator in the DPMO calculation. Now with these two decision variables, we develop the formulation for the defects per million opportunities.

5.1 Transformation into Rationalized Formulation

Existing formulation:

$$\text{Defects Per Million Opportunities (DPMO)} = \frac{\text{Defect Per Unit (DPU)}}{\text{Number Of Opportunities}} * 1000000$$

Improved Formulation:

$$\text{Defects Per Million Opportunities (DPMO)} = \frac{\text{Defect Per Unit (DPU)}}{\alpha * D1 + \beta * D2} * 1000000$$

Transformed denominator

Where,

α = Decision Variable, and equal to formula scale.

β = Decision Variable, and equal to the formula scale subtracted from 1.

D1 = Total Number of Opportunities for the product.

D2 = Total Number of Scaled Opportunities for the product.

5.2 Justification of the Decision Variables α and β

In the normal existing formulation, the number of opportunities is assumed to be one opportunity per component purchased or per product delivered. Hence by means of various combinations, the final number of opportunities is arrived at one whole number. Now with the new formulation, the number of opportunities is assumed to be reduced considerably because the characterizations developed for each process step reduces the number of opportunities. Here again, the assumption might lead to some minor errors in the formulation. To avoid this problem, the two decision variables are introduced which make the denominator reach a subtle value, which justifies the number of opportunities in the DPMO calculation.

5.3 Example for the Justification

Let us take an example which would justify the formulation to some extent. Let us make the analysis using both formulations and then compare the difference.

The assumed data for the analysis are as follows:

Total number of products manufactured = 5000

Total number of defects in the lot = 175

Number of Opportunities in the existing formulation = 1300

Number of Opportunities in the improved (scaled) formulation = 1100

The final formula scale is obtained by finding the average of the formula scale for all the opportunities.

Let us assume that the final formula scale is 0.772

Let us take α = Formula Scale = 0.772

$\beta = (1-0.772) = 0.228$

The calculation part for the existing and improved analysis is shown below:

Existing Analysis:

DPMO for existing analysis = ((175/5000) / 1300) * 1000000

= 26.92

Improved Analysis:

DPMO for improved analysis = ((175/5000) / (0.772 *1300 + 0.228 * 1100)) * 1000000

= 27.01

5.4 Sigma Level for the Analysis

The final sigma scale corresponding to the DPMO figure in the above example is 5.54 using the existing formulation and 5.53 using the improved formulation.

The sigma level using the improved formulation has come down a little from the original formulation. Though the change is not drastic, the improved formulation provides a more streamlined method for achieving the sigma level for one opportunity than to the original formulation. The VBA editor and macros are used in spreadsheets for the trials that were developed in the previous chapters. The new formulation is also employed in the spreadsheet calculation and the final sigma level for the number of opportunities is also determined.

5.5 Spreadsheet Calculations

The VBA editor and Excel macros have been employed for developing the analysis so that the values can be entered easily. The spreadsheet calculations are done with the three trials explained earlier and the final sigma level for the process is determined using the new formulation of Defects Per Million Opportunities. The screenshots of the analysis using various trials and the forms that were developed for the analysis are shown one after another for the three trials. The trials are formed on the basis of example in Section 5.3 of this chapter.

Figure 5.5.1 shows the spreadsheet screenshot of Trial 1 with the macros on the top of each factor. The macros are equivalent to the forms in the classical visual basic software where the input can be given. The command buttons are used for calculation and also for the output determination on the spreadsheet. The option buttons are used to select the equivalent scale depending on the nature of the part under analysis. The macros forms are also presented which are helpful for the spreadsheet calculation.

Rationalized Formula Scale for the Defect Opportunities in the Manufacturing of a Product

Trial 1

Severity | Occurence | Detection | Time Ratio | Time | Cost Ratio | Cost

Opportunity	Severity	Occurrence	Detection	Time Ratio	Time Rating	Cost Ratio	Cost Rating	Formula Scale	DPMopp	Sigma
1	10	10	10	50.00	10	20.00	9	0.98	9.26	5.81
2	9	7	4	33.33	10	66.67	10	0.8	9.52	5.8
3	9	4	2	133.33	10	50.00	10	0.7	9.68	5.8
4	7	9	3	75.00	10	75.00	10	0.78	9.55	5.8
5	5	6	6	75.00	10	30.00	10	0.74	9.62	5.8
6	4	5	7	71.43	10	20.00	9	0.7	9.68	5.8
7	8	6	8	75.00	10	42.86	10	0.84	9.46	5.81
8	3	6	9	100.00	10	80.00	10	0.76	9.58	5.8
9	4	7	10	10.00	9	83.33	10	0.8	9.52	5.8
10	10	9	6	25.00	10	62.50	10	0.9	9.38	5.81
11	7	10	10	20.00	9	83.33	10	0.92	9.35	5.81
12	3	8	6	16.67	9	71.43	10	0.72	9.65	5.8
13	2	5	2	42.86	10	75.00	10	0.58	9.87	5.8
14	1	9	5	75.00	10	70.00	10	0.7	9.68	5.8
15	4	9	1	300.00	10	200.00	10	0.68	9.71	5.8
16	6	8	7	25.00	10	13.33	9	0.8	9.52	5.8
17	10	8	2	50.00	10	66.67	10	0.8	9.52	5.8
18	8	6	9	200.00	10	200.00	10	0.86	9.43	5.81
19	9	4	4	25.00	10	25.00	10	0.74	9.62	5.8
20	6	3	3	66.67	10	66.67	10	0.64	9.77	5.8
								0.772	9.57	5.8025

Figure 5.5.1 Screenshot of the spreadsheet for trial 1 with the macros on the top.

The Defect Severity form used here is shown in Figure 5.5.2. The Defect severity form has various option buttons with the various definitions of the scale as presented in Tables of chapter 3. The user can choose the options and enter the values.

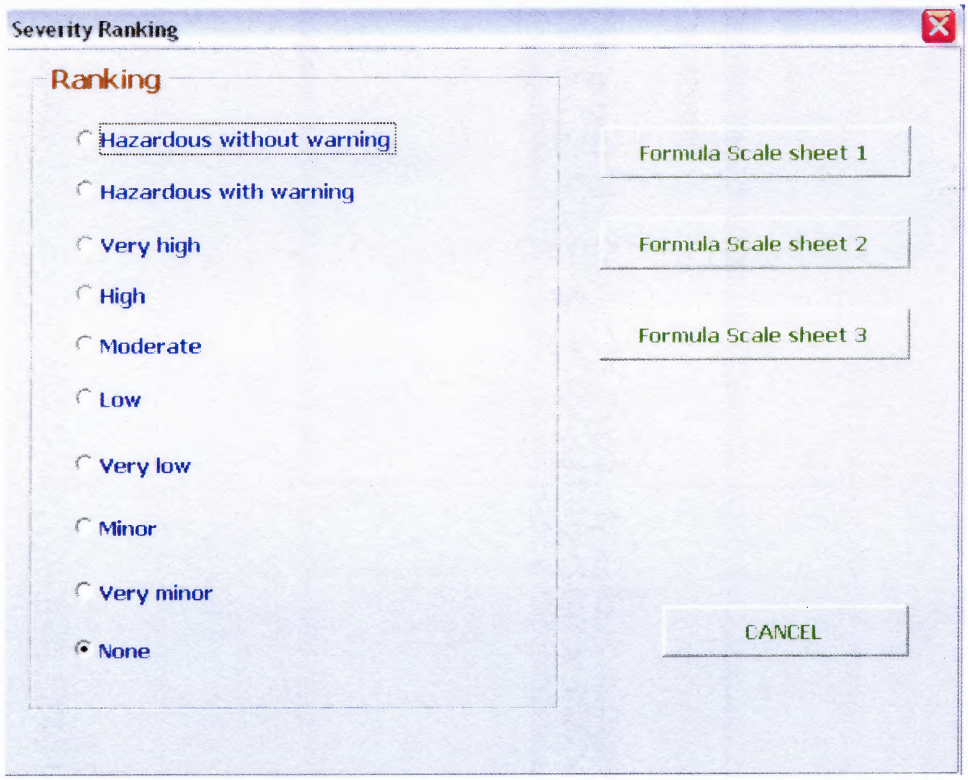


Figure 5.5.2 Defect Severity Form.

The Occurrence Frequency form is shown in Figure 5.5.3

Figure 5.5.3 Occurrence Frequency Form.

The forms for the three factors have three buttons namely formula scale 1, 2 and 3 for the three trials. The Detection Ease form is shown in Figure 5.5.4 and it has similar features as the other two factors. The cost/time ratio calculation form is shown in Figure 5.5.5

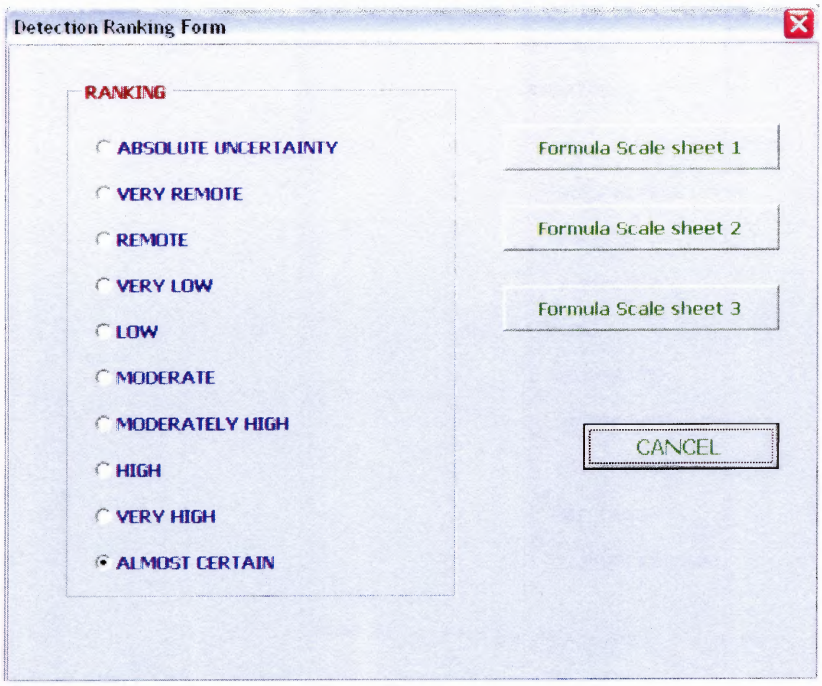


Figure 5.5.4 Detection Ease Form.

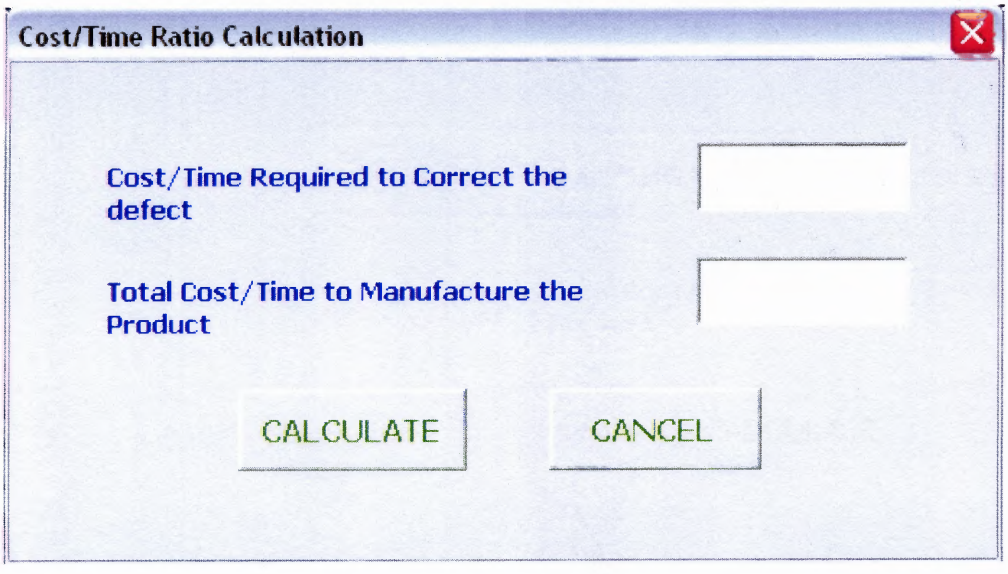


Figure 5.5.5 Cost / Time ratio Calculation Form.

The Correction Time form is shown in Figure 5.5.6 which has same features like other factors. The Cost Impact form is shown in Figure 5.5.7.

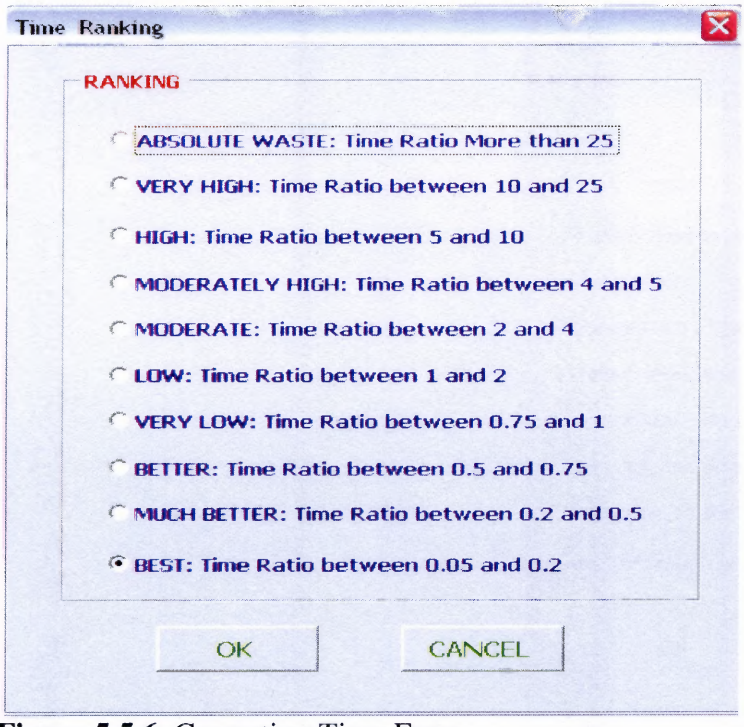


Figure 5.5.6 Correction Time Form.

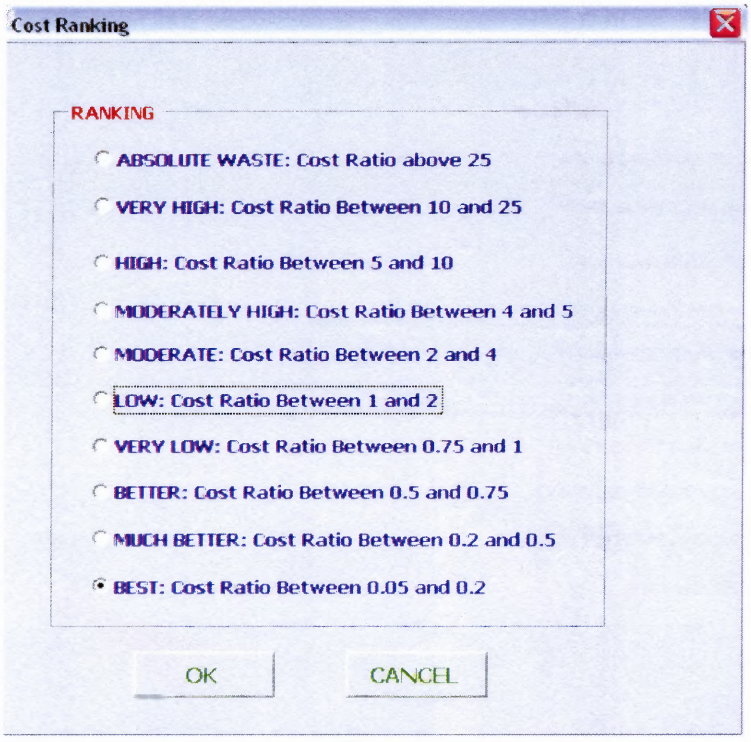


Figure 5.5.7 Cost Impact Form.

For Trials 2 and 3, the cost and time factors are grouped and the grouping form for the Trials is shown in Figure 5.5.8.

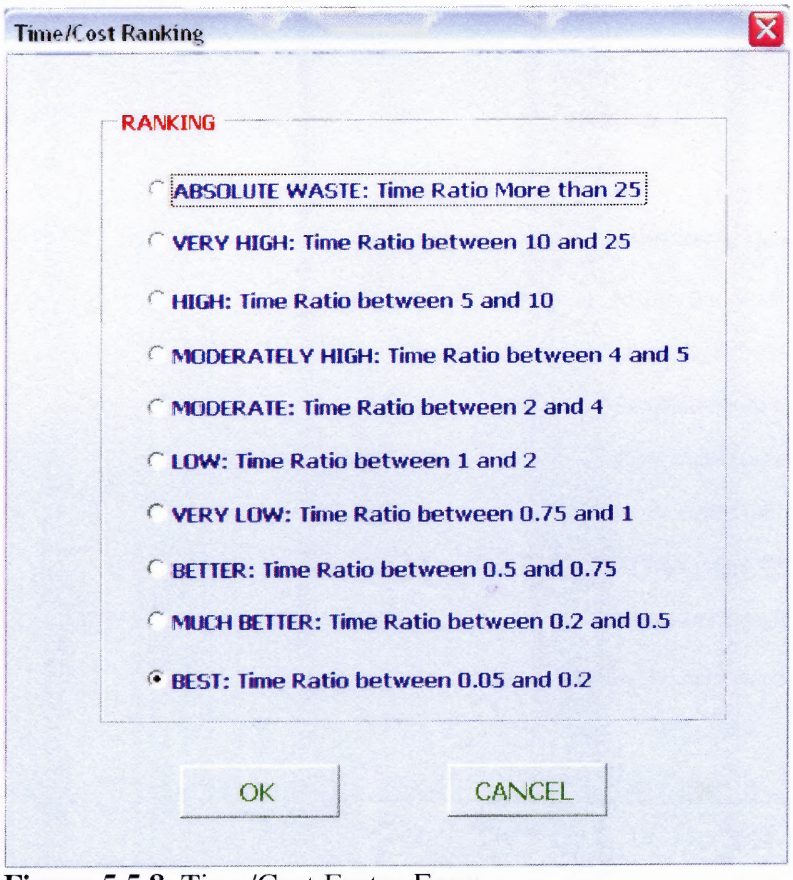


Figure 5.5.8 Time/Cost Factor Form.

Risk priority numbers are used for Trials 2 and 3 and the form is shown in Figure 5.5.9. Although Trial 3 uses priority number, the format of the form is the same as in the risk priority number form. The spreadsheet screenshot of trial 2 is shown in Figure 5.5.10 and it has the same numbers and assumptions. Similarly the spreadsheet screenshot of Trial 3 is shown in Figure 5.5.11. The screenshots show the format of the trials that have been implemented in the analysis section of the preceding chapters. The macros have been implemented to enhance the efficiency of the process. The sigma levels for the three trials are also presented in the discussion using the common assumptions.

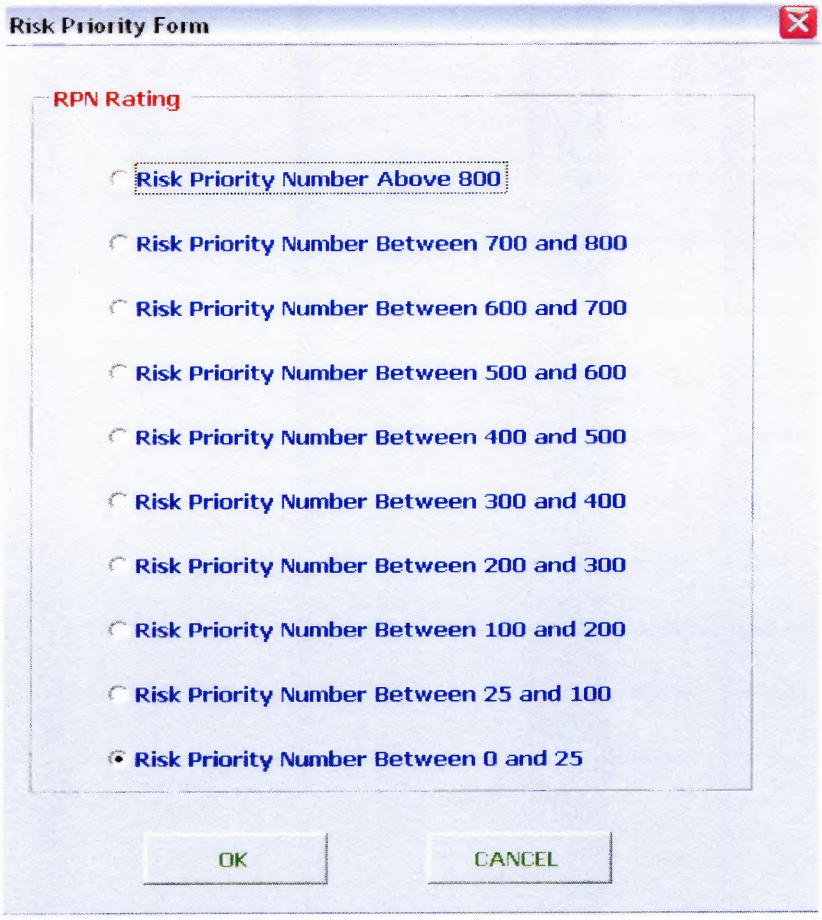


Figure 5.5.9 Risk Priority Number Form.

Rationalized Formula Scale for the Defect Opportunities in the Manufacturing of a Product

Trial 2

Severity	Occurrence	Detection	Risk Priority Number	Risk Priority Rating	Cost/Time Ratio	Cost/Time Rating	Formula Scale	DPMopp	Sigma
9	9	10	810.00	10	50.00	10	1	9.23	5.79
9	7	9	567.00	2	50.00	10	0.2	10.53	5.76
8	6	8	384.00	0.5	200.00	10	0.05	10.81	5.75
7	9	3	189.00	1	75.00	10	0.1	10.71	5.75
5	6	6	180.00	1	75.00	10	0.1	10.71	5.75
2	5	7	70.00	1	71.43	10	0.1	10.71	5.75
8	6	8	384.00	3	75.00	10	0.3	10.34	5.76
3	6	9	162.00	1	100.00	10	0.1	10.71	5.75
4	7	10	280.00	2	10.00	9	0.18	10.56	5.76
10	9	6	540.00	5	25.00	10	0.5	10.00	5.77
7	10	10	700.00	6	20.00	9	0.54	9.93	5.77
3	8	6	144.00	1	16.67	9	0.09	10.73	5.75
2	5	2	20.00	0	42.86	10	0	10.91	5.75
1	9	5	45.00	0.5	75.00	10	0.05	10.81	5.75
4	9	1	36.00	0.5	300.00	10	0.05	10.81	5.75
6	8	7	336.00	3	25.00	10	0.3	10.34	5.76
10	8	2	160.00	1	50.00	10	0.1	10.71	5.75
8	6	9	432.00	4	200.00	10	0.4	10.17	5.77
9	4	4	144.00	1	25.00	10	0.1	10.71	5.75
6	3	3	54.00	0.5	66.67	10	0.05	10.81	5.75
								10.51	5.757

Figure 5.5.10 Screenshot of the spreadsheet for trial 2.

Rationalized Formula Scale for the Defect Opportunities in the Manufacturing of a Product

Trial 3

Detection | Cost Time Ratio | Cost Time | Severity | Priority Rating | Occurence

Detection Rating	Cost/Time Ratio	Cost/Time Rating	Severity Rating	Priority Number	Priority Rating	Occurrence Rating	Formula Scale	DPMopp	Sigma
10	50.00	10	10	1000	10	9	0.9	9.38	5.78
9	50.00	10	9	810	10	7	1	9.23	5.79
8	200.00	10	8	640	6	6	0.6	9.84	5.77
3	75.00	10	4	120	1	9	0.1	10.71	5.75
6	75.00	10	6	360	1	6	0.1	10.71	5.75
7	71.43	10	5	350	1	5	0.1	10.71	5.75
8	75.00	10	4	320	3	6	0.3	10.34	5.76
9	100.00	10	4	360	1	6	0.1	10.71	5.75
10	10.00	9	3	270	2	7	0.18	10.56	5.76
6	25.00	10	3	180	5	9	0.5	10.00	5.77
10	20.00	9	5	450	6	10	0.54	9.93	5.77
6	16.67	9	6	324	1	8	0.09	10.73	5.75
2	42.86	10	4	80	6	5	0	10.91	5.75
5	75.00	10	3	150	0.5	9	0.05	10.81	5.75
1	300.00	10	4	40	0.5	9	0.05	10.81	5.75
7	25.00	10	5	350	3	8	0.3	10.34	5.76
2	50.00	10	4	80	1	8	0.1	10.71	5.75
9	200.00	10	7	630	4	6	0.4	10.17	5.77
4	25.00	10	5	200	1	4	0.1	10.71	5.75
3	66.67	10	4	120	0.5	3	0.05	10.81	5.75
								10.41	5.76

Figure 5.5.11 Screenshot of the spreadsheet for trial 3.

The DPMO column in the screenshots of all trials involves the implementation of the new formulation. The final sigma levels for the trials are calculated using the various assumptions presented in the Section 5.3 of this Chapter. The sigma level for the trials is compared with the original formulation of DPMO. The sigma level for Trial 1 is shown in Figure 5.5.12.

Normal	No. of Products Manufactured	5000	(Change the No. Of Products Manufactured here)
	Total No. of Defects	175	(Change the No. of defects here)
	DPU	0.035	
	No. of Opportunities	1300	(Change the Number of Opportunities here)
	DPMOpp	26.92307692	
	Sigma Level	5.54	(From the original scaling look up table)
Improved	No. of Products Manufactured	5000	
	Total No. of Defects	175	
	DPU	0.035	
	No. of Opportunities	1100	(Change the Number of Opportunities here)
	DPMOpp	27.91	
	Sigma Level	5.53	(From the original scale look up table)

Figure 5.5.12 Sigma Level for Trial 1.

The sigma level for Trial 2 is shown in Figure 5.5.13.

Normal	No. of Products Manufactured	5000	(Change the No. Of Products Manufactured here)
	Total No. of Defects	175	(Change the No. of defects here)
	DPU	0.035	
	No. of Opportunities	1300	(Change the Number of Opportunities here)
	DPMOpp	26.92307692	
	Sigma Level	5.54	(From the original scaling look up table)
Improved	No. of Products Manufactured	5000	
	Total No. of Defects	175	
	DPU	0.035	
	No. of Opportunities	1100	(Change the Number of Opportunities here)
	DPMOpp	30.67	
	Sigma Level	5.51	(From the original scale look up table)

Figure 5.5.13 Sigma Level for Trial 2.

The sigma level for Trial 3 is shown in Figure 5.5.14

Normal	No. of Products Manufactured	5000	(Change the No. Of Products Manufactured here)
	Total No. of Defects	175	(Change the No. of defects here)
	DPU	0.035	
	No. of Opportunities	1300	(Change the Number of Opportunities here)
	DPMOpp	26.92307692	
	Sigma Level	5.54	(From the original scaling look up table)
Improved	No. of Products Manufactured	5000	
	Total No. of Defects	175	
	DPU	0.035	
	No. of Opportunities	1100	(Change the Number of Opportunities here)
	DPMOpp	30.36	
	Sigma Level	5.52	(From the original scale look up table)

Figure 5.5.14 Sigma Level for Trial 3.

5.6 Case Study

The case study used for the analysis of the formulation is the manufacturing of printed circuit boards. Printed circuit boards have various parts, and the most important defect producing parts are listed and the opportunities for the parts to be defective are analyzed. The five major parts that define a printed circuit board are (i) Board (ii) Resistor (iii) Capacitor (iv) Diode (v) Solder Joint.

The number of defect opportunities for each part is assumed to be as shown in Table 5.6.1.

Table 5.6.1 Defect Opportunities count for parts in the board

Part in the Printed Circuit Board	Number of Opportunities
Board	1
Resistor	13
Capacitor	4
Diode	2
Solder Joint	38

The number of opportunities is 58 and now the same analysis is now done for each opportunity. The decision variables are also calculated and shown in the study. In addition to the two decision variables α and β, a new decision variable called γ is also introduced which is "the opportunity inflation factor". The opportunity inflation factor is calculated using a formula.

The formula for finding the Opportunity inflation factor is shown below,

$$\text{Opportunity inflation factor } \gamma = \frac{\text{Total Opportunities} - \text{Scaled Opportunities}}{\text{Scaled Opportunities}}$$

The final scale for the various opportunities (parts) is calculated using the macro forms developed for each trial. Every trial has a single form which has all the data needed for input and by giving the necessary inputs; the output is obtained in the spreadsheet. The input form for Trial 1 is shown in Figure 5.6.1.

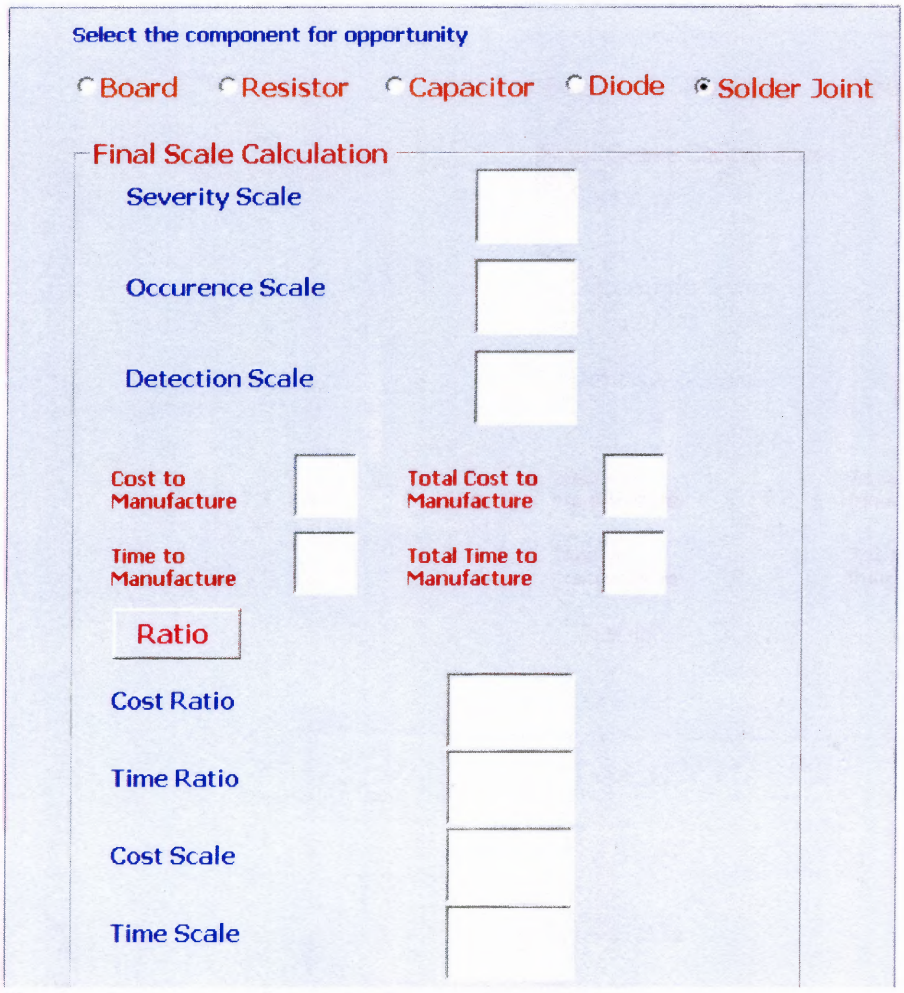


Figure 5.6.1 Input Form for Trial 1.

The input form for Trial 1 has the factors severity, occurrence and detection together with the cost ratio calculation input. The command button ratio gives the cost ratios and ratings directly. The final scale is also obtained.

The input form for trial 2 is shown in figure 5.6.2.

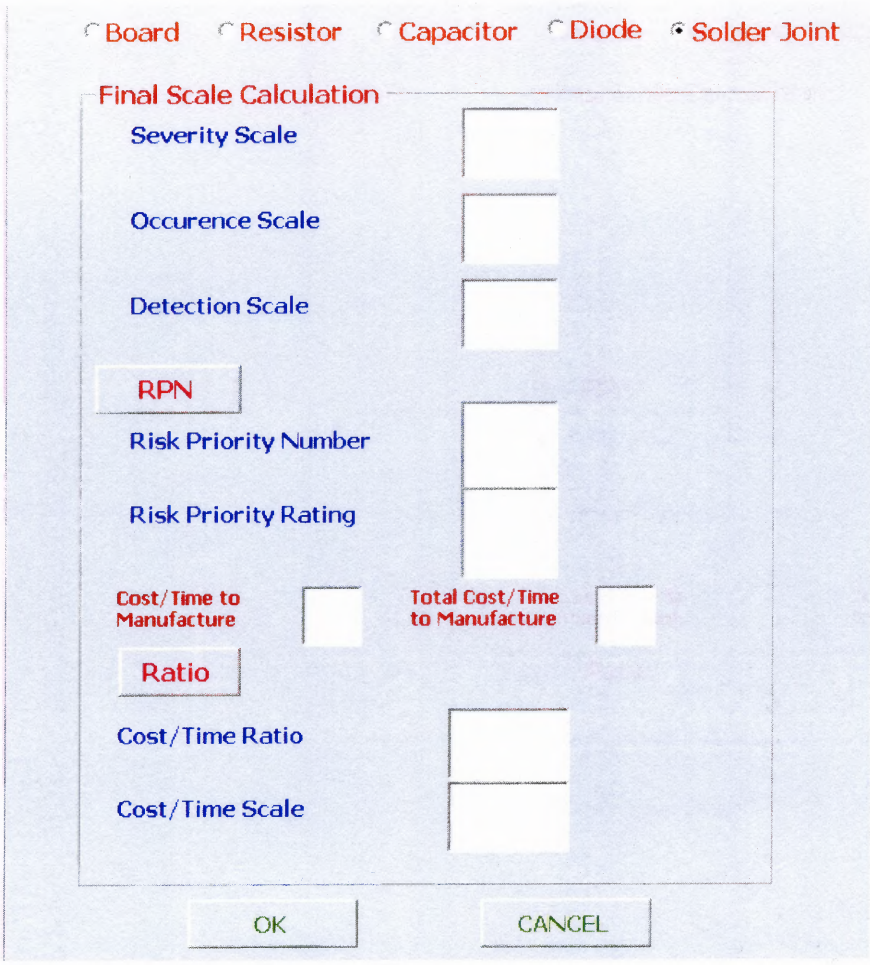


Figure 5.6.2 Input Form for Trial 2.

The input from for Trial 2 also has the factors severity, occurrence and detection but it also has the risk priority number and the rating. The command button RPN gives the values when the button is hit and then on giving the input for the time and total time for manufacturing, the cost/time ratio is obtained. The input form for Trial 3 is shown in Figure 5.6.3.

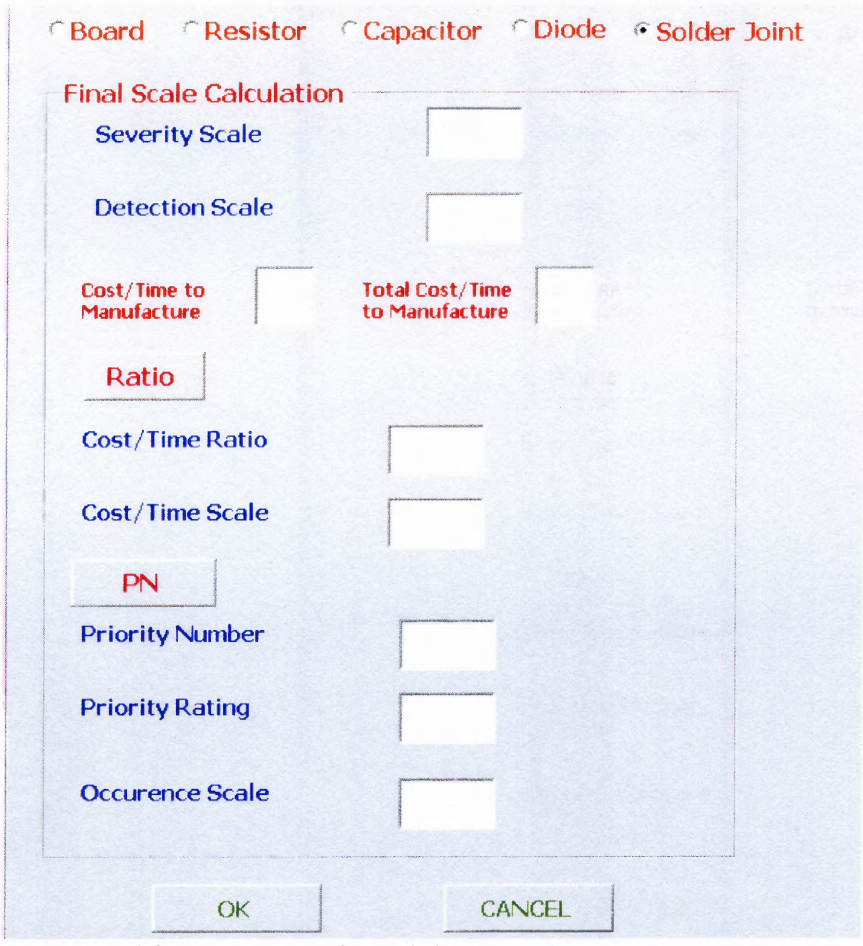


Figure 5.6.3 Input Form for Trial 3.

The input from for Trial 3 also has the factors severity and detection and the priority number and the rating. The command button RPN gives the values when the button is hit and then on giving the input for the time and total time for manufacturing, the cost/time ratio is obtained. Unlike Trial 2, Trial 3 has ratio command button first followed by the priority number command button. Finally, the final formula scale is obtained for each opportunity. The values for the three trials are shown in Appendix A.

When the process is done for 58 opportunities, the final formula scale for all opportunities is added to produce the "scaled opportunities". Once the scaled opportunities are obtained, the opportunity inflation factor can be determined. Then the decision variables α and β are also determined. Then using the new formulation, the

DPMO is determined and from the DPMO, the sigma level is determined using the sigma scale. The sigma scale is added for the 58 opportunities giving the final sigma level for printed circuit board manufacturing. The number of products manufactured and the defects are assumed.

Graphs are drawn between the Decision variable α and the sigma level for each opportunity. As the decision variable α decreases, the sigma level also decreases except at some points where it shoots up. This is because of the opportunity inflation factor. Hence as the scaled opportunity increases, the inflation factor decreases. The behavior of the graphs for various trials is shown. The behavior of the graphs for the three trials has the same assumption values as follows:

Total number of products manufactured = 5000

Total number of defects = 10

The graph for Trial 1 with 58 opportunities and 40.52 scaled opportunities is shown in Figure 5.6.4

Graphical Representation of the relationship between Alpha and Sigma Level

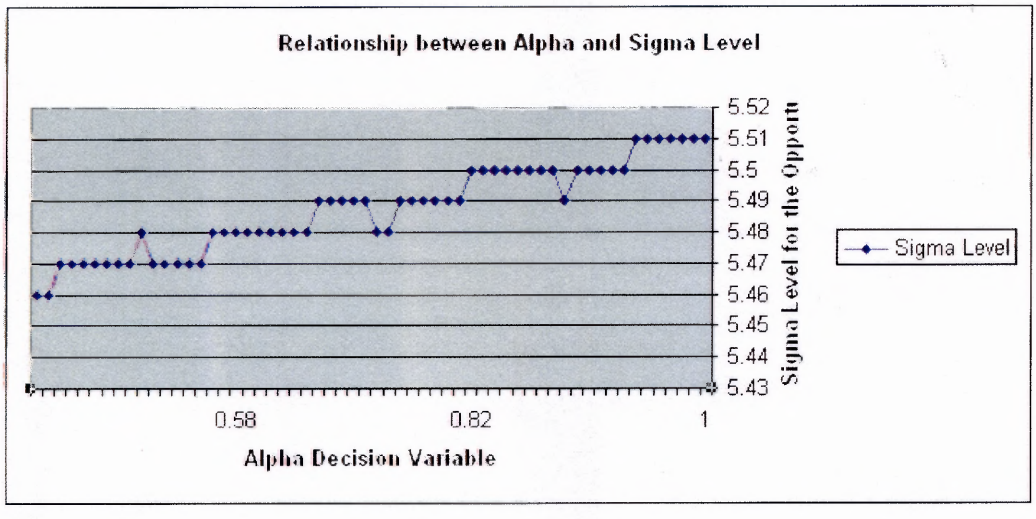


Figure 5.6.4 Graph for Trial 1.

The graph for Trial 2 with 14.52 final scaled opportunities is shown in Figure 5.6.5

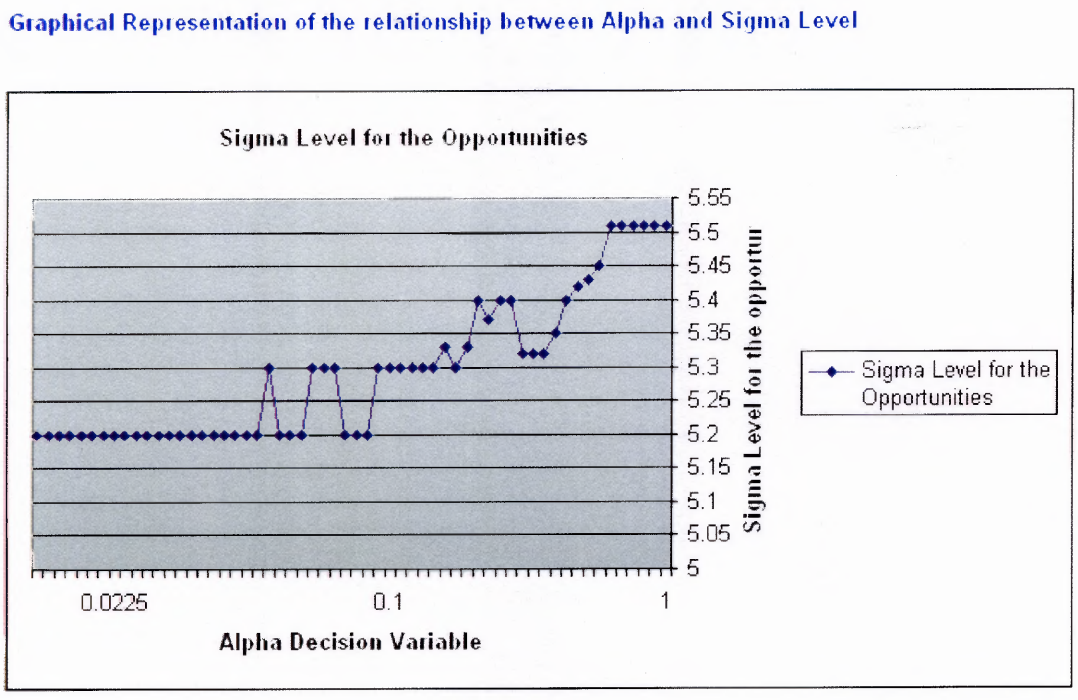


Figure 5.6.5 Graph for Trial 2.

The graph for Trial 3 with 14.52 scaled opportunities is shown in Figure 5.6.6

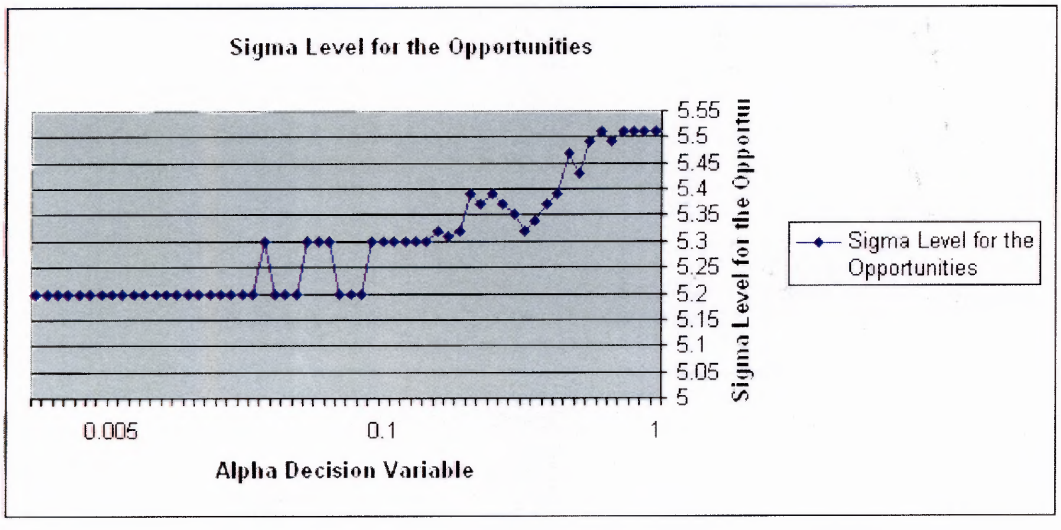


Figure 5.6.6 Graph for Trial 3.

For the same set of values, the final sigma level changes considerably in the Trials. The Alpha (α) decision variable (formula scale) for Trial 1 shows a decrease consistently for various values of the factors. It also shows a decrease when the sigma level decreases. The α values for Trials 2 and 3 keeps decreasing for smaller sigma levels. According to the formulation, as α decreases, the DPMO increases and hence the corresponding sigma level decreases. Hence the graphs for the Trials also show the similar behavior. The opportunity inflation factor γ is also calculated for all Trials. As γ increases, the total number of scaled opportunities decreases and hence the sigma level can experience erratic behavior. This is illustrated as follows:

Let N be the total number of opportunities and M be the total number of scaled opportunities. According to the definition of γ,

$\gamma = (N - M) / M$, which implies that $M\gamma = N - M$

Now, $M\gamma + M = N$

Finally, $\mathbf{M = N / (1 + \gamma)}$

As γ increases, M decreases. As M decreases, DPMO increases and the corresponding sigma level decreases. Hence for a better sigma level, the total number of scaled opportunities must be greater. From the analysis, the number of scaled opportunities for Trial 1 was 40.52 which had a better sigma rating than the other Trials.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

6.1 Conclusion

The rationalized formulation of the defect per million opportunities provides a definitive approach for sigma calculation. The multi-factor scheme developed using MS Excel provides an insight into the defects that are unaccounted and thereby resulting in a meaningful formulation. Every opportunity is considered and the factors corresponding to the opportunities are scaled properly to arrive at the scaled opportunity, which is later utilized to find the final sigma level and also the behavior of the product at the sigma levels. The results were plotted on a graph to see the effect of the opportunity inflation factor. The three trials employed the same set of input values for the factors and the final output graphs were compared to choose the best trials. The behavior of the graphs at various levels of defects can be analyzed using the macros of the MS Excel sheet.

The formulation can be extended to various levels of opportunities and also the behavior can be analyzed by the graphs between the variables and the sigma level. The sudden peak in the sigma level is due to the assumed numbers used in the spreadsheet. The best possible method is to characterize the components with highly pronounced defects initially followed by less pronounced defects so as to get a steeping curve touching the lower level of sigma. Sudden lower peaks experienced in this order might be because of the factors and hence those products can be discarded or reworked depending upon the cost constraints. Finally, too many lower peaks show that the product is suffering from a major problem and so the quality constraints must be made better with

lesser tolerances so that the product's quality remains in control. Thus the multi-factor method helps in evaluating the defect opportunities by modifying the classical Six Sigma formulation.

6.2 Scope for Future Research

The scope of this thesis was limited to five factors that were formed for the multi-factor scheme using MS Excel. The number of factors that have been employed can be increased and the factors must characterize the product in some aspect. The factors that are added can be scaled again and then can be grouped together to make the process tighter and in control. The trial values can be implemented and checked for some real value (data) and the final sigma level using the classical Six Sigma and the Rationalized formulated Six Sigma can be verified. There might be subtle differences between the two formulations but the differences would not be very large. The scope of the thesis allows the transformation of the formulation but the sigma level is transformed a little because the initial assumption was that the formulation skews and distorts depending on the defect rate. The only difference between the classical and the formulated approach is that the latter employs a well-defined multi-factor scheme for evaluating the defect opportunities while the former employs an assumption to reach the conclusion.

Immediate future research can employ real data and validate the formulation and analyze the behavior of the product subjected to various factor analysis. The final defect analysis and sigma level can also be cross-checked so as to ensure the consistency of the formulation.

APPENDIX A

RELATION BETWEEN SIGMA LEVEL AND DPMO

SL	F(SL + 1.5)	F(1.5 - SL)	Probability good	Probability of a defect	DPMO
0	0.933192771	0.933192771	0	1	1,000,000
0.25	0.959340886	0.894350161	0.065590726	0.934409274	934,409.2745
0.5	0.977249938	0.84134474	0.135905198	0.864094802	864,094.8023
0.75	0.987775567	0.77337272	0.214402846	0.785597154	785,597.1537
1	0.99379032	0.691462467	0.302327853	0.697672147	697,672.1472
1.25	0.997020191	0.598706274	0.398313908	0.601686092	601,686.0924
1.5	0.998650033	0.5	0.498650033	0.501349967	501,349.967
1.75	0.999422914	0.401293726	0.598129187	0.401870813	401,870.8127
2	0.999767327	0.308537533	0.691229794	0.308770206	308,770.206
2.25	0.999911555	0.22662728	0.773284276	0.226715724	226,715.7243
2.5	0.999968314	0.15865526	0.841313054	0.158686946	158,686.9458
2.75	0.999989304	0.105649839	0.894339465	0.105660535	105,660.5348
3	0.999996599	0.066807229	0.93318937	0.06681063	66,810.6296
3.25	0.999998982	0.040059114	0.959939868	0.040060132	40,060.1319
3.5	0.999999713	0.022750062	0.977249651	0.022750349	22,750.34914
3.75	0.999999924	0.012224433	0.98777549	0.01222451	12,224.50961
4	0.999999981	0.00620968	0.993790301	0.006209699	6,209.698895
4.25	0.999999996	0.002979819	0.997020177	0.002979823	2,979.823064
4.5	0.999999999	0.001349967	0.998650032	0.001349968	1,349.968213
4.75	1	0.000577086	0.999422913	0.000577087	577.0866996
5	1	0.000232673	0.999767327	0.000232673	232.673414
5.25	1	8.84446E-05	0.999911555	8.84446E-05	88.44459787
5.5	1	3.1686E-05	0.999968314	3.1686E-05	31.6860359
5.75	1	1.06957E-05	0.999989304	1.06957E-05	10.69568586
6	1	3.4008E-06	0.999996599	3.4008E-06	3.400803094
6.25	1	1.01833E-06	0.999998982	1.01833E-06	1.0183285
6.5	1	2.87105E-07	0.999999713	2.87105E-07	0.287105
6.75	1	7.62014E-08	0.999999924	7.62014E-08	0.076201358
7	1	1.90364E-08	0.999999981	1.90364E-08	0.019036399

SL – Sigma level DPMO – Defects per million opportunities

This table is taken from References (American Society for Quality, January 2002, Sigma Limits and Defects per million opportunities).

(http://www.asq.org/pub/qualityprogress/past/0102/27sidebar0102.html)

APPENDIX B

INPUT TABLE FOR THE TRIALS

Opportunity	Severity	Occurrence	Detection	Cost/time input values
1 (Board)	10	10	10	1/1
2 (Resistor)	10	10	10	1/1
3	10	10	9	1/0.5
4	9	10	10	0.5/1
5	9	9	10	0.5/1
6	9	10	9	1/1
7	9	9	9	1/1
8	9	9	9	1/5
9	9	8	9	2/6
10	8	8	8	2/6
11	8	8	7	0.5/4
12	7	8	7	0.5/4
13	7	7	7	0.5/4
14	7	7	8	4/7
15 (Capacitor)	10	8	7	3/5
16	8	8	8	2/6
17	7	8	8	2/6
18	7	8	9	3/6
19 (Diode)	7	7	7	3/6
20	7	6	7	3/6
21 (Solder Joint)	7	7	7	1/0.5
22	5	7	5	1/0.5
23	5	7	6	1/0.5
24	6	6	6	1/0.5
25	5	6	6	1/0.5
26	5	5	5	2/0.5
27	5	5	4	3/0.5
28	4	5	4	3/0.5
29	4	4	4	0.5/0.5
30	6	4	4	0.5/0.5
31	6	5	4	0.5/0.5
32	6	5	5	0.5/0.5
33	4	5	6	0.5/0.5
34	4	4	4	0.1/0.5
35	5	4	4	0.1/0.5
36	5	5	4	0.1/0.5
37	5	5	5	0.1/0.5
38	5	5	3	0.1/0.5

APPENDIX B (Continued)

39	5	4	3	0.1/0.5
40	5	3	3	0.1/0.5
41	4	4	3	0.1/0.5
42	4	3	3	0.1/0.5
43	3	3	3	0.2/1
44	3	3	2	0.2/1
45	3	2	2	0.2/1
46	2	2	2	0.2/1
47	4	2	2	0.2/1
48	4	2	4	0.2/1
49	4	2	3	0.2/1
50	3	2	3	0.2/1
51	2	2	3	0.2/1
52	1	2	2	0.2/1
53	1	1	2	0.2/1
54	2	1	2	0.2/1
55	2	1	1	0.2/1
56	1	1	1	0.2/3
57	1	1	1	0.2/3
58	1	1	1	0.2/3

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